Third International Workshop on
Compound Nuclear Reactions and Related Topics

Book of Abstracts

September 19 – 23, 2011
Prague, Czech Republic
Third International Workshop on
Compound Nuclear Reactions and Related Topics

Program

Sunday
18.00 – 20.00 registration + welcome drink

Monday

Openingsession chair M. Krtička

8.15 – 9.00 registration
9.00 – 9.10 opening of the CNR*11
9.10 – 9.50 T. Kawano (LANL)
Monte Carlo simulation for statistical decay of compound nucleus
9.50 – 10.30 I. Rotter (Max Planck Institut, Dresden)
Dynamical phase transitions in quantum mechanics
10.30 – 11.05 F.-J. Hambsch (EC-JRC-Institute, Geel)
Neutron induced fission of $^{234}U$
11.05 – 11.40 coffee break

Fission chair F.-J. Hambsch

11.40 – 12.15 A. Barabanov (NRC Kurchatov Institute, Moscow)
Fission via compound states and $J^\pi$ A.Bohr’s channels: What we can
learn from recent studies with slow neutrons
12.15 – 12.40 P. Talou (LANL)
Monte Carlo Hauser-Feshbach calculations of prompt neutrons and
gamma rays
12.40 – 13.05 N. Carjan (CENBG, NIPNE - HH Bucharest)
Non-adiabatic transition of the fissioning nucleus at scission: the time
scale
13.05 – 14.30 lunch

Surrogate reactions chair T. Kawano

14.30 – 15.05 J. Escher (LLNL)
Neutron-capture cross sections from indirect measurements
15.05 – 15.30  G. Boutoux (Centre d’Etudes Nucléaires de Bordeaux)
*Neutron-induced cross sections of short-lived nuclei via the surrogate reaction method*

15.30 – 15.55  J. Wilson (Institut de Physique Nucléaire d’Orsay)
*Level densities in the actinide region and indirect n,γ cross section measurements using the surrogate method*

15.55 – 16.30  coffee break

**Heavy Ion Reactions** *chair J. Randrup*

16.30 – 16.55  J. P. Wieleczko (GANIL)
*Asymmetric fission in Kr+Ca reactions at 5.5 AMeV*

16.55 – 17.20  A. Di Nitto (INFN, Napoli)
*Clustering effects in 48Cr composite nuclei produced via 24Mg + 24Mg reaction*

17.20 – 17.45  G. Politi (INFN and Dipartimento di Fisica e Astronomia, Catania)
*Study and comparison of the decay modes of the systems formed in the reactions 78Kr + 40Ca and 86Kr + 48Ca at 10 AMeV*

---

**Tuesday**

**Neutron-induced reactions** *chair F. Käppeler*

9.00 – 9.30  E. Chiaveri (CERN)
*Present status and future programs of n_TOF experiment*

9.30 – 10.00  B. Baramsai (North Carolina State University)
*Neutron capture experiments with 4π DANCE Calorimeter*

10.00 – 10.25  L. S. Leong (Institut de Physique Nucléaire d’Orsay)
*Criticality experiments for validation of cross sections: the neptunium case*

10.25 – 10.50  R. Firestone (LBNL)
*Analysis of statistical model properties from discrete nuclear structure data*

10.50 – 11.20  coffee break

**Gamma-Ray Strength Functions** *chair J. Kopecký*

11.20 – 11.50  E. Grosse (HZDR and TU Dresden)
*Description of dipole strength in heavy nuclei in conformity with their quadrupole degrees of freedom*

11.50 – 12.15  M. Guttormsen (University of Oslo)
*Do light nuclei display a universal γ-ray strength function?*
12.15 – 12.40  **J. Kroll** (Charles University in Prague)
*Scissors mode resonances built on excited levels in Gd nuclei studied from resonance neutron capture*

12.40 – 13.05  **R. Massarczyk** (HZDR and TU Dresden)
*Investigation of dipole strength at the ELBE accelerator in Dresden-Rossendorf*

13.05 – 14.30  lunch

**Nuclear Astrophysics**  *chair R. Capote*

14.30 – 15.00  **F. Käppeler** (Karlsruhe Institute of Technology)
*Stellar neutron capture rates and the s process*

15.00 – 15.25  **S. V. Harissopulos** (Demokritos, Athens)
*Capture reactions relevant to p-process nucleosynthesis*

15.25 – 15.50  **P. Navrátil** (TRIUMF, Vancouver)
*Ab initio calculations of $^3\text{H}(d,n)^4\text{He}$ fusion*

15.50 – 16.15  **V. A. Khryachkov** (IPPE, Obninsk)
*(n,α) reactions cross sections reasearch at IPPE*

16.15 – 16.45  coffee break

16.45 – 18.30  poster session

**Wednesday**

**Superheavy nuclei**  *chair N. Carjan*

9.00 – 9.30  **Y. Oganessian** (JINR Dubna)
*Reaction of synthesis and decay properties of superheavy element*

9.30 – 10.00  **R. Sagaidak** (JINR Dubna)
*Fusion probability and survivability in estimates of heaviest nuclei production*

10.00 – 10.25  **A. Zubov** (JINR Dubna)
*Population of rotational bands in superheavy nuclei*

10.25 – 10.50  **S. Kumar** (Chitkara University, Solan, India)
*Alpha decay chains study of new superheavy element Z = 117*

10.50 – 11.20  coffee break
Nuclear Level Density

chair M. Guttormsen

11.20 – 11.50 Y. Alhassid (Yale University)
Microscopic calculation of level densities: the shell model Monte Carlo approach

11.50 – 12.15 A. Voinov (Ohio University)
Recent experimental results on level densities for compound reaction calculations

12.15 – 12.40 C. Ozen (Kadir Has University, Istanbul)
Recent progress in shell model Monte Carlo studies of heavy nuclei

12.40 – 13.05 B. Zhuravlev (IPPE, Obninsk)
Statistical properties of excited nuclei in the mass range $47 \leq A \leq 59$

13.05 – 14.30 lunch

15.00 excursion to Prague Castle

Thursday

Various nuclear reactions

chair Y. Alhassid

9.00 – 9.40 H. Weidenmüller (Max Planck Institut, Heidelberg)
Compound-nucleus reactions induced by femtosecond multi-MeV laser pulses

9.40 – 10.05 C. Gustavsson (Uppsala University)
Inelastic neutron scattering from carbon, iron, yttrium and lead

10.05 – 10.30 Y. Iwata (GSI)
Momentum-dependent nucleus-nucleus interaction resulting in dissipative reaction dynamics

10.30 – 10.55 G. Arbanas (ORNL)
Extending the Kawai-Kerman-McVoy statistical theory of nuclear reactions to doorway states

10.55 – 11.25 coffee break

Fission

chair P. Talou

11.25 – 11.55 O. Bouland (CEA, Cadarache)
Analysis of the $(n,f)$ reaction in the Pu isotopes

11.55 – 12.20 R. Bernard (CEA, DAM, DIF)
Taking into account the intrinsic excitations and their coupling to collective modes during the fission process
12.20 – 12.45  **J. Mierzejewski** (University of Warsaw)
*The Incomplete Fusion reaction modeling*

12.45 – 13.05  **A. Yadav** (Aligarh Muslim University, Aligarh, India)
*Effect of alpha Q-value on reaction dynamics at energies ≈ 4 – 7 AMEV*

13.05 – 14.30  lunch

**Various aspects of fission**  chair O. Bouland

14.30 – 15.00  **J. Randrup** (LBNL)
*Brownian shape motion: Fission fragment mass distributions*

15.00 – 15.25  **R. Vogt** (LLNL)
*Applications of event-by-event fission modeling with FREYA*

15.25 – 15.50  **V. Rubchenya** (University of Jyväskylä)
*Theoretical and experimental studies of the neutron rich fission product yields at intermediate energies*

15.50 – 16.15  **L. G. Moretto** (LBNL)
*Experimental nuclear matter phase diagram from low energy compound nucleus fragment evaporation*

16.15 – 16.45  coffee break

**Optical model simulations**  chair M. Dupuis

16.45 – 17.15  **H. F. Arellano** (University of Chile, Santiago)
*On the unabridged 7D-folding structure of the optical model potential for nucleon-nucleus scattering*

17.15 – 17.40  **G. Blanchon** (CEA, DAM, DIF)
*RPA correction to the optical potential*

17.40 – 18.05  **R. Capote** (IAEA Vienna)
*A dispersive optical model potential for nucleon induced reactions on $^{238}$U nucleus with 15 coupled levels*

19.00  conference dinner
*restaurant Mlýnec, Novotného látvka 9, Prague 1*

---

**Friday**

**Pre-equilibrium**  chair J. Escher

9.00 – 9.30  **M. Dupuis** (CEA, DAM, DIF)
*Impact of collective states on direct pre-equilibrium emission*

9.30 – 9.55  **B. Carlson** (IT de Aeronáutica, São José dos Campos SP, Brasil)
*The density of available states of the DDHMS pre-equilibrium model*
9.55 – 10.20  A. A. Cowley (Stellenbosch University, iThemba Laboratory)
Pre-equilibrium emission of α-particles with energies in the region of those from compound nucleus decay

10.20 – 10.50  S. Kunieda (LANL)
Clustering pre-equilibrium model analysis for nucleon-induced alpha-particle spectra up to 200 MeV

10.50 – 11.20  coffee break

**Pre-equilibrium + applications**  chair František Bečvář

11.20 – 11.45  E. Bětá (SAS, Bratislava)
Iwamoto-Harada model of pre-equilibrium cluster emission: Should we care about angular momentum?

11.45 – 12.10  M. Avrigeanu (NIP & NE, Bucharest)
Deuteron-induced reaction mechanisms at low energies

12.10 – 12.35  V. Avrigeanu (NIP & NE, Bucharest)
On neutron-induced reaction mechanisms at medium energies

12.35 – 13.00  S. Rose (University of Oslo)
Minimization of actinide waste by multi-recycling of thoriaed fuels in the EPR reactor

13.00 – 13.10  conclusion of the CNR*11

13.10 – 14.30  lunch

**Poster Session**

Rajni Bansal (Panjab University, India)
The modified proximity potential in heavy ion fusion dynamics

Rubina Bansal (Thapar University, Punjab, India)
Influence of symmetry energy on multifragmentation

B. Carlson (IT de Aeronáutica, São José dos Campos SP, Brasil)
Bound state densities and the Helmholtz free energy

I. Companis (University Bordeaux)
Measurement of neutron capture and fission cross sections of $^{233}$U in the resonance region

A. Deppman (São Paulo University)
Fission-fragment mass distributions calculated by Monte Carlo simulations of proton- and photon-nucleus reactions
F. S. Dietrich (LLNL)
Target-state dependence of cross sections for neutron reactions on statically deformed nuclei and the adiabatic approximation

S. Goyal (Panjab University, India)
Dynamics of multifragmentation in Au+Au reactions at low incident energies

C. Granja (Czech Technical University in Prague)
Spatial- and Time-correlated detection of fission fragments

O. Grudzevich (IAITE, Obninsk, Russia)
Transition of highly excited composite system to compound nucleus

P. Gupta (Thapar University, Punjab, India)
Study of spatial correlation in multifragmentation

A. Hurst (LBNL)
Thermal neutron capture onto the stable tungsten isotopes

A. Jain (Thapar University, Punjab, India)
Effects of charge asymmetry on light mass fragment production

G. Kaur (Thapar University, Patiala, India)
Decay of 20\(^{1}\)Bi formed in 20\(^{8}\)Ne induced reaction at \(E_{CM} = 162\) MeV

Y. Malyshekin (J.-W. Goethe University, Frankfurt am Main)
Modeling spallation reactions in tungsten and uranium targets with the Geant4 toolkit

K. Mandeep (Panjab University, India)
Study of collision dynamics in heavy-ion reactions via nucleon’s trajectories in phase space

K. Maninder (Rayat and Bahra Institute of Engineering and Bio-technology, Punjab, India)
Fusion of neutron and proton rich nuclei

P. P. Singh (GSI)
How does incomplete fusion show up at slightly above barrier energies?

B. Sleaford (LLNL)
Capture gamma-ray libraries for nuclear applications

S. Soheyl (Bu-Ali Sina University, Hamedan, Iran)
Application of standard saddle-point statistical model in the prediction of angular anisotropies

S. Soheyl (Bu-Ali Sina University, Hamedan, Iran)
Determination of non-compound nucleus fission contribution for some induced fission systems with heavy ions

K. Sukhjit (Panjab University, India)
On the system size dependence of intermediate mass fragments and nuclear dynamics at peak center-of-mass energy
Y. K. Vermani (ITM University, Gurgaon, India)
Spectator matter fragmentation in heavy-ion collisions and phase space characteristics

K. S. Vinayak (Thapar University, Punjab, India)
Influence of density dependence of symmetry energy on nuclear stopping in heavy-ion collisions

J. Vrzalová (NPI ASCR Řež)
Measurements of cross-sections of (n,xn) threshold reactions in various materials

L. Yettou (Université Dr YAHIA FARES, Medea, Algeria)
Double differential cross sections of proton emission in neutron induced reaction on $^{27}$Al

Conference dinner:

restaurant Mlýnec, Novotného lávka 9, Prague 1

Internet access in the conference room (DHCP):

Network name: MS-KONFERENCE
Monte Carlo Simulation for Statistical Decay of Compound Nucleus

T. Kawano, P. Talou, and M.B. Chadwick
Los Alamos National Laboratory, Los Alamos, NM 87545, USA

We perform Monte Carlo simulations for particle and γ-ray emissions from a compound nucleus based on the Hauser-Feshbach statistical theory; the Monte Carlo Hauser-Feshbach (MCHF) method. The MCHF calculation, which gives us correlated information between emitted particles and γ-rays, will be a powerful tool in many applications, because we are able to probe nuclear reactions in more microscopic way. For example, the MCHF code can be used as an event generator in a radiation transport code. Having the correlated neutron and γ-ray emission process in the transport calculations, energy conservation is satisfied automatically event-by-event. In addition, the correlations amongst particles and γ-ray can be a signature of a particular nuclear reaction occurred in a nuclear system.

We have been developing the MCHF code, CGM, which solves the Hauser-Feshbach equation with the Monte Carlo method. The code includes all the common models that emerge in a standard Hauser-Feshbach code, namely the particle transmission generator, the level density module, interface to the discrete level database, and so on. The code allows to emit multiple neutrons, as long as the excitation energy of the compound nucleus is larger than the neutron separation energy. The γ-ray competition is always included at each compound decay stage, and the angular momentum conservation holds too. In this paper, we discuss our technique to calculate the particle and γ-ray correlations in the statistical model framework, and some simulation examples are shown.

LA-UR-11-10828
Dynamical phase transitions in quantum mechanics

Ingrid Rotter

Max-Planck-Institut für Physik komplexer Systeme, D-01187 Dresden, Germany

Abstract

1936 Niels Bohr: In the atom and in the nucleus we have indeed to do with two extreme cases of mechanical many-body problems for which a procedure of approximation resting on a combination of one-body problems, so effective in the former case, loses any validity in the latter where we, from the very beginning, have to do with essential collective aspects of the interplay between the constituent particles.

1963: Maria Goeppert-Mayer and J. Hans D. Jensen received the Nobel Prize in Physics for their discoveries concerning nuclear shell structure.

State of the art 2011:

– The nucleus is an open quantum system described by a non-Hermitian Hamilton operator with complex eigenvalues. The eigenvalues may cross in the complex plane ('exceptional points'), the phases of the eigenfunctions are not rigid in approaching the crossing points and the widths bifurcate. By this, a dynamical phase transition occurs in the many-level system.

– The dynamical phase transition starts at a critical value of the level density. Hence the properties of the low-lying nuclear states (described well by the shell model) and those of highly excited nuclear states (described by random ensembles) differ fundamentally from one another.

– The statement of Niels Bohr for compound nucleus states at high level density is not in contradiction to the shell-model description of nuclear (and atomic) states at low level density.

– Dynamical phase transitions are observed experimentally in different systems, including $\mathcal{PT}$-symmetric ones, by varying one or more parameters.

References

NEUTRON INDUCED FISSION OF $^{234}\text{U}$

F.-J. Hambsch$^1$, A. Al-Adili$^{1,2}$, S. Oberstedt$^1$, S. Pomp$^2$.

$^1$ EC-JRC-Institute for Reference Materials and Measurements, Retieseweg 111, B-2440 Geel, Belgium
$^2$Uppsala University, Uppsala, Sweden

The neutron induced fission of $^{234}\text{U}$ was investigated as a function of incident neutron energy at the JRC-IRMM Van de Graaff accelerator up to 5 MeV. Fission fragment properties like mass, angular distribution and kinetic energy are measured with a double Frisch-grid ionization chamber using both analogue and digital data acquisition techniques.

The reaction $^{234}\text{U}(n,f)$ is relevant for nuclear reactor applications, because it is the compound nucleus formed after neutron evaporation from highly excited $^{236}\text{U}^*$, the so-called second-chance fission of $^{235}\text{U}$ the main constituent in light water reactor fuel, takes place. Experimental data on fission fragment properties like fission fragment mass and total kinetic energy (TKE) as a function of incident neutron energy are rather scarce for this reaction. For the theoretical calculation of the reaction cross sections for Uranium isotopes this information is a crucial input parameter. In addition, $^{234}\text{U}$ is a relevant isotope in the Thorium-based fuel cycle. Fluctuations in the fragment properties have been observed in the threshold region where vibrational resonances are present [1]. One of the goals of the present study is to verify these fluctuations.

As a first result the strong anisotropy of the angular distribution around the vibrational resonance at $E_n = 0.77$ MeV could be confirmed [2,3] using the full angular range. The results will be presented together with fission fragment mass and TKE distributions. Also the advantages of the digital data acquisition technique will be discussed.

References
FISSION VIA COMPOUND STATES AND $J^πK$ A.Bohr's CHANNELS:
WHAT WE CAN LEARN FROM RECENT STUDIES WITH SLOW NEUTRONS

A.L. Barabano v 1, W.I. Furman 2

1 NRC "Kurchatov Institute", Moscow 123182, Russia; Moscow Institute of Physics and Technology, Dolgoprudny 141700, Moscow Region, Russia
2 Frank Laboratory of Neutron Physics, JINR, Dubna 141980, Russia

Fission of nuclei by slow neutrons is of great interest due to a possibility of studying of quantum aspects of the fission process. Really, modern high resolution time-of-flight technique makes possible an identification of quantum interference of amplitudes of fission via separated compound-states (neutron resonances) both in differential and in total cross section of $(n,f)$-reaction.

More exactly, the fission amplitudes are related to channels introduced by A.Bohr [1]. Each channel is characterised not only by spin $J$ and parity $\pi$ of the corresponding compound-state, but also by a projection $K$ of spin $J$ onto an axis of nuclear elongation. In fact, the channels are nuclear rotation states (transition states), and $K$ is a good quantum number due to conservation of axial symmetry of the fissioning nucleus up to scission. A consistent description of all observable quantities after scission was proposed by Strutinsky [2] in the frame of a so-called helicity representation. After the neck rupture, the projection $K$ transfers near-precisely into a total helicity of two fission fragments $\tilde{K}$ that is the projection of total spin $F$ of the fragments onto the fission axis. According Strutinsky, $\tilde{K}$ is also a good quantum number in the fission process due to insignificance of a relative orbital momentum of fragments. Thus, direct connection arises between the $J^πK$ A.Bohr’s channels and the observables in fission.

Our theoretical approach [3] is a direct extension of the Stutinsky pioneer concept. It allows us to understand and describe consistently a whole set of experimental data on $(n,f)$-reaction with slow polarized neutrons and aligned nuclei. In this work we review recent studies of fission induced by slow neutrons that have given us insight into the fission channels. Special attention is devoted to Dubna-Obnisk-Gatchina experiments [4] carried out with both unpolarized and polarized slow neutrons and spin-aligned target nuclei. Analysis of these data provides the most comprehensive information on fission channels with various $K$. The channel $K = 0$ is especially interesting because its contribution is very sensitive to the shape symmetry of the fissioning nucleus at first and second fission barriers.

Accuracy of the relation $\tilde{K} \simeq K$ can be verified by recent studies of T-odd angular correlations of products of binary and ternary fission of nuclei $^{233}$U and $^{235}$U induced by thermal polarized neutrons [5]. Small asymmetries ($\sim 10^{-3}$) of emission of a third particle ($\alpha$-particle in ternary fission or a neutron or $\gamma$-quantum from a fragment in binary fission) along and opposite to some direction related to the spin of incident neutron and the momentum of light fragment were discovered. We show that one of these asymmetries (a so-called 5-vector correlation) for neutrons and $\gamma$-quanta could emerge due to a violation $\tilde{K} \simeq K$. But the observed smallness of the asymmetry points out to the insignificance of this violation. It gives the phenomenological quantitative estimation of the accuracy of the approximation $\tilde{K} \simeq K$ crucial for the theoretical approaches [2,3].

The study of prompt fission neutrons has received much attention in recent years due to its importance in elucidating some fundamental questions of the nuclear scission process, as well as its relevance to applied nuclear programs. Looking beyond the ubiquitous Madland-Nix model, which can only provide an average neutron multiplicity and spectrum, new simulation tools have been developed to study more exclusive data, such as the neutron multiplicity for a given fission fragment, the neutron multiplicity distribution, neutron-neutron correlations, etc.

In the present work, we discuss some recent results obtained by performing exact Monte Carlo simulations of the Hauser-Feshbach equations describing the statistical decay of primary fragments. The competition between neutron and gamma-ray emissions is treated exactly for the first time, providing a wealth of new calculated results to compare with rather scarce experimental data. Results for $^{252}$Cf (sf) and $n_{th}+^{239}$Pu are presented in detail. Results for the prompt fission neutrons in the $n_{th}+^{239}$Pu reaction, and using the Weisskopf approximation only, are discussed in Ref. [1].

The excitation energy sorting mechanism recently proposed by K.-H. Schmidt and B. Jurado [2] is discussed in the context of those calculations. In particular, it will be shown that exclusive data such as neutron-neutron correlations can be used to probe the maximum entropy hypothesis. Finally, the impact of the initial spin distributions in the fission fragments on predicted prompt gamma rays and neutrons will be addressed.

References


Non-adiabatic transition of the fissioning nucleus at scission: the time scale

N. Carjan\textsuperscript{a,b}, M. Rizea\textsuperscript{b}

\textsuperscript{a} Centre d’Etudes Nucléaires de Bordeaux - Gradignan, UMR 5797, CNRS/IN2P3 - Université Bordeaux 1, BP 120, 33175 Gradignan Cedex, France
\textsuperscript{b} National Institute of Physics and Nuclear Engineering, “Horia Hulubei”, PO Box MG-6, Bucharest, Romania

The sudden approximation has been recently used to calculate the microscopic scission-properties during low-energy fission of $^{236}\text{U}$ [1, 2]. In this approach the scission process, i.e., the transition from two fragments connected by a thin neck to two separated fragments was considered to happen suddenly. The approach is stationary (the time evolution is not explicitly treated) and it only involves the two sets of neutron eigenstates for the two nuclear configurations considered: just before scission ($\alpha_i$) and immediately after scission ($\alpha_f$). The purpose of the present paper is to go beyond this mathematical approximation considering the real physical situation in which the above mentioned transition takes place in a time interval $\Delta T \neq 0$. For this we need to follow the evolution from $\alpha_i$ to $\alpha_f$ of all occupied neutron states by solving numerically the two-dimensional time-dependent Schrödinger equation with time-dependent potential. Calculations are performed for mass divisions from $A_L = 70$ to $A_L = 118$ ($A_L$ being the light fragment mass) taking into account all the neutron states ($\Omega = 1/2, 3/2, ..., 11/2$) that are bound in $^{236}\text{U}$ at $\alpha_i$. The diabatic-dissipative dynamics of the neck rupture is very complicated and its exact duration is unknown. $\Delta T$ is therefore taken as parameter having values from $0.25 \times 10^{-22}$ to $6 \times 10^{-22}$ sec. The resulting scission neutron multiplicities $\nu_{sc}$ and primary fragments’ excitation energies $E_{sc}^*$ are compared with those obtained in the frame of the sudden approximation (that corresponds to $\Delta T = 0$). As expected, shorter is the transition time more excited are the fragments and more neutrons are emitted, the sudden approximation being an upper limit. For $\Delta T = 10^{-22}$ sec, which is a realistic value, the time dependent results are 20% below this limit. For transition times longer than $5 \times 10^{-22}$ sec the adiabatic limit is reached: no scission neutrons are emitted anymore and the excitation energy at $\alpha_f$ is negligible. The spatial distribution of the neutron emission points at scission is also calculated as function of the transition time $\Delta T$ and a considerable change is noticed. Finally, the individual contributions of the light and heavy fragments to $\nu_{sc}$ and $E_{sc}^*$ are estimated. The relative contribution of the light fragment is found to increase with $\Delta T$.

References

Cross sections for direct, resonance, and compound reactions play an important role in models of astrophysical environments and simulations of the nuclear fuel cycle. Providing reliable cross section data remains a formidable task, and direct measurements have to be complemented by theoretical predictions and indirect methods, such as the ANC (asymptotic normalization coefficient) and Trojan Horse methods, Coulomb dissociation, and the surrogate reactions method. Indirect approaches come with their own challenges, as experimental observables have to be related to the quantity of interest. The surrogate method, for instance, aims at determining cross sections for compound-nuclear reactions on unstable targets by producing the compound nucleus via an alternative (transfer or inelastic scattering) reaction and observing the subsequent decay via $\gamma$ emission, particle evaporation, or fission. The decay probabilities that are extracted from the measurements depend on the reaction used to produce the compound nucleus. We present recent work that takes into account these differences between direct and surrogate reaction. Cross sections for $(n,\gamma)$ reactions on both stable and unstable isotopes will be presented.

* This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.
Neutron-induced cross sections of short-lived nuclei via the surrogate reaction method

G. Boutoux¹, B. Jurado¹, V. Méot², O. Roig², M. Aiche¹, A. Bail³, G. Barreau¹, E. Bauge², J.T. Burke⁴, N. Capellani¹, I. Companis¹, S. Czajkowski¹, J.M. Daugas², X. Derkx⁵, L. Gaudefroy², F. Gunsing¹, B. Haas¹, G. Kessedjian¹, L. Mathieu¹, P. Morel², N. Pilet², P. Romain², K.-H. Schmidt¹, O. Sérot³, J. Taieb², L. Tassan-Got⁶, C. Theroine², I. Tsekhanovich¹

¹. Centre d’Etudes Nucléaires de Bordeaux-Gradignan, CNRS/Université Bordeaux 1
². CEA DAM-DIF, Arpajon
³. CEA Cadarache, DEN/DER/SPRC/LEPh
⁴. CEA Saclay, DSM/DAPNIA/SPhN
⁵. Grand Accélérateur National d’Ions Lourds, CNRS/CEA, Caen
⁶. Institut de Physique Nucléaire d’Orsay, CNRS
⁷. LPSC Grenoble, CNRS
⁸. Lawrence Livermore National Laboratory, Californie, USA

Neutron-induced capture cross sections of short-lived nuclei are of great importance in many areas: fundamental nuclear physics, nuclear astrophysics and nuclear applications, such as nuclear reactors. However, very often the high radioactivity of the samples makes the direct measurement of these cross sections extremely difficult. The surrogate reaction method [1] is an indirect way of determining neutron-induced cross sections for reactions that proceed through a compound nucleus. In this method, the decaying nucleus of the desired reaction is produced via a transfer or an inelastic scattering reaction (figure 1). This technique presents the advantage that the target material can be stable or less radioactive than the material required for a neutron-induced measurement. Nevertheless, a significant question in the use of the surrogate reaction method lies in the difference between the spin and parity population in the neutron-induced and surrogate reactions.

Fig. 1: Schematic representation of the surrogate reaction method. The surrogate reaction is here a transfer reaction \( X(y,w)A^* \). Three possible exit channels (fission, capture and neutron emission) are also represented.

The CENBG collaboration has successfully applied this technique to determine the neutron-induced fission cross sections of several short-lived nuclei such as \(^{233}\text{Pa}\) [2], \(^{242,243}\text{Cm}\) and \(^{241}\text{Am}\) [3]. The results are in very good agreement with neutron-induced data. We are currently investigating whether this powerful technique can also be used to determine radiative capture cross sections. For this purpose, we have studied the transfer reactions \(^{174}\text{Yb}(^3\text{He},\gamma)\) \(^{176}\text{Lu}\) and \(^{174}\text{Yb}(^3\text{He},^4\text{He}\gamma)\) \(^{173}\text{Yb}\) as surrogates for the \(^{175}\text{Lu}(n,\gamma)\) and \(^{172}\text{Yb}(n,\gamma)\) reactions, respectively. The \(\gamma\) probabilities obtained in our experiment show clear discrepancies with already existing neutron-induced data. In this contribution we will present the experimental set-up and the data analysis. Then, we will focus on the origin of these discrepancies. Perspectives for the surrogate method applied to capture cross sections will be discussed.

Références

Level densities in the actinide region and indirect n,γ cross section measurements using the surrogate method

J.N. Wilson a, F. Gunsing b, L.A. Bernstein d, A. Bürger c, A. Görgen c, M. Guttormsen c, A-C. Larsen c, P. Mansouri c, T. Renstrøm c, S.J. Rose c, S. Siem c, M. Weideking d, T. Wiborg c

a Institut de Physique Nucléaire d’Orsay, Bât 100., 15 rue G. Clémenceau, 91406 Orsay cedex, France
b DSM/IRF, CEA Saclay, Bât 141, F-91191 Gif-sur-Yvette Cedex, France
c University of Oslo, Department of Physics, P.O. Box 1048, Blindern 0316 Oslo, Norway
d Lawrence Livermore National Laboratory, 7000 East Avenue, Livermore, CA 94550-9234, USA

Results from a program of measurements of level densities and gamma ray strength functions in the actinide region will be presented. Experiments at the Oslo cyclotron involving the Cactus/Siri detectors and 232Th(d,x) and 232Th(3He,x) reactions were carried out to help answer the question of which level density model is the most appropriate for actinide nuclei, since it will have an impact on cross section calculations important for reactor physics simulations. A new technique for extracting level densities and gamma ray strength functions from particle-gamma coincidence data is proposed and results from the development of this technique will be presented.

In addition, simultaneous measurements of compound nuclear gamma decay probabilities have been performed for the key thorium cycle nuclei 233Th, 231Th and 231Pa up to around 1MeV above the neutron binding energy and have enabled extraction of indirect neutron induced capture cross sections for the 232Th, 231Pa and 230Th nuclei using the surrogate reaction method. Since the neutron capture cross section for 232Th is already well known from direct measurements a comparison provides a stringent test of the applicability of the surrogate technique in the actinide region.
Asymmetric fission in Kr+Ca reactions at 5.5 AMeV

Decay modes of excited nuclei formed in the 78,82Kr+40Ca reactions at 5.5 AMeV are investigated by means of exclusive measurements using the INDRA detector at GANIL. Light-charged particles in coincidence with fragments show that, in the mechanism of asymmetric fission, the light partner (with atomic number 6≤Z≤10) is produced at excitation energy below the emission particle threshold. This result provides important constraints on various key characteristics of the process as the energetic balance, the sharing of the excitation energy and the fragments cross-sections indicate the influence of the nuclear level density at excitation energy below the emission threshold. Comparison with statistical and dynamical models suggests the role of multichance emission to explain the observed feature of the fragment cross-sections. The set of data provides some hints for further explorations in the context of reactions induced with neutron rich projectile to be delivered in future facilities.
Clustering Effects in $^{48}$Cr Composite Nuclei Produced via $^{24}$Mg + $^{24}$Mg Reaction


1INFN and Dipartimento di Scienze Fisiche dell’Università di Napoli, I-80126 Napoli, Italy.
2Laboratori Nazionali di Legnaro, I-35020 Legnaro (Padova), Italy.
3INFN Sezione di Firenze, I-50125 Firenze, Italy.

INTRODUCTION

The phenomena of clustering in nuclei have recently raised much interest [1]. These phenomena have been enlightened by the observation of relatively narrow resonances in the elastic and inelastic channels for $\alpha$-like nuclei [2]. One possible interpretation of these structures is that they correspond to states of very large deformations in the di-nuclear system, acting as doorway states to fusion reactions. These states could affect the evaporative decay as indicated by recent studies on $^{58}$Ni, $^{32}$S and $^{40}$Ca nuclei, for which unexpected large deformations have been found.

A narrow resonance for the system $^{24}$Mg + $^{24}$Mg with J=36 at $E_{lab}=60$ MeV has been observed [3]. The measured resonance width of 170 keV implies a relatively long lifetime of $4\times10^{-21}$ s.

A study has been recently carried out on this resonance [4], in order to investigate its decay into the inelastic and fusion-evaporation channels, and results are in agreement with molecular model predictions. Furthermore, a Jacobi shape transition is predicted by the Lublin–Strasbourg Drop Model for this composite system from J=28 $\hbar$ to 32 $\hbar$, at $E_{c.m.} \sim 60$ MeV.

In this framework, we have undertaken at the Tandem accelerator of LNL the study of the $^{24}$Mg + $^{24}$Mg reaction at the bombarding energy of $E_{lab}=91.7$ MeV, corresponding to the resonance J=36$^+$ at $E_{c.m.}=60$ MeV. The light charged particles (LCP) emitted from the compound nucleus de-excitation have been measured with the 8πLP apparatus [5]. Evaporation residues (ER) have been detected with a Parallel Plate Avalanche Counter in the forward direction. ER-LCP and LCP-LCP coincidence events have been collected.

The comparison of the data with the predictions of the Statistical Model code (LILITA_N97) is expected to be particularly elucidating for this study.

In particular, the $\alpha$ - $\alpha$ angular correlations simulated by the LILITA_N97 code are reported in Fig.1 for two sets of the deformation parameters. The first one corresponds to a deformation according Rotating Liquid Drop Model (RLDM) (axis ratio b/a =1.51 for at J = 35 $\hbar$), the second set of parameters corresponds to an Highly Deformed nucleus (b/a = 2.0 at J = 35 $\hbar$), with deformed emission barriers taken from systematics. The geometry of 8πLP detectors has been included in the simulations and in figure the correlations are reported as a function of its detector number. As it can be inferred from the figure, this observable is sensitive to the nuclear deformation.

Fig. 1. Simulated angular multiplicity distributions of alpha particle-alpha particle coincidences with the trigger at $\theta=42.7^\circ$ with respect to the beam direction in the vertical plane, as a function of the identification number of the BALL detectors of 8πLP. The polar angle of the detectors decreases with increasing identification number from about 155° (ring A) to 42° (ring G).

<table>
<thead>
<tr>
<th>$\alpha_1$</th>
<th>$\alpha_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>RLDM</td>
<td>Highly Deformed</td>
</tr>
<tr>
<td>Mp</td>
<td>1.35</td>
</tr>
<tr>
<td>M$\alpha$</td>
<td>1.32</td>
</tr>
</tbody>
</table>

Furthermore, the high efficiency of 8πLP apparatus allows to select particular fusion-evaporation channels, whose fold and LCP-LCP distributions, are predicted to be very sensitive to the nuclear deformation.

In particular this selection is possible for the $\alpha$3$\alpha$ and $\alpha$2$\alpha$, two of the most intense channels, expected to be weekly affected by the pollution from higher fold channels.

In the experiment a good statistics was achieved which will allow us to extract angular correlations, LCP multiplicities and to analyse high fold events. Data analysis is in progress.

Study and comparison of the decay modes of the systems formed in the reactions $^{78}\text{Kr}+^{40}\text{Ca}$ and $^{86}\text{Kr}+^{48}\text{Ca}$ at 10 AMeV

S. Pirrone$^1$, G. Politi$^{2,1}$, M. La Commarca$^{3,4}$, J.P. Wieleckzko$^5$, G. Ademard$^5$, E. De Filippo$^1$, M. Vigilante$^{3,4}$, F. Amorini$^6$, L. Auditore$^{7,8}$, C. Beck$^9$, I. Berceanu$^{10}$, B. Borderie$^{11}$, G. Cardella$^1$, A. Chibihi$^3$, M. Colonna$^6$, A. D’Onofrio$^{3,4}$, J.D. Frankland$^5$, E. Geraci$^{2,1}$, E. Henry$^{12}$, E. La Guidara$^{1,13}$, G. Lanzalone$^{14,6}$, P. Lautesse$^{15}$, D. Lebherzt$^5$, N. Le Neindre$^{16}$, I. Lombardo$^{2,6}$, D. Loria$^{7,8}$, K. Mazurek$^5$, A. Pagano$^1$, M. Papa$^1$, E. Piasecki$^{17}$, F. Porto$^{2,6}$, M. Quinlann$^{12}$, F. Rizzo$^{2,6}$, E. Rosato$^{3,4}$, P. Russotto$^{2,6}$, W.U. Schroeder$^{12}$, G. Spadaccini$^{3,4}$, A. Trifirò$^{7,8}$, J. Toke$^{12}$, M. Trimarchi$^{7,8}$ and G. Verde$^1$

1) INFN Sezione di Catania, Italy; 2) Dipartimento di Fisica e Astronomia, Università di Catania, Italy; 3) Dipartimento di Scienze Fisiche, Università Federico II Napoli, Italy; 4) INFN Sezione di Napoli, Italy; 5) GANIL Caen, France; 6) INFN Laboratori Nazionali del Sud, Italy; 7) Dipartimento di Fisica, Università di Messina, Italy; 8) INFN Gruppo collegato di Messina, Italy; 9) IN2P3 - IPHC Strasbourg, France; 10) IPNE, Bucharest, Romania; 11) IN2P3 - IPN Orsay, France; 12) University of Rochester, USA; 13) Centro Siciliano Fisica Nucleare e Struttura della Materia, Catania, Italy; 14) Università Kore, Enna, Italy; 15) IN2P3 - IPN Lyon, France; 16) IN2P3 - LPC Caen, France; 17) University of Warsaw, Poland.

The first results of the ISODEC experiment, performed at the INFN-Laboratori Nazionali del Sud (LNS) by using the CHIMERA detector, will be presented. The principal aims of this experiment is to study the competition between the various disintegration modes of $^{118,134}\text{Ba}$ compound nuclei produced in the reactions $^{78}\text{Kr}+^{40}\text{Ca}$ and $^{86}\text{Kr}+^{48}\text{Ca}$ at 10 AMeV, exploring the isospin dependence of the decay modes of medium mass compound nuclei formed by fusion processes. The experiment complements data already obtained at 5.5 MeV/A for $^{78,82}\text{Kr}+^{40}\text{Ca}$ reactions [1], previously realized with beams delivered by GANIL facility and by using the INDRA detector.

The studied systems allow to produce compound nuclei with a large variation of N/Z, at very high angular momentum, and with similar excitation energy. Indeed, the neutron enrichment of the compound nuclei is expected to play an important role on the various emission mechanisms, providing crucial information on fundamental nuclear quantities as level density, fission barrier or viscosity.

First results show evident staggering effects in the Z distributions, as well as different isotopic composition and enrichment for the reaction products in the two systems. Absolute cross sections calculations of the reaction products are in progress, to provide important indication on the isospin influence on the reaction mechanism and fragments production. Such a set of data will in fact provide new constraint on sophisticated models attempting to describe statistical and/or dynamical properties [2] of excited nuclei.
Present Status and Future Programs of n_TOF Experiment

E. CHIAVERI for n_TOF Collaboration

The neutron time-of-flight facility n_TOF at CERN, Switzerland, operational since 2001, delivers neutrons using the Proton Synchrotron (PS) 20 GeV/c proton beam impinging on a lead spallation target. The facility combines a very high instantaneous neutron flux, an excellent TOF resolution, a low intrinsic background and a wide range of neutron energies, from thermal to GeV neutrons.

These characteristics provide a unique possibility to perform neutron-induced capture and fission cross-section measurements, for applications in nuclear astrophysics and in nuclear reactor technology.

The overall efficiency of the experimental program and the range of possible measurements achievable with the construction of a second experimental area (EAR-2), vertically located 20 m on top of the n_TOF spallation target, might offer a substantial improvement in measurement sensitivities. A feasibility study of the possible realisation will be also presented.

The most relevant measurements performed up to now and foreseen for the future will be presented in this contribution.
Neutron Capture Experiments with 4π DANCE Calorimeter.

B. Baramsai, G.E. Mitchell, C. Walker and DANCE Collaboration
North Carolina State University, Raleigh, NC

In recent years we have made a series of neutron capture experiments with the DANCE detector array located at the Los Alamos Neutron Science Center. The radiative decay spectrum from the compound nucleus contains important information about nuclear structure and the reaction mechanism.

The primary goals of the measurements are to obtain improved capture cross sections, to determine properties of the photon strength function, to improve neutron level densities and strength functions by determining the spin and parity of the capturing states. We shall present examples of our recent results.

This work was supported in part by US DOE grants Nos. DE-FG52-06NA29460 and DE-FG02-97-ER41402 and performed under the auspices of the U.S. DOE under contracts Nos. DE-AC52-07NA27344 and DE-AC52-06NA25396.
Criticality experiments for validation of cross sections: the neptunium case.


Institute de Physique Nucleaire, Orsay
Facultad de fisica, Universidade de Santiago de Compostela, 15782, Spain

Neptunium 237 is a long lived (2 My) radioactive isotope, which belongs to the transuranium actinides. It is one of the most generated nuclear waste produced in nuclear power stations and a candidate for incineration to reduce on the long term the radiotoxicity of the final disposal. The incineration is possible in fast neutron reactors because of the high fission cross section at high energy, beyond the fission threshold. This requires a good knowledge of its cross section and this triggered several measurements in the last decade.

We carried out a fission cross section measurement at the n_TOF neutron facility at CERN, spanning a very broad energy range, from a fraction of eV to GeV. Our setup was made of 9 targets, including 4 Np237 samples with 1 U235 and 1 U238 targets as references, and the fission fragments were detected in coincidence with parallel plate avalanche counters (PPACs). When compared to previous measurements it appears that our fission cross section is higher by 5-7% beyond the first fission threshold. I will show however that several previous measurements, although consistent with each other, are dependent through re-normalization procedures.

To check the relevance of our data we simulated an experiment, performed at Los Alamos, where a sphere of Np237 of 6 kg is surrounded by enriched Uranium 235 so as to reach criticality with fast neutrons. When introducing our data for the fission cross section of Np237 the simulation gives a better agreement with the experiment as the deviation of 750 pcm is reduced to 250 pcm. We explored also the hypothesis of an inaccurate inelastic cross section for U235 which has been invoked by some authors to explain the deviation of 750 pcm, and I will show that large distortions should be applied to reconcile the critical experiment with its simulation. In conclusion these outcomes support the hypothesis of a higher fission cross section of Np237.
The Evaluated Nuclear Structure Data File (ENSDF) is a comprehensive repository of adopted level and gamma ray data for all nuclei. It is the basis of the Reaction Input Parameter Library (RIPL) used in nuclear reaction calculations and nuclear data evaluations. The Evaluated Gamma Ray Activation File (EGAF) contains a library of thermal neutron capture gamma-ray cross sections for isotopes of elements with Z=1, 3-60, 62-83, 90 and 92. These data sources contain a wealth of experimental level density and width information, especially at low excitation energies, and gamma-ray transition probabilities for energies up to a few MeV. In this talk I will present a systematic analysis of level densities, and photon strengths that is derived from these databases. The dependence of the level density on level spin and parity will be explored. E1, M1, and E2 photon strengths will be compared with various models and primary gamma-ray strengths observed in thermal and average resonance neutron capture will be compared with those from low-lying level. A new database level properties and gamma-ray transition probabilities will be made available to anyone interested in investigating these data further.
Description of dipole strength in heavy nuclei in conformity with their quadrupole degrees of freedom.

E. Grosse, A. Junghans, R. Massarczyk, R. Schwengner and G. Schramm
HZDR and TU Dresden, Germany

The width of the isovector giant dipole resonance (IVGDR) plays an important role in predictions for the electric dipole strength in heavy nuclei. Based on the presumption that the tail of the IVGDR determines this strength down to low energies a good knowledge of this parameter is essential: Away from the maximum the height of a Lorentzian is directly proportional to its width. Cross sections for compound nucleus reactions with photons are thus strongly depending on it. Attempts to obtain values for this width $\Gamma$ by Lorentzian fits to the IVGDR peak region for each nucleus individually – as e.g. presented within RIPL-3 – have resulted in surprisingly strong variations of $\Gamma$ with A and Z. This scatter is reduced when the splitting of the IVGDR in strongly deformed nuclei is accounted for by using the sum of two Lorentzians for the fit, but for the many neither well deformed nor spherical nuclei it persisted.

In contrast, theoretical descriptions of collective nuclear degrees of freedom have postulated a direct relation between the width $\Gamma$ of the IVGDR and the resonance energy $E_o$, which varies smoothly with A and Z. A power law $\Gamma \propto E^\delta$ has been proposed since long; calculations for triaxial shapes by Bush and Alhassid have determined $\delta \approx 1.6$.

Detailed investigations of low energy quadrupole excitations in heavy nuclei by multiple Coulomb excitation as analysed via model-independent invariants has given a clear proof of earlier assumptions about non-zero triaxial deformation in many nuclei. Very recently a systematic study of low energy nuclear structure was carried out at CEA and IPN Orsay together with INT at Seattle using the Hartree-Fock-Bogoliubov theory with the Gogny interaction allowing also triaxial shapes. Both, experiment as well as theory, show that ground states of ‘transitional’ nuclei should be parameterized by deformation $\beta$ and triaxiality $\gamma$ eventually comprising sphericity in the predicted large standard deviations.

We have used that information to calculate the IVGDR shapes by using a sum of three Lorentzians (TLO) combined to the concept of instantaneous shape sampling (ISS). We get good agreement to photonuclear data with $\Gamma \propto E^{1.6}$ and find no strong deviations from the TRK sum rule for the majority of heavy nuclei, for which such data exist. Concerning the low energy tail, the agreement to resonance fluorescence as well as other data is satisfactory, when magnetic and isoscalar electric strength are taken into account. For the interpretation of decay spectra in case of small level density Porter Thomas fluctuations play a surprisingly strong role.

Our interest is now concentrating on compound nucleus reactions with photons in the exit channel, and especially radiative capture of fast neutrons. We will present first results for comparisons of TLO-predictions to published capture data. Such processes are of importance related to nuclear technology for waste transmutation and alternative reactor concepts. Part of our research is connected to respective EURATOM funded programs such as the FP7 project ERINDA (www.erinda.org).
Do light nuclei display a universal $\gamma$-ray strength function?

Department of Physics, University of Oslo, N-0316 Oslo, Norway

S.Harissopulos, T.Konstantinopoulos, A.Lagoyannis, G.Perdikakis, and A.Spyrou
Institute of Nuclear Physics, NCSR "Demokritos", Athens, Greece

M. Kmiecik, and K. Mazurek
Institute of Nuclear Physics PAN, Kraków, Poland

M. Krtička,
Institute of Particle and Nuclear Physics, Charles University, Prague, Czech Republic

T.Lönnroth, and M.Norrby
Department of Physics, Åbo Akademi University, FIN-20500 Åbo, Finland

A.Schiller, and A.Voinov
Department of Physics and Astronomy, Ohio University, Athens, Ohio 45701, USA

Particle-$\gamma$ coincidences from the bombardment of 15 MeV and 32 MeV protons on a $^{46}$Ti target are utilized to obtain $\gamma$-ray spectra as a function of excitation energy for $^{44,45,46}$Ti [1-3]. The Oslo method has been used to extract simultaneously level density and $\gamma$-ray strength functions ($\gamma$-SFs). The rich $^{46}$Ti data set of 110 million events allows analysis of the coincidence data for many independent data sets. As expected, the results are consistent with one common level density.

A method to study the evolution of the deduced $\gamma$-SFs as a function of excitation energy will be described. The $\gamma$-SFs are found to display strong variations for different initial and final excitation energies if transitions to the lowest states are involved. The differences in the $\gamma$-SFs can be explained as a consequence of Porter-Thomas fluctuations of individual intensities, and shows that this energy region cannot be used for determination of the universal $\gamma$-RSF. Even though, the deduced $\gamma$-SFs based on transitions within the quasi-continuum still indicate that the decay is governed by a universal $\gamma$-SF.

References:

3. A.C. Larsen et al., University of Oslo, in preparation
Scissors Mode Resonances Built on Excited Levels in Gd Nuclei
Studied from Resonance Neutron Capture


1 North Carolina State University, Raleigh, NC 27695
2 Lawrence Livermore National Laboratory, Livermore, CA 94551
3 Charles University in Prague, CZ-180 00 Prague 8, Czech Republic
4 Los Alamos National Laboratory, Los Alamos, New Mexico 87545

Spectra of γ rays following neutron capture at isolated resonances of all stable Gd nuclei were measured with highly segmented BaF$_2$ detector DANCE at the Los Alamos LANSCE spallation neutron source. The main emphasis was put on studying the γ-cascade decay of neutron resonances to get unique information on photon strength. An analysis of the accumulated γ-ray spectra within the extreme statistical model leads to an inescapable conclusion that scissors mode resonances are built not only on the ground-state, but also on excited levels in all product nuclei studied. The results on summed $B(M1)↑$ strength and energy of the scissors mode are compared with reliable systematics of scissors mode parameters for the ground-state transitions deduced from nuclear resonance fluorescence measurements on even-even deformed nuclei. A specific feature of our experiments is the investigation of scissors mode resonances of odd nuclei, for which the nuclear resonance fluorescence provides only limited information.
Investigation of dipole strength at the ELBE accelerator in Dresden-Rossendorf

R. Massarczyk, R. Schwengner, A.R. Junghans, E. Grosse, G. Schramm, A. Wagner

Institute for Radiation Physics, Helmholtz-Zentrum Dresden-Rossendorf, Germany

Systematic studies of the dipole strength in medium mass nuclei took place at the ELBE accelerator of the Helmholtz-Zentrum Dresden-Rossendorf. The facility, which allows experiments with bremsstrahlung up to photon energies of 18 MeV in order to study dipole excitations up to the neutron separation, will be presented as well as current experiments and their results.

For the first time a high-pressure gas target has been investigated in Dresden. The talk will give an overview at the example of $^{86}$Kr over the data analysis and simulation methods, which allow us to deduce the intensity of unresolvable peaks due to decreasing level spacing. Finally the photo-absorption cross section will be presented in the context of further photon-scattering experiments performed in Rossendorf on the stable isotopes at the closed neutron shell $N = 50$ [1,2,3].

In addition to this we performed twin experiments at Dresden and the research reactor in Budapest. The states populated in cold neutron capture and photon excitation in the two pairs of $^{77}$Se/$^{78}$Se and $^{195}$Pt/$^{196}$Pt should have the similar parity and spin. For the analysis of these experiments and further investigations of the influence of strength functions and level densities on the deexcitation of excited states a new very fast and extremely statistical code has been developed [4] and will be presented.

The experiments were supported by the transnational access activity of the EURATOM FP6 project EFNUDAT (036434).

References
[4] G. Schramm et al., to be submitted
Stellar neutron capture rates and the $s$ process

F. Käppeler
Karlsruhe Institute of Technology, Campus Nord, IK, 76021 Karlsruhe, Germany

Neutron reactions are responsible for the formation of the elements heavier than iron. The corresponding scenarios relate to helium burning in Red Giant stars ($s$ process) and to supernova explosions ($r$ and $p$ processes). The $s$ process, which operates in or near the valley of $\beta$-stability, has produced about half of the elemental abundances between Fe and Bi. Accurate $(n, \gamma)$ cross sections are the essential input for $s$ process studies, because they determine the abundances produced by that process. The $s$-abundance patterns found in solar system material or in presolar grains provide important constraints for the physical conditions at the stellar sites of the $s$ process.

The experimental methods for the determination of stellar $(n, \gamma)$ rates are outlined at the example of recent cross section measurements and the remaining quests will be discussed in the light of present possibilities and future developments.
Capture reactions relevant to p-process nucleosynthesis

Sotirios V. Harissopulos and Paraskevi Demetriou

Institute of Nuclear Physics, National Centre for Scientific Research “Demokritos”,
POB 60228, 153.10 Aghia Paraskevi, Athens, Greece.

The origin in the cosmos of the so-called \( p \) nuclei is one of the most puzzling problems yet to be solved by any model of heavy-element nucleosynthesis. The class of \( p \) nuclei consists of 35 proton-rich stable nuclei that are heavier than iron and cannot be synthesized by the two neutron-capture processes referred to as \( s \) and \( r \) process. To date, these nuclei have been observed only in the solar system. The reproduction of \( p \)-nuclei abundances on the basis of astrophysical processes occurring outside the solar system, such as exploding supernovae (SNII) or He-accreting white dwarves with sub-Chandrasekhar mass, will enable us not only to understand the nuclidic composition of the solar system but also to further elucidate our fundamental picture of its creation.

So far, all the models of p-process nucleosynthesis are able to reproduce most of the \( p \)-nuclei abundances within a factor of 3, but they fail completely in the case of the light \( p \) nuclei. Due to the huge number of reactions involved in abundance calculations, the latter have to rely almost completely on the reaction cross-section predictions of the Hauser-Feshbach (HF) theory. It is therefore of key importance, on top of any astrophysical model improvements, to investigate the uncertainties in the nuclear data, and in particular in the nuclear level densities (NLD), nucleon-nucleus optical model potentials (OMP), and \( \gamma \)-ray strength functions entering the HF calculations.

In view of these problems, we have performed several in-beam cross sections measurements of proton- as well as \( \alpha \)-capture reactions in the Ni-Te region at energies well below the Coulomb barrier. Our aim is to contribute to a cross-section database relevant to the modelling of the \( p \) process and to obtain global models of input parameters (OMP, NLD) for HF calculations. This contribution reports on more than 30 capture reactions. Our results, as well as all other existing data, are compared with HF calculations using various microscopic and phenomenological models of the nuclear input (NLD, OMP). Several aspects of all the experiments performed so far, as well as plans for additional measurements, are presented. Finally, the question of whether there is sufficient experimental information to put constraints on the theory and draw final conclusions is discussed.
We build a new ab initio many-body approach [1] capable of describing simultaneously both bound and scattering states in light nuclei, by combining the resonating-group method [2] with the ab initio no-core shell model [3]. In this way, we complement a microscopic-cluster technique with the use of realistic interactions, and a microscopic and consistent description of the nucleon clusters. We will present the first results of the \(d-^3H\) and \(d-^3H\) fusion calculation obtained within our ab initio approach. We will also discuss our \(d-^4He\), \(^3H-^4He\) and \(^3H-^3H\) scattering calculations and the outline of the extension of the formalism to include three-cluster final states with the goal to calculate the \(^3H(^3H,2n)^4He\) cross section.

*Prepared in part by LLNL under Contract DE-AC52-07NA27344. Computing support for this work came from the LLNL Institutional Computing Grand Challenge program. Support from the LLNL LDRD Grant No. PLS-09-ERD-020 and the NSERC grant No. 401945-2011 is acknowledged.

(n,α) REACTIONS CROSS SECTIONS RESEARCH AT IPPE

V.A.Khryachkov, I.P.Bondarenko, B.D.Kuzminov, N.N.Semenova, A.I.Sergachev

FSUE “SSC RF – IPPE”, 249033, Russia, Kaluga reg., Obninsk, Bondarenko sq.,1.

During last few years systematic studies of (n,α) reactions cross sections on a set of nuclei for wide neutron energy region was carried out in IPPE. This research was done with new spectrometer based on an ionisation chamber with Frisch grid and a wave form digitizer. Both methods for gaseous and solid targets were developed. Information extracted from digital signals allows us to significantly decrease background from parasitic reactions and reach higher reliability for obtained cross section values. The description of experiment specialities and cross section measurement results for $^{16}$O(n,α), $^{14}$N(n,α), $^{14}$N(n,t), $^{20}$Ne(n,α), $^{36,40}$Ar(n,α), $^{10}$B(n,α) and $^{50}$Cr(n,α) reactions are given in the report.
Reaction of Synthesis and Decay Properties of Superheavy Element

Yu. Oganessian
Flerov Laboratory of Nuclear Reactions,
Joint Institute for Nuclear Research,
141980 Dubna, Moscow region, Russia
oganessian@jinr.ru

The essence of talk is the mass limit of the atomic nuclei. In this connection one of the fundamental and prediction of the modern theory about possible existence of the “stability islands” in the domain of the hypothetical very heavy (superheavy) elements are considered. The enhanced stability has been expected for the deformed nuclei near Z=108 and N=162, yet much stronger effect has been predicted for heavier spherical nuclei close to the shells Z=114 and N=184, next to the doubly-magic nucleus $^{208}$Pb (Z=82, N=126). The talk is devoted to the experimental verification of these predictions – the synthesis and study of both the decay and chemical properties of the superheavy elements.

For the synthesis of the heaviest elements with atomic number 104-113 fusion reactions of the nuclei of $^{208}$Pb, $^{209}$Bi with the projectiles of $^{50}$Ti, $^{54}$Cr,... $^{70}$Zn have been used. In this reactions the most heavy compound nuclei have an excitation energy of about 12-15 MeV only (cold fusion). They cool down to the ground state by emission one neutron and gamma-rays. Cold fusion reaction allowed to investigate decay properties of the nuclides with Z=104-113 and N=151-165 in the region of the deformed shells Z=108 and N=162. The nuclides Z=110-113 ($T_{1/2} \sim$ ms) produced in these reactions [1, 2] undergo sequential $\alpha$-decays with total decay time of few seconds.

The synthesis of even heavier nuclei (Z=112-118) has been carried out in the fusion reactions of $^{226}$Ra, $^{233,238}$U, $^{242,244}$Pu, $^{245,248}$Cm, $^{249}$Bk and $^{249}$Cf with the $^{48}$Ca projectiles. The maximal yield of the superheavy elements was obtained at the excitation energy of about 40-45 MeV (hot fusion); the compound nuclei cool down mostly by emission 3 and 4 neutrons and gamma-rays. Eight more neutrons compare with above mentioned cold fusion reaction (Pb-based target) made possible to study decay properties of the nuclides with c Z=104-118 with the higher neutron number, N=161-177 [3].

The decay properties of 48 synthesized nuclei were compared with the theoretical calculations made in various theoretical models. It is shown that the obtained results provide direct experimental evidence of the existence of the superheavy nuclei that considerably changing the mass limits of atomic nuclei and expand the Periodical Table of the chemical elements.

The experiments were carried out at the U-400 heavy ion cyclotron of the Flerov Laboratory of Nuclear Reactions (FLNR, JINR). In the talk are used the results obtained in collaboration FLNR (Dubna, Russia), LLNL (Livermore, USA), ORNL (Oak Ridge, USA) and PSI (Villigen, Switzerland).

Fusion probability and survivability in estimates of heaviest nuclei production

Roman Sagaidak

Flerov Laboratory of Nuclear Reactions, Joint Institute for Nuclear Research, Dubna 141980, Russia

A number of theoretical models have been recently developed to predict production cross sections for the heaviest nuclei in fusion-evaporation reactions. All the models reproduce cross sections obtained in experiments quite well. At the same time they give fusion probability values $P_{\text{fus}}$ differed within several orders of the value (see, e.g., [1]). This difference implies a corresponding distinction in the calculated values of survivability.

![Fig. 1: Fusion probabilities (symbols) derived from fission experiments [5] and calculated with the diffusion model [6].](image1)

The production of the heaviest nuclei (from Cm to the region of superheavy elements (SHE) close to $Z=114$ and $N=184$) in fusion-evaporation reactions induced by heavy ions has been considered in a systematic way within the framework of the barrier-passing (fusion) model coupled with the standard statistical model (SSM) of the compound nucleus (CN) decay. Both models are incorporated into the HIVAP code [2]. Available data on the excitation functions for fission and evaporation residues (ER) produced in very asymmetric combinations can be described rather well within the framework of HIVAP [2–4]. Cross-section data obtained in these reactions allow one to choose model parameters quite definitely. Thus one can scale and fix macroscopic (liquid-drop) fission barriers for nuclei involved in the evaporation-fission cascade. In less asymmetric combinations (with $^{22}$Ne and heavier projectiles) effects of fusion suppression caused by quasi-fission are starting to appear in the entrance channel of reactions. In Fig. 1, the $P_{\text{fus}}$ values derived from the capture-fission and fusion-fission cross-sections obtained at energies above the Bass barrier [5] are shown as a function of the Coulomb parameter.

For more symmetric combinations one can deduce the $P_{\text{fus}}$ values semi-empirically, using the ER and fission excitation functions measured in experiments, and applying SSM model with parameters obtained in the analysis of a very asymmetric combination leading to the production of (nearly) the same CN, as was done for reactions leading to the pre-actinide nuclei formation [3]. The examples of the $P_{\text{fus}}$ values derived with the capture-fission and ER cross-sections obtained recently for asymmetric projectile-target systems are shown in Fig. 2. Data on the ER production in different fusion-evaporation reactions leading to the very heavy compound nuclei with $Z_{\text{CN}} \geq 100$ are considered and discussed in detail.

![Fig. 2: Fusion probabilities (symbols) derived with ER cross-section data and HIVAP calculations [2, 4].](image2)

Considering the fusion probability and survivability for the heaviest nuclei with $Z > 108$, one should bear in mind that the macroscopic component of fission barriers disappears as the shell-stabilized SHE region is approached. Thus the calculated survivability of nuclei produced in the $^{48}$Ca reactions induced on actinide targets [7] depends mainly on the microscopic (shell) corrections to nuclear masses used in calculations.

The spectroscopy of superheavy elements (SHE) is very important for the modern nuclear physics. Comparing the structure predictions of different theoretical models with the experimental data, one can find out their applicability in the region of SHE. This can be very useful for the determination of the next proton magic number beyond $Z = 82$.

Using the statistical approach, we study the population of rotational bands in superheavy nuclei produced in fusion-evaporation reactions. The reactions $^{208}\text{Pb}(^{48}\text{Ca}, 2n)^{254}\text{No}$, $^{206}\text{Pb}(^{48}\text{Ca}, 2n)^{252}\text{No}$, and $^{204}\text{Hg}(^{48}\text{Ca}, 2n)^{250}\text{Fm}$ are considered.

The population cross section of state $L^+$ depends on survival of the compound nucleus against fission. The calculated relative intensities of $E2$-transitions at different spins, which can be compared with the experimental values, are defined by these partial population cross sections. Fermi-gas model is used for the calculation of level densities, and damping of shell effects with excitation energy and angular momentum is taking into account. For more accurate description of the capture process near the Coulomb barrier we use the quantum diffusion approach based on the formalism of reduced density matrix. Taking the same set of parameters, we also describe the excitation functions for these reactions. The results are in a good agreement with the experiment data. Using the parameter of damping of shell effects with angular momentum, we can estimate the moment of inertia of the nucleus at the saddle point.
The superheavy mass region extends effectively due to the availability and advancement in the radioactive nuclear beam technology. The $^{48}$Ca beam is most prominent at present for the synthesis of superheavy elements (SHE). The neutron rich superheavy elements $Z=112$-$116$, and 118 have been produced by (the doubly magic nucleus) $^{48}$Ca induced reactions with actinide targets $^{238}$U, $^{237}$Np, $^{244}$Pu, $^{243}$Am, $^{248}$Cm and $^{248}$Cf respectively at low excitation energies at FLNR in Dubna, Russia. The recently observed alpha-decay chains $^{293,294}$117 were produced by the fusion reactions with target $^{249}$Bk and projectile $^{48}$Ca at Dubna in Russia. The reported cross-sections for the mentioned reaction are 0.5(+1.1,-0.4) pb and 1.3(+1.5,-0.6) pb at $E^*=35$MeV and $E^*=39$MeV, respectively. The two isotopes 293 and 294 of the element $Z=117$ undergo in to sequential alpha-decays [1].

The Preformed Cluster Model (PCM) [2] which is based on Quantum Mechanical Fragmentation Theory is used for the alpha-decay calculations for all the parents of the two alpha decay chains. The calculated results are compared with the experimental data and the other theoretical model calculations.

Microscopic calculation of level densities: the shell model Monte Carlo approach

Yoram Alhassid

Center for Theoretical Physics, Sloane Physics Laboratory, Yale University
New Haven, Connecticut 06520, U.S.A.

The shell model Monte Carlo (SMMC) approach provides a powerful technique for the microscopic calculation of level densities in model spaces that are many orders of magnitude larger than those that can be treated by conventional methods. We discuss a number of developments:

(i) Spin distribution. We used a spin projection method to calculate the exact spin distribution of energy levels as a function of excitation energy [1]. In even-even nuclei we find an odd-even staggering effect (in spin). Our results were confirmed in recent analysis of experimental data [2].

(ii) Heavy nuclei. The SMMC approach was extended to heavy nuclei [3,4]. We have studied the crossover between vibrational and rotational collectivity in families of samarium and neodymium isotopes in model spaces of dimension \( \sim 10^{29} \) [5]. We find good agreement with experimental results for both state densities and \( \langle J^2 \rangle \) (where \( J \) is the total spin).

(iii) Collective enhancement factors. We have calculated microscopically the vibrational and rotational enhancement factors of level densities versus excitation energy [5]. We find that the decay of these enhancement factors in heavy nuclei is correlated with the pairing and shape phase transitions.

(iv) Odd-even and odd-odd nuclei. The projection on an odd number of particles leads to a sign problem in SMMC. We discuss a novel method to calculate state densities in odd-even and odd-odd nuclei despite the sign problem [6].

(v) State densities versus level densities. The SMMC approach has been used extensively to calculate state densities. However, experiments often measure level densities (where levels are counted without including their spin degeneracies.) A spin projection method [1] enables us to also calculate level densities in SMMC. We have calculated the SMMC level density of \( ^{162}\text{Dy} \) and found it to agree well with experiments [7].

Recent experimental results on level densities for compound reaction calculations

A.V. Voinov

Department of Physics and Astronomy, Ohio University, Athens OH 45701, USA

There is a problem related to the choice of the level density input for Hauser-Feshbach model calculations. Modern computer codes have several options to choose from but it is not clear which of them has to be used in some particular cases. Availability of many options helps to describe existing experimental data but it creates problems when it comes to predictions. Traditionally, different level density systematics are based on experimental data from neutron resonance spacing which are available for a limited spin interval and one parity only. On the other hand reaction cross section calculations use the total level density. This can create large uncertainties when converting the neutron resonance spacing to the total level density that results in sizable uncertainties in cross section calculations.

It is clear now that total level densities need to be studied experimentally in a systematic manner. Such information can be obtained only from spectra of compound nuclear reactions. The question is does level densities obtained from compound nuclear reactions keep the same regularities as level densities obtained from neutron resonances? Are they consistent?

We measured level densities of \(^{59-64}\text{Ni}\) isotopes from proton evaporation spectra of \(^{6,7}\text{Li}\) induced reactions. Experimental data are presented. Conclusions of how level density depends on the neutron number and on the degree of proximity to the closed shell (\(^{56}\text{Ni}\)) are drawn. The level density parameters have been compared with parameters obtained from the analysis of neutron resonances and from model predictions.
Recent Progress in Shell Model Monte Carlo Studies of Heavy Nuclei

Cem Özen
Department of Information Technologies,
Kadir Has University,
Istanbul, 34083, Turkey

Abstract

The shell model Monte Carlo (SMMC) approach allows for the determination of thermal properties of nuclei at finite temperatures in unprecedentedly large model spaces while taking into account the important correlations among the valence nucleons [1]. Recently, this approach has been extended to heavy nuclei with proton-neutron imbalance and successfully reproduced the rotational character of \(^{162}\text{Dy}\) [2]. In this talk, we report further progress by demonstrating microscopically the crossover from vibrational to rotational collectivity in heavy nuclei [3]. In particular, the temperature dependence of \(\langle J^2 \rangle\) in families of samarium and neodymium isotopes is shown to bear a signature of this crossover. We also calculate the total nuclear level densities using the SMMC and HFB approaches and extract the collective enhancement factors. The decay of these factors with excitation energy are found to be related to the pairing and shape phase transitions in these nuclei. We also discuss a novel method for calculating level densities of odd-even and odd-odd nuclei which normally present a challenge for the SMMC approach due to a sign problem [4]. We present the first results in the rare-earth region.

References


Level densities and their energy dependences for nuclei in the mass range $47 \leq A \leq 59$ have been determined from the measurements of neutron evaporation spectra in $(p,n)$ reaction. Knowledge of the level density values and their functional peculiarities is very important for the creation of consistent theoretical description of excited nucleus statistical properties and in making nuclear reaction cross-section calculations in the framework of statistical model. The general features of nuclear level density are known, but there are considerable uncertainties of its functional forms conditioned by the unhomogeneity of a single-particle state spectrum, residual interaction, effects of collective nature et al. The required accuracy of level density knowledge for nuclear cross-section calculation problems is $\sim 10\%$ in a wide range of excitation energy from 0.1 MeV to 20 MeV, and the existing data are often differed in 1.5 times. The experimental data on the nuclear level densities for many nuclei are derived, in the main, from the analyses of neutron resonance and low-lying level data. But this information is limited to rather narrow ranges of excitation energy and spin, and its extrapolation can lead to essential errors both in absolute value of nuclear level density and its energy dependence, especially, in transition field from well-identified discrete states to continuum part of excitation spectrum. Obviously, it is necessary to attract other experimental methods of nuclear level density determination with scope of more wide ranges of excitation energy and spin. One of the information sources on nuclear level density in a range between the discrete states and the neutron binding energy are the spectra of particles emitted in nuclear reactions. In this case the type of reaction and the energy of incident particles should be chosen so that the contribution of non-equilibrium processes was reduced to a minimum. These conditions are satisfied with the $(p,n)$ reaction at proton energy up to 11 MeV. In the present work neutron spectra from $(p,n)$ reaction on nuclei of $^{47}$Ti, $^{48}$Ti, $^{49}$Ti, $^{53}$Cr, $^{54}$Cr, $^{57}$Fe, $^{59}$Co have been measured at proton energies between 7 and 11 MeV. The measurements of neutron spectra were performed by time-of-flight fast neutron spectrometer on the pulsed tandem accelerator EGP-15 of IPPE. Analyses of the measured data have been carried out in the framework of statistical equilibrium and pre-equilibrium models of nuclear reactions. The calculations are done with use of the exact formalism of the statistical theory as given by Hauser-Feshbach with the generalized superfluid model of nucleus, the back-shifted Fermi-gas model and the composite formula of Gilbert-Cameron for nuclear level density. The nuclear level densities of $^{47}$V, $^{48}$V, $^{49}$V, $^{53}$Mn, $^{54}$Mn, $^{57}$Co, $^{59}$Ni and their energy dependences have been determined. The obtained results have been discussed in totality with existing experimental and model systematic data.

This work has been supported in part by the Russian Foundation for Basic Researches and Kaluga Scientific Center (grant 09-02-97515).
Compound–Nucleus Reactions Induced by Femtosecond Multi–MeV Laser Pulses

Hans A. Weidenmüller
Max–Planck–Institut für Kernphysik
Heidelberg, Germany

June 15, 2011

I wish to draw the attention of the community to an emerging field of compound–nucleus reactions: The interaction of nuclei with pulsed laser beams with pulses of short duration (≈ 10^{-19} s or less), high energy (several MeV per photon), high intensity (10^{10} or more photons per pulse), and with fully coherent photons.

Experimental efforts are now under way to produce such pulsed laser beams. In the framework of ELI (the “extreme light infrastructure”), an ultrastrong but otherwise conventional laser beam is planned to hit a diamond–like carbon foil of a few nanometer thickness, thereby accelerating a sheet of electrons from within the foil to relativistic velocities. Compton–backscattering of a conventional second laser beam on that sheet produces pulses with the above–mentioned properties.

Depending on photon energy and photon number, there are two scenarios for the interaction of nuclei with the resulting laser pulse. (i) The nuclear Giant Dipole Resonance is singly excited. (ii) Multiple absorption of photons produces a “plasma” of nucleons distantly similar to that of a precompound reaction.

The criteria for either scenario are discussed. Theoretical approaches to both scenarios and results that can eventually be compared with data, are presented. In case (i) the time dependence of neutron emission from the compound nucleus is non–exponential and leads to a novel test of random–matrix theory in nuclei. In case (ii) a fraction of dipole–excited nucleons is emitted directly without intermediate compound–nucleus formation. For the remainder, multiple dipole absorption leads to highly excited compound nuclei with comparatively small total spin. That offers the possibility to investigate the compound nucleus in domains of spin and excitation energy that are not readily accessible at present. It is expected that multiple dipole absorption saturates at an excitation energy near half the total binding energy. Subsequent multiple neutron decay is expected to populate a chain of nuclei with masses extending far off the line of stability into the proton–rich domain, offering the possibility to investigate such exotic nuclei spectroscopically.
Inelastic neutron scattering from carbon, iron, yttrium and lead

Cecilia Gustavsson, Jan Blomgren, Angelica Öhrn, Stephan Pomp

Department of physics and astronomy, Uppsala University, Sweden

Double-differential cross sections and angular distributions of inelastic neutron scattering on $^{12}$C, $^{56}$Fe, $^{89}$Y and $^{208}$Pb have been measured at 96 MeV at The Svedberg Laboratory, Uppsala, Sweden. Results on elastic neutron scattering at 96 MeV from these nuclei have been reported previously [1]. To obtain the inelastic cross sections, a forward-folding technique has been applied. A physically reasonable trial spectrum has been folded with the response function of the detector system and the output has been compared with the experimental data. To create the trial spectrum, a Gaussian has been used for the elastic part and the PRECO code [2] for the inelastic part. Other models were tested for the pre-equilibrium contribution and the method was found to be model independent. The response function of the detector setup has been obtained experimentally at the smallest possible angle, in this case at 9 deg.

The resulting inelastic scattering data cover an excitation energy range up to 45 MeV and the angular intervals 28 to 58 deg for $^{12}$C, 26 to 65 deg for $^{56}$Fe and 26 to 52 deg for $^{89}$Y and $^{208}$Pb. The results are discussed and compared to several model codes as well as existing experimental data for (n,n’x), (n,p’x) and (p,p’x).

Momentum-dependent nucleus-nucleus interaction resulting in dissipative reaction dynamics

Yoritaka Iwata, Hans Feldmeier

GSI Helmholtzzentrum fur Schwerionenforschung, Darmstadt, Germany

Momentum-dependent nucleus-nucleus interaction is studied based on time-dependent energy-density functional calculations. In particular, macroscopic collective Lagrangian is derived from the microscopic dissipative dynamics (for momentum-dependent dissipative dynamics in collisions between two identical $^{16}$O nuclei, see [1]). Here it is notable that large dissipation arising from the spin-dependent interactions (e.g. spin-orbit interaction) [2] and the fast charge equilibration dynamics [3] should not be necessarily reduced to the wall-window type dissipation mechanism [4]. Consequently, momentum-dependent nucleus-nucleus interaction is systematically profiled using the protocol shown in [5] (for the preceding works, e.g., see [6,7]).


This work was supported by the Helmholtz Alliance HA216/EMMI.
Extending the Kawai-Kerman-McVoy Statistical Theory of Nuclear Reactions to Doorway States

G. Arbanas¹, C.A. Bertulani², D.J. Dean³, A.K. Kerman⁴,⁵, and K.J. Roche⁶

¹Oak Ridge National Laboratory, P.O. Box 2008, Oak Ridge, TN 37831-6171, USA
²Texas A&M University - Commerce, P.O. Box 3011, Commerce, TX 75429, USA
³Department of Energy, Washington, D.C., USA
⁴The University of Tennessee, Knoxville, TN, USA
⁵Massachusetts Institute of Technology, 77 Massachusetts Ave., 6-306, Cambridge, MA 02139, USA
⁶Pacific Northwest National Laboratory, P.O. Box 999, Richland, Washington 99352, and The University of Washington, Box 351560, 3910 15th Ave. NE, Seattle, WA 98195-1560, USA

Kawai, Kerman, and McVoy (KKM) have shown that a statistical treatment of many open channels that are coupled by direct reactions leads to modifications of the Hauser-Feshbach (HF) expression (Ann. of Phys. 75, 156 [1973]). The KKM theory may thus be viewed as an improved description of the energy-averaged cross section while being conveniently expressed in terms of the optical transmission matrix elements. The cross section is energy averaged using a large averaging interval, approximately 0.5–1.0 MeV, corresponding to the width of a single particle resonance.

When the energy-averaging interval is decreased to approximately 0.05–0.1 MeV, corresponding to a width of a doorway state, then a so-called intermediate structure appears in the cross section. We show how the KKM theory can be extended to describe the intermediate structure by explicitly accounting for doorway states in the framework of Feshbach’s projection operators.

Furthermore, we quantify the effect of the approximations used in deriving the KKM expressions by comparing them to numerical computations for large sets of compound nuclear states. The compound states are coupled to open channels by random couplings taken from a normal distribution. The width of this normal distribution is used to vary the amount of overlapping among the compound resonances, in order to study the resolved and overlapping resonance regimes and a transition between the two.
ANALYSIS OF THE (N,F) REACTION IN THE Pu ISOTOPES

O. BOULAND\textsuperscript{1}, J.E. LYNN\textsuperscript{2}, AND P. TALOU\textsuperscript{2}
\textsuperscript{1}LEPh/DEN, CEA CADARACHE, FRANCE
\textsuperscript{2}LOS ALAMOS NATIONAL LABORATORY, LOS ALAMOS, NM, USA

The description of the decay of the compound nucleus by fission is a multi-dimensional problem, which requires very many parameters. The elucidation and physical understanding of these parameters is an ongoing research process, and in this paper we report on our progress on the study of the fission cross-sections of the full sequence of plutonium isotopes. There are two purposes here: one is to further our understanding of the fission process, the other is for application to evaluating the cross-sections of nuclides for which measurements are unavailable or very poor.

Fission barrier heights are the a priori parameters for the evaluation of cross-sections. Several decades of theoretical work using Strutinsky macroscopic-microscopic or HFB methods, have revealed many of the important trends in the fission barrier topography, but an accurate quantitative evaluation of the heights remains elusive. At this stage of our understanding of fission, we depend on analysis of data to extract these parameters. If this can be done accurately enough, we can interpolate or extrapolate to poorly known nuclei with some reliability. In doing this analysis it is most important to include as detailed a knowledge as we have of the physics of fission, complicated greatly by the double-humped nature of the fission barrier in most of the actinide nuclides. In our AVXSF code we do a full Monte Carlo simulation of the intermediate and fine structure coupling and sample from all the width and spacing distributions to obtain the average cross-sections. When the number of open channels becomes large we use approximation formulae to determine the fluctuation averaging factors. The correct modeling of the intermediate structure and its associated fluctuation properties can change the estimate of barrier heights by some hundreds of keV from values deduced using the simple statistical factor.

For the fissile odd-even targets the barrier height of the even compound nucleus is deduced by similar analysis of experimental data on the (t,pf) reaction. Over the range of Pu isotopes from $^{239}$Pu to $^{245}$Pu (compound nuclei) we find a pronounced odd-even difference (lower barriers in the even nuclides).

Our analysis of (n,f) cross-section data extends over the full range to 5.5 MeV, i.e. just below the threshold to second-chance fission. At energies above the barrier the densities of the transition states at both barriers are the crucial factors in determining cross-sections. We use a quasiparticle-vibration-rotation model for both the barrier states and the level density of the target nucleus. Our analysis reveals that the pairing gap parameters for barrier densities must be significantly larger than those at the ground state deformation. This correlates with odd-even difference in barrier heights.

In this paper we shall also discuss the use of our results in evaluating unknown cross-sections of other nuclides.
Fission is a complex process which highlights many nuclear properties. A major challenge in theoretical nuclear physics nowadays is the development of a consistent approach able to describe on the same footing the whole fission process, i.e. properties of the fissioning system, fission dynamics and fission fragment distributions. As a first step, a microscopic time-dependent and quantum mechanical formalism has been developed based on the Gaussian Overlap Approximation of the Generator Coordinate Method with the adiabatic approximation. Pioneering results obtained for the low-energy fission of $^{238}\text{U}$ encouraged us to perform new studies of fission along these lines with some additional improvements. For instance, at higher energies, a few MeV above the barrier, the adiabatic approximation doesn’t seem valid anymore, and intrinsic excitations have to be taken into account.

For that purpose, a new theoretical framework called the Schrodinger Collective Intrinsic Model (SCIM) has been developed, which allows in a microscopic way a simultaneous coupling of single particle and collective degrees of freedom. Such an approach is based on a generalized Generator Coordinate Method (GCM), where the general GCM ansatz of the nuclear wave function is extended by a few excited configurations. Indeed, one considers as generating wave functions not only Hartree Fock Bogoliubov ground-state configurations with different values for the collective generator coordinate but also two quasi particle excited states. Such an approach has the advantage of describing in a completely quantum-mechanical fashion and without phenomenological parameters the coupling of quasi-particle degrees of freedom to the collective motion of the nucleons.

In this talk, I will focus on the derivation of the newly developed SCIM formalism. I will first discuss the generalized Hill and Wheeler equation and its transformation into a non local Schrodinger equation by inverting the expansion of the overlap kernel. Then, I will present numerical results of the overlap kernel in a wide range of deformation in $^{236}\text{U}$. The final Schrodinger equation, written in a convenient form that has the advantage to exhibit typical terms occurring in the formalism will then be discussed. Finally, perspectives will be sketched.
The Incomplete Fusion reaction modeling

Jan Mierzejewski
Heavy Ion Laboratory, University of Warsaw, Poland

Abstract

We would like to present a new model describing the dynamics of the Incomplete fusion reaction. Calculated mass distributions as well as alpha particle spectra will be compared to the set of experimental data.

Our model is a development of Sum Rule Model [1]. It is based on an assumption that incomplete fusion (ICF) is a two stage process. In the first stage, the projectile breaks apart when colliding with the target. In the second stage the projectile residue fuses with the target while the rest escapes in some effective potential. The escaping („projectile like”) fragment is emitted in forward angles, usually observed at θ<60° in laboratory frame. ICF influence on high spin states population was shown [2], nevertheless so far proposed models don't handle the dynamics of the process - the creation of the compound nuclei and a „projectile like” fragment emission. Recently γ-ray fold distributions for the $^{51}$V+$^{97}$Mo reaction at energy of 4.5 AMeV of $^{51}$V, measured with the γ-detector array GASP [3], have been compared to the predictions of our model.

We would like to present the basics of the model as well as its software implementation – the COMPA code. It works in event by event mode, gives a complete information on the reaction products: the entry state spin and energy distribution, reaction point coordinates, directions and velocities of the recoil and emitted light particles. The stopping of the reaction products in the passive elements of the setup, like support, target and backing, is taken into account. This way the COMPA allows for easy comparison with the experimental results. Simulated α particle spectra will be compared to the experimental data in ~10 AMeV region for the reactions $^{12}$C+$^{160}$Gd [4] and $^{12}$C+$^{51}$V [5] as well as $^{20}$Ne+$^{122}$Sn, studied with the new EAGLE [6] array recently put into operation at Heavy Ion Laboartory of the University of Warsaw.

Bibliography

Effect of alpha Q-value on reaction dynamics at energies ≈ 4-7 AMeV

Abhishek Yadav¹, Vijay R. Sharma¹, Pushpendra P. Singh², Manoj K. Sharma³, Devendra P. Singh¹, Unnati¹, R. Kumar⁴, B. P. Singh¹, R. Prasad¹ and R. K. Bhowmik⁴

¹Physics Department, Aligarh Muslim University, Aligarh (U.P.)-202 002, INDIA
²INFN-Laboratori Nazionali di Legnaro, I-35020 Legnaro, ITALY
³Physics Department, S.V. College, Aligarh (U.P.)-202 001, INDIA
⁴NP-Group: Inter University Accelerator Centre (IUAC), New Delhi-110067, INDIA
Email: *abhishekyadav117@gmail.com

In recent years, the study of incomplete fusion (ICF) reactions has got resurgent interest after the observation of its unexpected presence at low energies i.e. 4-7 AMeV [1-6]. In previous studies, the onset and strength of ICF have been studied in terms of different observables, viz; the projectile energy, the mass asymmetry (μA=A_f/A_t+p) of interacting partners, the input angular momenta (ℓ) imparted to the system etc. The unexpected presence of ICF at such a low energy has been justified as the consequence of high input angular momenta imparted into the system due to non-central interactions [3]. It has been observed that in order to release the excess input angular momenta above the fusion limit (ℓ_{crit}) the projectile breaks into its constituents to provide sustainable input angular momenta to the system to fuse. In this case only a part of projectile fuses with target nucleus, while the remnant flows at forward angles with almost projectile velocity.

Most of the latter studies have been carried out with projectiles such as ¹²C, ¹⁸O, ²⁰Ne, which have α-cluster structure. In fact the cluster structure has been suggested as one of the factors leading to forward peaked alpha particles in ICF reactions. However, no systematic studies have been carried out to ascertain this aspect. As such, a program have been undertaken to carry out some conclusive experiments using ¹²C, ¹⁵N, and ¹⁸O beams on different targets, which will provide us a rich data set to understand the underlying dynamics. The present work is the first step in this direction, where, the excitations functions of ¹²C and ¹³C on ¹⁵⁹Tb target at energies ≈ 4-7 AMeV have been studied. The experiments have been performed at Inter University Accelerator Center (IUAC), New Delhi using the gamma-spectroscopy. The measured EFs have been analyzed within the framework of statistical model code PACE4 [7] and significant enhancement in the alpha-emitting channels have been observed for both the systems, which attributed as the contribution coming from ICF reaction dynamics. It is not out of place to mention that the binding energy of the alpha particle for ¹²C and ¹³C is equal to -7.37 and -10.6 MeV, respectively. On the other hand, the ground state Q-values (Q_{gg}) for reactions leading to the emission of the alpha particle is -9.42 and -7.5 MeV for the ¹²C and ¹³C with ¹⁵⁹Tb. In general, the yield of residues produced in the interaction follow the Q_{gg} systematic. However, the present measurements with the data of ref.[8] on ¹²C + ¹⁸O interactions shows the instead of Q_{gg} of the reaction the alpha Q-value plays important role on reaction dynamics which will be presented during the conference.

References
Brownian shape motion: Fission fragment mass distributions

Jørgen Randrup
Nuclear Science Division, Lawrence Berkeley Laboratory, Berkeley, California 94720, USA

Although nuclear fission can be understood qualitatively as an evolution of the nuclear shape, a quantitative description has proven to be very elusive. In particular, until now, there exists no model with demonstrated predictive power for the fission fragment mass yields. Exploiting the expected strongly damped character of nuclear dynamics, we treat the nuclear shape evolution in analogy with Brownian motion and perform random walks on five-dimensional fission potential-energy surfaces which were calculated previously and are the most comprehensive available [1]. Test applications give good reproduction of highly variable experimental mass yields, as is illustrated in the figures below [2]. This novel general approach requires only a single new global parameter, namely the critical neck size at which the mass partition is frozen in, and the results are remarkably insensitive to its specific value.

Left: Calculated and measured charge yields for fission of $^{240}$Pu and $^{236,234}$U. The data in (a–c) are for (n$_{th}$,f) reactions leading to $E^* \approx 6.5$ MeV [3], while the data in (d) is for ($\gamma$,f) reactions leading to $E^* \approx 8 - 14$ MeV; they include contamination from $^{233}$U ($\approx 15\%$) and $^{232}$U ($\approx 5\%$)[4]; the calculation was made for $E^* = 11$ MeV.

Right: Calculated charge yields from $^{222,224,226,228}$Th compared to experimental data [4]. (From [2].)

In order to achieve a better understanding of these results, we have embarked on more involved calculations using the friction tensor implied by the one-body wall dissipation [5]. Generally, an anisotropic friction deflects the multi-dimensional shape trajectory away from the directions of the the driving force provided by the deformation energy (and thus changes the shape evolution), but there are reasons to expect that this complication will have only a minor bearing on the mass partition. The results [6] should be available at the time of the conference and, if so, they will be discussed as well.

Relative to previously employed methods, the present approach represents a significant advance with regard to predictive power. Thus, it can be readily employed in regions of the nuclear chart that are of special astrophysical interest and it may, for example, help to clarify the importance of fission recycling for the r-process. Taking explicit account of the equilibration process, our treatment extends in a natural way the compound nucleus concept and it builds directly on the general picture of low-energy nuclear dynamics as being dissipation dominated.

Applications of Event-by-Event Fission Modeling with FREYA†

R. Vogt1,2 and J. Randrup3

1Lawrence Livermore National Laboratory, Livermore, CA 94551, USA
2Physics Department, University of California at Davis, Davis, CA 95616, USA
3Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA

The recently developed code FREYA (Fission Reaction Event Yield Algorithm) generates large samples of complete fission events, consisting of two receding product nuclei as well as a number of neutrons and photons, all with complete kinematic information. Thus it is possible to calculate arbitrary correlation observables whose behavior may provide unique insight into the fission process.

The presentation first discusses the present status of FREYA, which has now been extended to include pre-equilibrium emission and multichance fission for neutron induced fission. We also discuss the extension of FREYA to spontaneous fission.

Concentrating on \(^{239}\text{Pu}(n, f)\) and \(^{252}\text{Cf}(sf)\), we discuss the neutron multiplicity correlations, the dependence of the neutron energy spectrum on the neutron multiplicity, and the relationship between the fragment kinetic energy and the number of neutrons and their energies. We also suggest novel fission observables that could be measured with modern detectors.

†The work of R.V. was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344. The work of R.V. was also supported in part by the National Science Foundation Grant NSF PHY-0555660. The work of J.R. was performed under the auspices of the U.S. Department of Energy by Lawrence Berkeley National Laboratory under Contract DE-AC02-05CH11231.
Theoretical and experimental studies of the neutron rich fission product yields at intermediate energies.

V.A. Rubchenya\textsuperscript{1,2}, J. Äystö\textsuperscript{1}, H. Penttilä\textsuperscript{1}, D. Gorelov\textsuperscript{1}

\textsuperscript{1} Department of Physics, University of Jyväskylä, POB 35, 40351-Jyväskylä, Finland
\textsuperscript{2} V.G. Khlopin Radium Institute, St.-Petersburg 194021, Russia

Nuclear fission is a promising source for discovering, producing, and investigating exotic nuclei with high neutron excess [1]. Reliable predictions of fission product yields are also important for the technical application of nuclear reactions at intermediate energy for the energy production and transmutation of nuclear waste in hybrid reactors and for developing advanced new generation nuclear GEN-IV reactors. New method to measure independent fission product yields was developed recently at the Accelerator Laboratory of the University of Jyväskylä (JYFLTRAP) [2]. This method combines the capability of the ion guide (IGISOL) technique and high mass resolving power of the Penning trap. The consistent model for the description of the independent fission product formation cross section at the light projectile energies up to about 100 MeV is developed. This model is a combination of new version of the two-component exciton model [3] and a time-dependent statistical model for fusion-fission process with inclusion of dynamical effects [4] for accurate calculations of nucleon composition and excitation energy of the fissioning nucleus at the scission point. For each member of the compound nucleus ensemble at the scission point, the primary fission fragment isobaric chain yields are calculated using multimodal approach. The charge distribution of the primary fragment isobaric chains was considered as a result of the frozen quantal fluctuations of the isovector nuclear matter density at the finite scission neck radius [5]. Isotopic fission fragment yields in the proton induced fission of \textsuperscript{232}Th and \textsuperscript{238}U measured with JYFLTRAP are compared with the theoretical predictions.

Experimental Nuclear Matter Phase Diagram from Low Energy Compound Nucleus Fragment Evaporation.

Luciano G. Moretto
University of California and LBNL Berkeley CA

ABSTRACT: The Liquid Vapor phase diagram for infinite uncharged, symmetric nuclear matter has been extracted from low energy evaporation data from a number of compound nucleus reactions. This approach appears to be more robust and requires less corrections and assumptions than that based upon ‘Multifragmentation’. The elimination of Coulomb effects and the corrections about finite size described elsewhere allows for the experimental definition of the saturated vapor concentrations and fragment size distributions as a function of temperature. Excellent quality Fisher plots lead to the final complete phase diagram and to the associated critical parameters.
On the unabridged 7D-folding structure of the optical model potential for nucleon-nucleus scattering

H. F. Arellano† and E. Bauge‡
† Department of Physics - FCFM - University of Chile
‡ CEA, DAM, DIF, F-91297 Arpajon, France

Abstract

Microscopic optical model potentials for nucleon-nucleus collisions, based on density-dependent effective interactions, involve multi-dimensional integrals to account for the Fermi motion of the bound nucleons of the target. If a spherical matter distribution is assumed, each matrix element of the optical potential, \( U(k', k; E) \), requires the evaluation of seven-dimensional integrals [1], i.e.

\[
U = \int d^3P \rho(P - \frac{q}{2}, P + \frac{q}{2}) \frac{t}{2\pi^2} \int_0^\infty z^3dz \int d^3Q d^3P \rho(P - \frac{Q}{2}, P + \frac{Q}{2}) j_1(|z| Q - q) \frac{\partial g_z}{\partial z},
\]

with \( t \) the off-shell nucleon-nucleon (NN) scattering matrix and \( \partial g_z/\partial z \) the gradient of the \( g \) matrix at the isoscalar density \( \rho(z) \). Here \( \rho \) denotes the target mixed density. In this contribution we report results when a full account of these integrals is in place, retaining the genuine off-shell structure of the nucleon-nucleon effective interaction given by solutions for the \( g \) matrix in the Brueckner-Bethe-Goldstone framework. These calculations are very intensive in CPU computing time, becoming feasible only with the use of multiprocessor platforms. The resulting non-local potentials, based on \( g \) matrices from the Paris nucleon-nucleon (NN) potential, are applied to proton elastic scattering from \(^{16}\text{O}\) and \(^{90}\text{Zr}\) at beam energies between 30 and 65 MeV. We have compared these results with those obtained with alternative approximations [2], observing moderate differences among their scattering observables. In this presentation we shall also address issues regarding the coordinate-space structure implied by the unabridged optical potential, aiming to disclose its equivalence with traditional coordinate-space approaches based on local effective interactions within the local density approximation [3].


Work funded in part UCH-VID under grant ENL1106
This work is dedicated to a microscopic derivation of the optical potential involved in nucleon elastic scattering studies, in the case of doubly closed-shell target nuclei and generally to nuclei well described by the random phase approximation (RPA). We use the so-called ”nuclear structure approach” developed by Vinh Mau and Bouyssy. First, we present results for a calculation using the Gogny force consistently to generate both the real Hartree-Fock term and the complex RPA term of the microscopic optical potential (MOP). Then we present the results obtained adding the RPA potential to the one obtained from g-matrix calculations (Melbourne and Santiago). The MOP is non-local complex and energy dependent. The integro-differential Schrödinger equation corresponding to the scattering problem is solved without any localization procedure. Illustrations are given for proton and neutron scattering from $^{40}$Ca and $^{208}$Pb.
A new dispersive coupled-channel optical model potential (OMP) for $^{238}\text{U}$ nucleus is presented. The derived OMP couples almost all $^{238}\text{U}$ excited levels below 1 MeV of excitation energy, including the ground state, octupole, beta, gamma, and non-axial bands. The coupled-channel potential is based on a vibrational-rotational description of the target nucleus structure, where dynamic vibrations are considered as perturbations of the rigid rotor underlying structure.

OMP parameters that show a smooth energy dependence and energy independent geometry were determined from fits to the available experimental database (including strength functions and scattering radius) for neutron and proton scattering. The energy range 0.001-200 MeV is covered.

Derived high-quality OMP is used to calculate the reaction cross section and corresponding theoretical uncertainties in nucleon-induced reactions on U-238. Theoretical calculations are compared with available results derived from existing experimental data on total cross-sections and angular distributions measurements based on the Wick's limit. Reduction of the uncertainty of the calculated reaction cross-section for neutron-induced reactions on $^{238}\text{U}$ is discussed.

d---
e-mail: r.capotenov@iaea.org
Impact of collective states on direct pre-equilibrium emission  
M. Dupuis, S. Peru, E. Bauge, J.-P. Delaroche, T. Kawano

We report on microscopic model calculations of the one-step direct pre-equilibrium emission process for nucleon induced reactions on spherical or axially deformed nuclei.

In the case of spherical target nuclei, the inelastic scattering \((n,n')\) or \((p,p')\) processes, that contribute to the direct pre-equilibrium emission, are calculated within the DWBA framework and a fully microscopic approach is used: transition potentials for the inelastic processes are built from the (Q)RPA [(Quasi-particle) Random Phase Approximation] wave functions, obtained with the D1S Gogny force, and a g-matrix is used as the effective interaction for the transition (residual interaction). All component of the residual interaction, included the spin-orbit and tensor parts, are used to generate the non-local transition potentials. Inelastic cross sections, obtained from these potentials, are calculated for all excitations in the target predicted by the (Q)RPA model, and are combined to provide the one-step direct pre-equilibrium cross section.

We will focus on the target spectrum details, such as its collective content, and the presence of high spin and non natural parity states, that strongly impact on the pre-equilibrium emission [1]. Results of the present microscopic model are in good agreement with experimental measurements and it will be shown that a precise description of both the residual interaction and the target spectrum are needed to perform reliable predictions of pre-equilibrium cross-sections. Specific examples will be given for nucleon induced reactions on double magic nuclei (RPA based calculations), or on spherical nuclei with paring (QRPA-based calculations).

Calculations performed for deformed target in a coupled channel framework will also be depicted. The semi-microscopic JLM convolution model [2] is used together with microscopic QRPA wave functions [3], that include collective effect, to build the relevant optical and transition potentials that are involved in the description of a nucleon inelastic scattering process off an axially deformed nucleus. This method will be applied to predict the pre-equilibrium emission in the case of 10-20 MeV neutron induced reaction on \(^{238}\text{U}\), in order to explain the large neutron emission observed at high emission energy [4].

The density of available states of the DDHMS pre-equilibrium model

B.V. Carlson e D. F. Mega

Instituto Tecnológico de Aeronáutica, São José dos Campos SP, Brasil

Griffin's exciton model of pre-equilibrium emission [1] and Blann's hybrid model [2] have proven extremely successful in describing the energy dependence and, to a certain extent the angular dependence, of nucleon and composite particle emission in pre-equilibrium reactions [3]. However, the conceptual basis of these models was called into question by Bisplinghoff already some time ago. [4] Numerical calculations of our own corroborate his doubts. [5] In response to Bisplinghoff, Blann proposed the hybrid Monte Carlo simulation model (HMS), [6] which uses only the densities of available states for creation and decay of single particle-hole pairs. The model was later extended, in collaboration with Chadwick, to the double-differential HMS, which we call the DDHMS. [7] This extension is based on Chadwick and Oblozinsky's prescription for approximating the energy-angular distribution of available two-particle-one-hole states. [8,9] Here, we show how this distribution can be calculated exactly and compare the exact result to the approximate one, both directly and in calculations within the DDHMS model.

References
Pre-equilibrium emission of $\alpha$-particles with energies in the region of those from compound nucleus decay

A. A. Cowley

Department of Physics, Stellenbosch University, Private Bag X1, Matieland 7602, South Africa, and
iThemba Laboratory for Accelerator Based Sciences, P O Box 722, Somerset West 7129, South Africa

Nucleon-induced pre-equilibrium particle emission in the incident-energy range 100 to 200 MeV is of considerable interest. Unambiguous identification of the reaction mechanisms leading to emission of composite ejectiles, such as $\alpha$-particles, remains a challenge. Recently Bevilacqua [1] found that the TALYS [2] formulation, when compared with the proton-induced experimental data of [3], overestimates high-energy emission of $\alpha$-particles and underestimates it at low outgoing energy. Of course, when the knockout-pickup input in the TALYS code is adjusted for better agreement with the trend towards higher emission energy, the problem is exacerbated at the low energy end. Although suggesting a negligible knockout component at comparatively high emission energies, the results of Bevilacqua [1] are in qualitative agreement with a statistical multistep knockout analysis of Cowley et al. [3]. Based on explicit exclusive proton induced knockout studies, the present work suggests that the excitation of low-lying states in the target system, which undergoes $\alpha$-particle decay, contributes largely to the continuum spectrum at low-energies. This has a profound influence on $\alpha$-particles with energies down to values comparable to those associated with emission from the compound system.

Clustering Pre-equilibrium Model Analysis for Nucleon-induced Alpha-particle Spectra up to 200 MeV

S. Kunieda*, T. Kawano*, M. B. Chadwick*, T. Fukahori† and Y. Watanabe‡

* Theoretical Division, Los Alamos National Laboratory
† Nuclear Data Center, Japan Atomic Energy Agency
‡ Department of Engineering Science, Kyushu University

The clustering exciton model of Iwamoto and Harada [1] is applied to the analysis of pre-equilibrium alpha-particle energy spectra. The model describes the pickup process within the exciton model framework, where the alpha-particle formation factor is calculated by the overlap of wave functions between the alpha-particle and four excitons. In the present work, the formation factor is calculated exactly, while the original Iwamoto-Harada model employed a root-mean-square approximation where no correlation exists between the coordinates in the phase-space. The model is incorporated into the GNASH code [2] to obtain the alpha-particle energy spectra that are consistent with the \((N,x\alpha)\) cross sections. The exciton model parameters are independently obtained to reproduce experimental \((N,xN)\) pre-equilibrium spectra, while the pickup radius \(\Delta R\) is determined to describe measured \((N,x\alpha)\) spectra. According to this analysis, the model gives a global description of experimental spectra with a simple parameterization up to 150 MeV, although it tends to underestimate the measured data at higher energies. In this talk, we show the difference between the exact and the approximation calculations. The calculated spectra are presented for the nucleon incident energies up to 200 MeV, and behavior of the major parameters are investigated.

References


Iwamoto-Harada model of pre-equilibrium cluster emission: Should we care about angular momentum?

E. Bětáčk a,b

a Institute of Physics SAS, 84511 Bratislava, Slovakia
b Fac. of Philos. and Sci., Silesian Univ., 74601 Opava, Czech Rep.
E-mail betak@savba.sk

Abstract

The Iwamoto-Harada model of pre-equilibrium cluster emission [1, 2] was formulated within spin-independent exciton model. The inclusion of angular momentum into the pre-equilibrium reactions [3] proved to be important and essential for the γ emission [4]. The angular-momentum couplings have not yet been applied to the light cluster emission; however, the connection with deformation suggested by Blann [5] has been shown to have visible effects. Our study is aimed to consider, whether and how the angular-momentum couplings influence the light cluster emission within the Iwamoto-Harada model.

References:

Deuteron-induced reaction mechanisms at low energies

M. Avrigeanu* and V. Avrigeanu

"Horia Hulubei" National Institute for Physics & Nuclear Engineering,
P.O.Box MG-6, Bucharest-Magurele, Romania

The deuteron-induced reactions at low and medium energies have a great importance within several on-going strategic research programmes at international large-scale facilities as ITER, SPIRAL-2, and IFMIF. The accurate knowledge of the deuteron activation cross sections is critical for selecting and validating their best structural materials and a number of key technologies, while the actual data of deuteron-induced reaction are less extensive and mature than for neutrons. A main reason for this status is the weak binding energy of the deuteron that is responsible for a supplementary variety of reactions initiated by the neutrons and protons coming from deuteron breakup. The present work concerns a deeper understanding of deuteron breakup, stripping and pick-up reactions, all together and consistently with the better-known and described statistical emission. Moreover, an increased attention is paid to the inelastic- and elastic-breakup components very poorly accounted so far in deuteron activation analysis. Overall, the theoretical description of the deuteron interactions with nuclei needs significant improvements that can be validated only by suitable description of experimental data. At the same time setting up of well-documented proposals for further measurements is planned.

* mavrig@ifin.nipne.ro


On neutron-induced reaction mechanisms at medium energies

V. Avrigeanu*, M. Avrigeanu, and F.L. Roman

"Horia Hulubei" National Institute for Physics & Nuclear Engineering,
P.O.Box MG-6, Bucharest-Magurele, Romania

The cross sections for nuclear reactions induced by fast neutrons below 20 MeV are generally considered to be reasonably well known in spite of many fast neutron reactions for which the several data are either conflicting or incomplete even around 14 MeV (e.g. ¹ and Refs. therein). It is the reason why having recent sets of accurate measured cross sections still below 20 MeV is highly desirable. Actually the model calculations of these data are most sensitive to the parameters related to nuclei in the early stages of the reaction, i.e. within the pre-equilibrium emission (PE) processes which then become dominating at higher energies. Since the corresponding model assumptions are thus better proved by analysis of the data above 20-30 MeV, this work underlines the usefulness of further measurements to be performed at large-scale facilities, e.g. SPIRAL-2 and n_TOF, for incident energies up to 40 as well as 100 MeV.

A particular consideration is given to PE parameters and assumptions of the Geometry-Dependent Hybrid (GDH) model - the most important for the medium energies where the global predictions have shown a larger variance with respect to the measured data. Thus, there is a good opportunity to look for the understanding of the model constraints which are responsible for the calculated cross section variations, concerning particularly (a) the incident energies below 20 MeV, where the model calculations are most sensitive to the parameters related to residual nuclei and emitted particles which are populating them, and (b) the energies above 20-30 MeV, where the PE processes become dominating so that the measured data analysis may better prove the corresponding model assumptions as, e.g., the nuclear potential finite-depth correction in the GDH model for the partial, particle-hole, level density (PLD) formula². Moreover, a specific interest will be related to the question if recent global OMP for α-particles that describe well both the elastic scattering on the (cold) ground-state nuclei and α-particle induced reaction data³ are still underestimating the statistical α-particle emission⁴.

* vavrig@ifin.nipne.ro

Minimization of actinide waste by multi-recycling of thoriated fuels in the EPR reactor

S. J. Rose\textsuperscript{a}, J. N. Wilson\textsuperscript{b}, N. Capellan\textsuperscript{b}, S. David\textsuperscript{b}, P. Guillemin\textsuperscript{c}, E. Ivanov\textsuperscript{d}, O. Méplan\textsuperscript{c}, A. Nuttin\textsuperscript{c}, S. Siema

\textsuperscript{a} University of Olso, \textsuperscript{b} Institut de Physique Nucléaire d’Orsay, \textsuperscript{c} Laboratoire de Physique Subatomique et Cosmologie, \textsuperscript{d} Institut de radioprotection et de Sûreté Nucléaire

The multi-recycling of innovative uranium/thorium oxide fuels for use in the European Pressurized water Reactor (EPR) has been investigated, using the Monte-Carlo based simulation code MURE (MCNP Utilities for Reactor Evolution), based on MCNP5. If increasing quantities of $^{238}\text{U}$, the fertile isotope in standard UO\textsubscript{2} fuel, are replaced by $^{232}\text{Th}$, then a greater yield of new fissile material ($^{233}\text{U}$) is produced during the cycle than would otherwise be the case. This leads to economies of natural uranium of around 30\% if the uranium in the spent fuel is multi-recycled. In addition we show that minor actinide and plutonium waste inventories are reduced and hence waste radio-toxicities are up to a factor of 20 lower after $10^3$ years. Two innovative fuel types named S90 and S20, ThO\textsubscript{2} mixed with 90\% and 20\% enriched UO\textsubscript{2} respectively, are compared as an alternative to standard uranium oxide (UOX) and uranium/plutonium mixed oxide (MOX) fuels at the longest EPR fuel discharge burn-ups of 65 GWd/t. Fissile and waste inventories are examined, waste radio-toxicities and decay heats are extracted and safety feedback coefficients are calculated. Finally, we discuss the economics of such strategies.
Third International Workshop on
Compound Nuclear Reactions and Related Topics

Book of Abstracts

Poster Session

September 19 – 23, 2011
Prague, Czech Republic
The modified proximity potential in heavy ion fusion dynamics

Rajni Bansal

Department of Physics, Panjab University, Chandigarh-160014, INDIA
email: rajnibansl@gmail.com

The systematic study of heavy-ion fusion reactions leads to several new phenomenon including the formalism of super heavy elements. The precise knowledge of ion-ion interaction potential plays an important role in understanding the various parameters of heavy-ion fusion reaction like fusion barrier positions, height and cross sections. Large number of theoretical effects has been put forward to give simple and more understandable form of the ion-ion potential. Among such attempt, proximity potentials are well known for its simplicity and numerous applications. It is the backbone of all microscopic/macroscopic heavy ion fusion studies. The proximity potential based on proximity theorem provides a simple formula for nucleus-nucleus interaction energy as a function of separation between the surfaces of approaching nuclei. From the literature, it is manifested that original proximity potential Prox 77 overestimates the experimental data by 4%. We here attempt to modify the original proximity potential by using suitable set of parameters available with the advancement in the field. Among these parameters, we use the modified form of universal function due to Blocki et al., recent form of surface energy coefficients due to Molten and Nix and a recent radius formula due to Royer et al. We notice that with the use of above parameters our modified proximity potential reproduces the experimental data nicely as compared to its older versions.
Influence of symmetry energy on Multifragmentation

Rubina Bansal and Suneel Kumar

School of Physics and Materials Science, Thapar University, Patiala-147004, Punjab (INDIA).

We study influence of symmetry energy on fragment production in the collision of Ne, Ca, Zr, Xe, Au nuclei at different scaled impact parameter and at energy 50, 100, 200, 400, 600, 1000 MeV/nucleon. Three different type of cross-section eg. Constant, isospin dependent and isospin independent with Isospin Quantum Molecular Dynamics (IQMD) Model. Analysis is being carried out on the fragment production and their associated flow.
Bound state densities and the Helmholtz free energy

F.T. Dalmolin\(^1\), M. Dutra\(^1\), B.V. Carlson\(^1\), R. Donangelo\(^2,3\), S. R. Souza\(^2,4\)

\(^1\)Instituto Tecnológico de Aeronáutica, São José dos Campos SP, Brasil
\(^2\)Instituto de Física, Universidade Federal do Rio de Janeiro, Rio de Janeiro RJ, Brazil
\(^3\)Instituto de Física, Universidad de la República, Montevideo, Uruguay
\(^4\)Instituto de Física, Universidade Federal do Rio Grande do Sul, Porto Alegre RS, Brazil

Bohr's conception of the compound nucleus is based on the idea of 'long-lived' nuclear states in which all single particles are bound.\(^{[1]}\) We analyze the properties of the density of bound states and then use two prescriptions, that of Bonche, Levit e Vautherin \(^{[2,3]}\) and that of Brack and Quentin \(^{[4,5]}\) to calculate the equivalent temperature-dependent quantity – the Helmholtz free energy. We compare the temperature dependence of the latter, as well as that of the excitation energy and entropy, obtained using the two prescriptions in self-consistent calculations within the relativistic Hartree and Skyrme models. We then discuss the extended, temperature-dependent liquid-drop approximation to the excitation and free energies \(^{[6]}\) obtained from fits to the self-consistent calculations over a wide range of charge and mass numbers.

References
\(^{[1]}\) N. Bohr, Nature \textbf{137} (1936) 344.
Measurement of neutron capture and fission cross sections of $^{233}$U in the resonance region

I. Companis$^{1,4}$, M. Aïche$^1$, L. Mathieu$^1$, G. Kessedjian$^2$, P. Schillebeeckx$^3$, G. Barreau$^1$, G. Boutoux$^2$, S. Czajkowski$^{11}$, B. Haas$^3$, B. Jurado$^3$, I. Tsekhanovich$^3$, A. J. M. Plompen$^3$

1) Centre d'Etudes Nucléaires Bordeaux Gradignan, CNRS/IN2P3, Univ. Bordeaux 1, Chemin du Solarium, 33175 GRADIGNAN, France
2) Laboratoire de Physique Subatomique et de Cosmologie, CNRS/IN2P3, Univ. Joseph Fourier, INPG, 53 avenue des Martyrs, FR - 38026 Grenoble Cedex, France
3) EC-JRC, Institute for Reference Materials and Measurements, Reteiseweg 111, B-2440 Geel, Belgium
4) Horia-Hulubei National Institute for Physics and Nuclear Engineering, P. O. Box MG-6, 077125 Bucharest-Magurele, Romania

In the framework of studies concerning new fuel cycles and nuclear wastes incineration experimental data of the alpha ratio between capture and fission cross sections of $^{233}$U(n,f) reactions play an important role in the Th/U cycle. The safety evaluation and the detailed performance assessment for the new generation IV nuclear energy system projects strongly depend on this rapport. Since the current data are scarce and sometimes contradictory new experimental studies are required. The measurement will take place at the neutron time-of-flight facility GELINA at Geel, designed to perform neutron cross section measurements with high resolution for the incident neutron energy. A dedicated high efficiency fission ionization chamber (IC) as a fission fragment detector and six C$_6$D$_6$ liquid scintillators are used. The method, based on the IC energy response study, allowing to distinguish between gammas originating from fission and capture in the resonance region, will be presented.
Fission-fragment mass distributions calculated by
Monte Carlo simulations of proton - and
photon-nucleus reactions

Airton Deppman
Institute of Physics - São Paulo University
Brazil
July 2, 2011

Abstract
Recent experiments have shown that the multimode approach for de-
scribing the fission process is compatible with the observed results. A sys-
tematic analysis of the parameters obtained by fitting the fission-fragment
mass distribution to the spontaneous and low-energy data has shown that
the values for those parameters present a smooth dependence upon the
nuclear mass number. In this work, a new methodology is introduced for
studying fragment mass distributions through the multimode approach.
It is shown that for fission induced by energetic probes (E>30 MeV) the
mass distribution of the fissioning nuclei produced during the intranuclear
cascade and evaporation processes must be considered in order to have a
realistic description of the fission process. The method is applied to study
$^{208}\text{Pb}$, $^{235}\text{U}$, $^{239}\text{Np}$ and $^{241}\text{Am}$ fission induced by protons or photons.
Target-State Dependence of Cross Sections for Neutron Reactions on Statically Deformed Nuclei and the Adiabatic Approximation

F. S. Dietrich, I. J. Thompson
Lawrence Livermore National Laboratory, Livermore, CA 94551, USA

T. Kawano
Los Alamos National Laboratory, Los Alamos, NM 87545, USA

As part of an effort to understand how neutron-induced reactions on excited states in deformed nuclei differ from those on ground states, we have carried out coupled-channels calculations of the angle-integrated cross sections on the ground and excited states of several actinide nuclei with differing $K$-values for the ground-state band ($^{233}$U, $K = \frac{5}{2}$; $^{235}$U, $K = \frac{7}{2}$; $^{238}$U, $K = 0$; and $^{239}$Pu, $K = \frac{1}{2}$). Of particular interest is the compound-nucleus formation cross section. We find that the ratio of the excited to ground-state compound formation cross sections is very close to unity in all cases (within $\approx 0.1\%$) over the range studied (1 keV to 20 MeV). This result requires that sufficient rotational-band levels be coupled to ensure convergence (approximately 14 levels for odd-A nuclei). These results are close to the predictions of the adiabatic model for scattering from statically deformed nuclei. This model yields compound formation cross sections, as well as total cross sections, that are independent of both the $K$-value of the band and the spin $I$ of the target state within the band. We have tested this prediction by comparing adiabatic calculations with the full, nonadiabatic ones as a function of $K$ and $I$. Our calculations show that the actual cross sections are surprisingly close to the adiabatic limit, even at very low incident energies. We have also carried out calculations for deformed rare-earth nuclei ($^{165}$Ho, $K = \frac{7}{2}$; $^{169}$Tm, $K = \frac{1}{2}$; $^{170}$Yb, $K = 0$), as well as for a deformed $s$-$d$ shell nucleus ($^{20}$Ne, $K = 0$). For these cases we find results similar to those in the actinide nuclei.

* This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344, and by Los Alamos National Laboratory under Contract DE-AC52-06NA25396.

Dynamics of multifragmentation in Au+Au reactions at low incident energies.

Supriya Goyal† and Rajeev K. Puri††

†Department of Physics, Panjab University, Chandigarh-160 014, India
††Email address: rkpuri@pu.ac.in

The most interesting and sought-after phenomenon of multifragmentation is observed in many reaction types: light ion induced reactions at large incident energies (in the GeV range), central heavy-ion collisions from 30 to 100 MeV/nucleon, and peripheral heavy-ion collisions between 20 and 1000 MeV/nucleon or above. In the low energy regime, fusion-fission, binary decays, compound nucleus formations etc. are the most dominant channels [1], which are followed by one set of multifragmentation and vaporization as the incident energy increases. In the present study, we used Quantum Molecular Dynamics (QMD) model [2] for phase space simulations along with Minimum Spanning Tree (MST) clusterization algorithm [2], in order to see the phenomenon at low incident energies for Au+Au collisions over entire colliding geometries i.e. b = 0-13 fm. The mass of the largest fragment (<A_{max}>) at the final time step gives us a possibility to look for fusion-fission phenomenon [2]. The variation of <A_{max}> with impact parameter is shown in Fig. 1 at 35-100 MeV/nucleon.

![Fig. 1. The variation of <A_{max}> as a function of the impact parameter.](image)

As it is clear from the Fig. 1 that, as the impact parameter increases, the size of <A_{max}> also increases. The <A_{max}> in low energy collisions is nearly independent of the impact parameter, whereas a strong impact parameter dependence is observed as energy increases. One also sees that the <A_{max}> is nearly independent of the bombarding energy at peripheral collisions and the size of <A_{max}> is nearly equal to 180. Our study indicates that at peripheral geometries, one can see the incomplete fusion-fission phenomenon. Due to the lack of proper antisymmetrization in QMD model, the simulations at very low energies cannot be performed. One should note that, the size of <A_{max}> also depends upon the clusterization algorithm one is using.

Spatial- and Time-Correlated Detection of Fission Fragments

Carlos Granja\textsuperscript{1}, Vaclav Kraus\textsuperscript{1}, Yuri Kopatch\textsuperscript{2}, Sergei A. Telezhnikov\textsuperscript{2}, and Stanislav Pospisil\textsuperscript{1}

\textsuperscript{1}Institute of Experimental and Applied Physics, Czech Technical University in Prague, Czech Republic
\textsuperscript{2}Frank Laboratory of Neutron Physics, JINR Dubna, Russia

Work carried out in frame of the Medipix Collaboration

With the goal to measure angular correlations of fission fragments in rare fission decays (e.g. ternary and quaternary fission), a multi-detector coincidence system based on two and up to four position sensitive pixel detectors Timepix has been built. In addition to the high granularity, wide dynamic range and per pixel signal threshold, these devices are equipped with per pixel energy and time sensitivity providing more complete information (position, energy, time), enhances particle-type identification and selectivity of event-by-event detection. Operation of the device with the integrated USB 2.0 based readout interface FITPix and the control and data acquisition software tool Pixelman enables online visualization and flexible/adjustable operation for a different type of experiments. Spatially correlated fission fragments can be thus registered in coincidence (see Fig. 1). Also triggered measurements are performed using a spectrometric module with integrated analogue signal chain electronics. The current status of development together with demonstration of the technique with a \textsuperscript{252}Cf source is presented.

Fig. 1. Spatially-correlated (top figures) detection of pairs of fission fragments in coincidence by two Timepix pixel detectors operated in time mode and in high threshold (to suppress the alpha particles). Frames shown collected in 300 ms exposure time. The spatial information, registered in the 256 × 256 pixel matrix of each detector, is coupled to the time-correlated information given by the color scale in the range 650–950 ms. The time stamp of single events is displayed also in the time scale (bottom) with amplitude given by the number of pixels in each event (or cluster size). Correlated events are linked by dash arrows. The time stamp of two pairs of single events is explicitly included for illustration (one uncorrelated event is shown by black label for illustration too).
Transition of Highly Excited Composite System to Compound Nucleus

Oleg Grudzevich
IATE, Obninsk, Russia

Abstract

The physical criterium of the equilibration time choice in the frameworks of the multi-particle preequilibrium model is proposed. The movement of the composite system formed by the nucleons of 100 MeV-3 GeV energies to the equilibrium is discussed. The comparison of calculated neutron multiplicities in $^{208}$Pb + p reaction with experimental data has served as the basis for the testing of the proposed method. It is appeared, that calculated neutron multiplicities are in good coincidence with experimental data without parameter fitting.

The characteristics of the coincidence of the preequilibrium and evaporational spectrum shapes are given in a fig.1 for the analysis of radiations of the composite systems formed in reactions of protons with the energies up to 1500 MeV with $^{208}$Pb target.

Fig. 1. Deviations of calculated by MCP model neutron spectra from an evaporation shape as a dependence on numbers of ph-configuration and energy of protons in $^{208}$Pb+p reaction. The arrow marks $N_{ph}^{max} = 30$ configuration.

Fig. 2. The neutron multiplicities of $^{208}$Pb + p reaction. The symbols are the experimental data. The dashed lines are the results of calculations with the fixed $M_n = 5, M_p = 2$ (curve#1) and with $M_n = 25, M_p = 10$ (curve # 2). The results of calculations with fixed maximal preequilibrium configuration are shown by solid curve # 3.

To avoid the parameter fitting in calculation of the secondary particle multiplicity of the intermediate and high energy reactions with multiparticle preequilibrium model we fixed the highest particle-hole configuration (#30) of the composite system which emits preequilibrium nucleons. The more complicated configurations were declared as the states of the compound nucleus. The results of the neutron multiplicity calculations coincide with the experimental data for the wide projectile energy region of $^{208}$Pb + p reaction (fig.2).

References

Study of Spatial correlation in multifragmentation

Pallavi gupta and Suneel Kumar#

#School of Physics and Material Science, Thapar University Patiala.

Abstract

In the present study, we review the formation of fragments in Au-Au reaction at two different incident energies at $E=100$ MeV/nucleon and 600 MeV/nucleon. For the present analysis, IQMD model has been used as event generator. To address the stability of fragments, three different clusterization algorithms has been employed MST, MSTB and MSTP. The results shows that the fragment created are not stable even at 100 fm/c and an additional binding energy check helps to discard the unbound fragment. MST and MSTP identifies the fragments early and also there at 600 MeV/nucleon have more destruction as compared to 100 MeV/nucleon and creation of unstable/unbound fragments is much more at 600 MeV/nucleon as compared to 100 MeV/nucleon.
Recent thermal neutron-capture measurements onto the stable tungsten isotopes have been performed using the guided thermal-neutron beam at the Budapest Reactor. Prompt singles spectra were collected and analyzed for the compound tungsten systems $^{183}$W, $^{184}$W, and $^{187}$W using individual isotopically-enriched samples. These new data provide both confirmation and new insights into the decay schemes and structure of the tungsten isotopes reported in the Evaluated Gamma-ray Activation File (EGAF) based upon previous elemental analysis. The experimental data have also been compared to Monte Carlo simulations of $\gamma$-ray emission following the thermal neutron-capture process using the statistical-decay code DICEBOX. Together, the experimental cross sections and modeled-feeding contribution from the quasi continuum, have been used to determine the total radiative thermal neutron-capture cross sections for the tungsten isotopes and provide improved decay-scheme information in the neutron data libraries.
Effects of Charge Asymmetry on Light Mass Fragment Production

Anupriya Jain¹, Suneel Kumar¹*

¹School of Physics and Material Science, Thapar University, Patiala 147004, Punjab, India

Abstract

The multifragmentation of excited nuclear system with various N/Z ratios and fixed mass numbers (A=124 isobars with Z=47,48,49,50,51,52,53,54,55,56,57,58,59) and (A=40 isobars with Z=14,15,16,17,18,19,20,21,22,23) is studied with different cross-sections (isospin dependent and another is isospin independent). Simulations are carried out using the Isospin dependent Quantum Molecular Dynamical Model (IQMD). Fragment production is influenced by different cross-sections and charge asymmetry of colliding partners.
Decay of $^{201}$Bi formed in $^{20}$Ne induced reaction at $E_{CM}=162$ MeV.

Gurvinder Kaur and Manoj K. Sharma

School of Physics and Materials Science, Thapar University, Patiala- 147004, India.

The collision between heavy ion projectile and a target nucleus may lead to the formation of Compound Nucleus (CN) or a Non-Compound Nucleus (NCN) depending on the choice of reaction partners, energy involved and angular momentum contribution etc. Alternatively, we can also experience the CN and NCN contributions simultaneously for a target–projectile colliding at low energy regime. The simultaneous existence of CN and NCN is of great interest because such studies provide a comprehensive picture of nuclear reaction dynamics and related physical phenomenon. The CN and NCN cross-sections data is available for $^{20}$Ne$^{10+}$+$^{181}$Ta$^{73}$$\rightarrow$$^{201}$Bi$\rightarrow$ $A_1+A_2$ reaction at two different energies [1] and the same is tested in the framework of Dynamical Cluster Decay Model DCM [2, 3]. It may be noted that evaporation residue(ER) data for reaction under consideration have contributions from CN as well as NCN process. The evaporation residue cross-section $\sigma_{ER}$ has been fitted within DCM using spherical consideration and also by including higher multipole deformations upto hexadecapole using optimum orientation approach at $E_{CM}=162$ MeV. Figure 1 clearly shows that the potential energy surfaces get influenced significantly with the inclusion of deformation effects.

![Fragmentation Potential as a function of Fragment Mass.](image)

Figure 1: Fragmentation Potential as a function of Fragment Mass.

The $\sigma_{ER}$ has also been fitted using four different residual projectiles $^{16}$O, $^{14}$N, $^6$Be, and $^4$He which have been formed due to the break-up of original projectile $^{20}$Ne$^{10}$ (a transfer reaction in the incomplete fusion process). As expected the contribution of $^4$He transfer reaction is maximum followed by $^6$Be, $^{14}$N, $^{16}$O transfer reactions. In summary DCM based $\sigma_{ER}$ and $\sigma_{ER}$ compare nicely with experimental data. The calculations for fission part are in progress and we plan to present the complete decay mechanism of $^{201}$Bi formed in $^{20}$Ne$^{10+}$+$^{181}$Ta$^{73}$ reaction by the time of conference.

Modeling spallation reactions in tungsten and uranium targets with the Geant4 toolkit

Yury Malyshkin\textsuperscript{1}, Igor Pshenichnov\textsuperscript{1,2}, Igor Mishustin\textsuperscript{1,3}, Walter Greiner\textsuperscript{1}

\textsuperscript{1}Frankfurt Institute for Advanced Studies, J.-W. Goethe University, 60438 Frankfurt am Main, Germany
\textsuperscript{2}Institute for Nuclear Research, Russian Academy of Science, 117312 Moscow, Russia
\textsuperscript{3}Kurchatov Institute, Russian Research Center, 123182 Moscow, Russia

We study primary and secondary reactions induced by 600 MeV proton beams in monolithic cylindrical targets made of natural tungsten and uranium. Neutron yields and energy deposition in the targets’ volume are calculated with a specialized code MCADS (Monte Carlo for Accelerator-Driven Systems) created at FIAS. This application is based on the Geant4 toolkit \cite{1, 2, 3}, which is widely used in nuclear and particle physics. Several sets of models (Geant4 physics lists) were involved to simulate neutron production by protons as well as neutron propagation inside the targets. Three options of intranuclear cascade model were considered to simulate the interactions of energetic nucleons with nuclei. They include Bertini intranuclear cascade model and Binary cascade model with corresponding deexcitation codes, and IntraNuclear Cascade Liège (INCL) with ABLA model \cite{4}. In all cases Neutron High Precision models (NeutronHP) of Geant4, which are based on evaluated nuclear data, where used to transport neutrons with energies below 20 MeV. Simulation results obtained with different physics list options are compared with each other. The results are mostly similar for the tungsten target but diverge for the uranium one, due to differences in the description of nuclear fission.

Mass distributions of fission fragments are calculated with Bertini and INCL models and compared with recent experimental data on proton-induced fission of uranium nuclei \cite{5}. A rather good agreement with data is obtained with INCL and ABLA.

Neutron yields, energy deposition, space and time distributions of neutron flux obtained with a common computational tool for W and U targets are compared. In this way the role of fission in the performance of the spallation targets is evaluated. It is found that about 450 MeV per beam proton is deposited in the tungsten target, while the energy deposition in the uranium target reaches 600-700 MeV due to additional contribution from fission.

References

\cite{1} S. Agostinelli et al. (Geant4 Collaboration), Nucl. Instr. Meth. A \textbf{506} (2003) 250
\cite{3} J. Apostolakis et al. (Geant4 Collaboration), Radiat. Phys. Chem. \textbf{78} (2009) 859
We study the space-time characteristics of participant and spectator matter. For this, we simulated the semi-central collisions of $^{40}\text{Ca} + ^{40}\text{Ca}$ and $^{197}\text{Au} + ^{197}\text{Au}$ at incident energies of 400AMeV within the quantum molecular dynamics (QMD) approach. Our numerical calculations based on the molecular dynamics approach show that incident energy of the projectile influences the reaction observables drastically. The characteristics of the trajectories followed by the nucleons suffering maximal and minimal binary collisions are analyzed. Nucleons suffering maximum collisions are seen to be emitted as a bunch that traverses nearly in the same direction, whereas those facing minimum collisions are emitted randomly in different direction.
Fusion of neutron and proton rich nuclei

Maninder Kaur

Rayat and Bahra Institute of Engineering and Bio-technology, Mohali Campus,
Punjab, INDIA

e-mail: maninderphysics@gmail.com

We have studied the complete analysis of the fusion probabilities for neutron-rich or neutron-deficient colliding pairs for a wider mass range by using different potentials based on different assumptions for three series Ne-Ne, Ca-Ca, and Zr-Zr. The knowledge of the ion-ion potential is very important for the analysis of nuclear reactions. With the help of ion-ion potential between nuclei, one can find cross-sections of different nuclear reactions. Here, we have tried to analyze that how fusion probabilities are affected by the different ingredients of nuclear potentials for that we have observed that fusion barrier position increases and barrier height decreases with the addition of neutrons and reverse is true for neutron-deficient or proton-rich nuclei. Here we have seen that the $\gamma$ plays deceive role in the fusion studies. We have also observed that $R_B$ and $V_B$ vary from model to model. This difference arises due to the presence of different ingredients in different potentials. We have studied that the normalized variation of barrier height and barrier position obeys a second order non-linear parametrization whereas the normalized variation of fusion cross-section follows first order straight line fit. This happens because of the stronger variation of barrier position in neutron-deficient colliding nuclei that is counterbalanced by the barrier height variations. We have seen that the enhancement for the fusion cross-section is larger for lower incident energies and independent of the choice of the reacting partners. The fusion probabilities are maximum near the fusion barrier energy that diminishes to insignificant level at higher energies. Also we have observed the isospin dependence of the different potentials. Finally, we come to the conclusion that with the addition of neutrons the fusion probabilities also increases. This is in agreement with actual results.
How does incomplete fusion show up at slightly above barrier energies?

Pushpendra P. Singh1,∗ Abhishek Yadav2, Vijay R. Sharma2, D. P. Singh2, Unnati Gupta2, K. S. Golda4, Manoj K. Sharma3, R. Kumar4, R. P. Singh4, B. P. Singh2, S. Muralithar4, R. K. Bhowmik4, and R. Prasad2

1GSI Helmholtz Centre for Heavy Ion Research GmbH, Planckstrae 1, D-64291 Darmstadt, Germany
2Accelerator Laboratory, Department of Physics, A. M. University, Aligarh - 202 002, India
3Physics Department, S. V. College, Aligarh - 202 001, India and
4NP-Group, Inter-University Accelerator Center, New Delhi - 110 067, India

The onset of incomplete fusion (ICF - where only a part of incident projectile fuses with target nucleus) at slightly above barrier energies (E_{lab}≈V_b), and its strong influence on complete fusion (CF) at energies ≈ 1 - 1.5 Vb gained resurgent interest in recent years [1−3, 5]. Since the very first experimental observations, ICF has been intensively investigated in terms of; (i) projectile energy, (ii) mass-asymmetry (\mu_A), (iii) input angular momenta, and (iv) the shape of interacting partners. Despite a variety of existing studies (see refs.[1] for detail), low energy ICF is not yet fully understood.

To probe low-energy ICF, high quality data have been achieved in a variety of experiments at the Inter-University Accelerator Center (IUAC), New Delhi. The spin-distributions (SDs) of xn, pxn, \alpha xn, and 2\alpha xn- channels have been measured in \(^{12}C,^{16}O+^{169}Tm\) systems at 10 energies (from 1.02V_b to 1.64V_b) [1, 2]. Particle(Z = 1,2)-\gamma-coincidences have been recorded for channel selection. Distinctly different decay patterns have been observed during the de-excitation of CF and ICF composites, indicating reaction dependent entry state spin-population. The CF events have been found to be strongly fed over a broad spin range. While, narrow range feeding (only for high-spin states) has been observed in ICF. The direct \alpha(associated with ICF)- multiplicity, emitted in the forward cone, increases with driving angular momenta. The mean value of \ell_{ICF-\alpha xn} is found to be higher than \ell_{CF-xn/\alpha xn}, which reveals the possibility to populate high spin states via ICF.

The significant fraction of ICF has been observed at slightly above barrier energies (i.e., E_{lab} = 1.075 Vb), where CF is supposed to be the sole contributor. High \ell-values (\ell ≥ \ell_{crit}), imparted into the system in non-central interactions, have been found to be responsible for low energy ICF [1, 2]. Existence of ICF at low projectile energies has been supplemented by the measurement of forward ranges (FRs) of heavy recoils [3]. The degree of linear-momentum transfer in the production of different residues has been reconstructed from the analysis of FRs of heavy recoils in the framework of break-up fusion model [4]. More than one LMT components associated with full and/or partial fusion of projectile have been observed, which proves the presence of ICF at these energies.

Further, in order to gain insights into the onset and ICF fraction (F_{ICF}), the ICF strength function has been measured as a function of various entrance channel parameters [5]. The value of F_{ICF} has been found to be ≈7% at ≈ 7.5% above the barrier, and increasing up to 18% at highest measured energy. A significant fraction of ICF has been observed even at relatively lower value of v_{rel} than that proposed by Morgenstern et al. [6] (i.e., v_{rel} ≈ 0.06). The value of F_{ICF} is found to be ≈7 % at v_{rel} ≈ 0.027 for \(^{12}C+^{169}Tm\) system, and ≈10% at v_{rel} ≈ 0.014 for \(^{16}O+^{169}Tm\) system. Detailed results and systematics obtained from aforementioned measurements will be presented.

∗ Electronic address: pushpendrapSingh@gmail.com
Capture Gamma-Ray Libraries for Nuclear Applications*

B.W. Sleaford, N. Summers, J.E. Escher
Lawrence Livermore National Laboratory, Livermore, CA 94551, U.S.A.

R.B. Firestone, A. Hurst, S. Basunia
Lawrence Berkeley National Laboratory, Berkeley, California, USA

M. Krticka
Charles University in Prague, Prague, Czech Republic

G. Molnar, T. Belgya, Z. Revay
Institute of Isotope and Surface Chemistry, Budapest, Hungary

The Evaluated Gamma-ray Activation file (EGAF) is a new thermal neutron capture database of discrete line spectra and cross sections for over 260 isotopes. This database is used to improve the capture gamma production in ENDF libraries. For medium to heavy nuclei the unresolved quasi continuum part of the gamma cascades are not experimentally available. This can contain up to 90 percent of all the decay energy; in this work it is modeled with the statistical nuclear structure code Dicebox. For the capture of higher energy neutrons there is little experimental data available. We are analyzing experimental data from surrogate reactions with Hauser Feshbach codes and comparing these results with Dicebox results. This can then be used to simulate the cascades following neutron capture at incident energies up to 20 MeV in order to improve the gamma-ray spectrum in neutron data libraries used for transport modeling for nuclear applications.

* This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

Application of standard saddle-point statistical model in the prediction of angular anisotropies

S. Soheyli

Bu-Ali Sina University, Department of Physics, Hamedan, Iran

Abstract

In the literature, it is reported that the entrance channel mass asymmetry $\alpha = \frac{(A_T - A_P)}{(A_T + A_P)}$ (where $A_T$ and $A_P$ are the target and projectile mass numbers, respectively) with respect to the Businaro-Gallone critical mass asymmetry $\alpha_{BG}$ plays a very dominant role in the reaction dynamics. For systems with $\alpha > \alpha_{BG}$, the mass flow takes place from the projectile to the target and the composite system leads to the formation of a compound nucleus, which may later undergo decay via fission or particle evaporation. For these reaction systems, standard saddle point statistical model has been generally used to explain the observed anisotropy data and it is based on the assumption that the fission fragments are emitted along the nuclear symmetry axis and the K component of the total angular momentum $I$ along the symmetry axis is conserved during the descent saddle to scission point. On the contrary, if $\alpha < \alpha_{BG}$, the mass flow takes place in the reverse direction, that is, from target to projectile, and a dinuclear system will be formed, which will decay before equilibrating in all degrees of freedom, leading to quasifission and the angular anisotropies have an anomalous behaviors. However, it has been observed that the measured anisotropies for several heavy ion induced reaction systems with $\alpha > \alpha_{BG}$ are significantly larger than those of the standard saddle-point statistical model predictions, as well as it has been found that the measured anisotropies for several systems with $\alpha < \alpha_{BG}$ exhibit a normal behavior. In this work, the large body of experimental data on fission anisotropies is analyzed, afterwards the role of the mass numbers of projectile and target has been studied to ascertain a cause of the observed anomalous anisotropies in several heavy ion induced reaction systems. The contribution of non compound nucleus fission has also determined for these systems based on the comparison between the experimental anisotropies and the standard saddle-point statistical model predictions.

PACS numbers: 25.70.Jj
Determination of non-compound nucleus fission contribution for some induced fission systems with heavy ions

S. Soheyli∗

Bu-Ali Sina University, Department of Physics, Hamedan, Iran

Abstract

The contributions of non-compound nucleus fission have been calculated for the $^{32}S + ^{184}W$, $^{32}S + ^{182}W$, $^{32}S + ^{208}Pb$, $^{19}F + ^{232}Th$, and $^{16}O + ^{238}U$ reaction systems. It is presented a method of calculation for the contribution of non-compound nucleus fission that is based on the comparison between the prediction of standard saddle-point statistical model, as well as the experimental angular anisotropy data for heavy ion induced fission systems with an anomalously behavior in fission fragment angular distributions. It is also found some limitations in the previous works by comparing the calculated contributions with the results of the previous works.

PACS numbers: 25.70.Jj

∗ Corresponding author: soh@basu.ac.ir
On the system size dependence of intermediate mass fragments and nuclear dynamics at peak center-of-mass energy

Sukhjit Kaur

House No. 465, Sector-1B, Nasrali, Mandi Gobindgarh-147301, Punjab, India.

email: sukhjitk85@gmail.com

The heavy-ion collision at intermediate energies is excellent tool to study the nuclear matter at high density and temperature. Many theoretical models can be applied to study these heavy-ion reactions. The model used in the present study is the Quantum Molecular Dynamics (QMD) model. In the present study, we simulate the central reactions of \( ^{20}\text{Ne}+^{20}\text{Ne} \), \( ^{40}\text{Ar}+^{45}\text{Sc} \), \( ^{58}\text{Ni}+^{58}\text{Ni} \), \( ^{86}\text{Kr}+^{90}\text{Nb} \), \( ^{129}\text{Xe}+^{118}\text{Sn} \), \( ^{86}\text{Kr}+^{197}\text{Au} \), and \( ^{197}\text{Au}+^{197}\text{Au} \) for different values of energies using different model ingredients. We observe that the multiplicity of intermediate mass fragments (IMFs) shows a rise and fall behavior. The system size dependence of peak center-of-mass energy \( E_{\text{c.m.}}^{\text{max}} \) and peak IMF multiplicity \( <N_{\text{IMF}}^{\text{max}} \) is also studied where it is observed that \( E_{\text{c.m.}}^{\text{max}} \) increases linearly with system mass whereas \( <N_{\text{IMF}}^{\text{max}} \) shows a power law \( (\propto A_i^{\tau}) \) dependence with \( \tau \approx 1.0 \). A comparison between two clusterization methods, the minimum spanning tree and the minimum spanning tree method with binding energy check (MSTB) is also made. We find that MSTB method reduces the \( <N_{\text{IMF}}^{\text{max}} \), especially in heavy systems. A power law dependence is also observed for various fragments at \( E_{\text{c.m.}}^{\text{max}} \). We study the various properties of fragments, like stability of fragments, thermalization and stopping etc., at \( E_{\text{c.m.}}^{\text{max}} \) using Hard EOS along with Cugnon cross section employing minimum spanning tree method with binding energy check (MSTB) for clusterization. The mass dependence of various quantities (such as the participant and spectator matter, average and maximum central density, collision dynamics as well as the time zone for hot and dense nuclear matter) is also presented and in all cases power law dependence is obtained.
Spectator Matter Fragmentation in Heavy-Ion Collisions and Phase Space Characteristics

Yogesh K. Vermani and Ashok Jangid

Department of Applied Sciences and Humanities, ITM University, Gurgaon-122017, INDIA

Abstract

Heavy Ion collisions at intermediate energies is dominated by the process of breaking of colliding nuclear matter into many pieces (commonly known as multifragmentation) and associated production of kaon and pion particles. At relativistic beam energies, collective flow also affects the clusterization process [1,2]. In the present paper, we aim to draw attention towards importance of minimization of fragments’ binding energy in advanced recognition of fragments [2] and understanding the mechanism of spectator matter fragmentation. We shall study the phase space characteristic and nucleon density distribution of the intermediate mass fragments (IMFs) \(5 \leq A \leq 65\) produced in peripheral Au+Au collisions at beam energy of 1000 AMeV. Calculation are done within the QMD transport model [3] using a soft equation of state and energy dependent \(n-n\) cross section. The results obtained with simulated annealing clusterization algorithm (SACA) method at 60 fm/c are then compared with conventional minimum spanning tree (MST) method [3] at 200 fm/c. Preliminary calculations suggest that IMFs are abundantly produced using the SACA method in forward rapidity region \(y_{\text{cm}} / y_{\text{beam}} \geq 0.5\). It is marked by larger nucleon density in the reaction plane Z-X. The MST approach, however, underestimated the IMF yield consistent with earlier predictions [2]. Tracing back the location of nucleons bound in the cluster at the time of initial contact between colliding nuclei, one can observe that SACA method significantly contributes spectator matter disintegration.

References

Influence of density dependence of symmetry energy on nuclear stopping in heavy-ion collisions

Karan Singh Vinayak and Suneel Kumar

School of Physics and Material Science, Thapar University, Patiala 147004, Punjab, India

Abstract

The effect of density dependence of symmetry energy on nuclear-stopping is studied using isospin-dependent quantum molecular dynamics model (IQMD). We have used the reduced isospin-dependent cross-section with soft equation of state for the full colliding geometry to explore the various aspects of nuclear stopping. The aim is to pin down the nature of the nuclear stopping with density dependent symmetry energy.
As members of international collaboration “Energy and Transmutation of Radioactive Waste” we routinely use \((n,xn)\) threshold reactions in various materials to measure high energy neutron flux from spallation reactions. Unfortunately, no experimental cross-section data exist for reactions with \(x\) higher than four and neutron energies over \(\sim 40\) MeV. With the support from EFNUDAT we performed seven successful \((n,xn)\) cross-section measurements in two campaigns exploiting the quasi-monoenergetic neutron source at The Svedberg Laboratory in Uppsala, Sweden. Neutron energies from the \(^7\text{Li}(p,n)^7\text{Be}\) based source were in the region 22 to 94 MeV. We carried out additional five irradiations with neutron energies from 17 up to 34 MeV using the quasi-monoenergetic neutron source of the Nuclear Physics Institute in Řež. We have developed procedure for the subtraction of contribution of the background neutrons. We studied Al, Au, Bi, I, In, Ta and Y materials in the form of thin foils. We observed good agreement with the data in EXFOR database and also with the calculations performed in deterministic code TALYS.
Double differential cross sections of proton emission in neutron induced reaction on $^{27}$Al

Leila YETTOU$^1$, Mohamed BELGAID$^2$

$^1$Université Dr YAHIA Fares, Faculté des Sciences et de la Technologie Quartier Ain d’Heb 26000 Médéa
$^2$Laboratoire SNIRM, Faculté de Physique, USTHB BP 32 El Alia 16111 Bab Ezzouar
yetouleila@yahoo.fr

Abstract:
Double differential cross sections for proton emission on aluminium are presented for 40 MeV incident neutron energies. Angular distributions, energy differential and total production cross sections are obtained. The results are compared to existing data and to nuclear model calculations which include preequilibrium and compound decay mechanisms. The EMPIRE code treats these mechanisms in the framework of TUL model for multistep direct and NVWY model for multistep compound. The Hauser Feshbach theory is used to calculate emission from the compound nucleus, with a full conservation of spin and parity.

Keywords: neutron induced reactions, double differential cross sections, proton emission spectra and production cross section preequilibrium reaction theory, EMPIRE code.
List of participants

Yasuhisa Abe  abey@rcnp.osaka-u.ac.jp
Yoram Alhassid  yoram.alhassid@yale.edu
Goran Arbanas  arbanasg@ornl.gov
Hugo F. Arellano  arellano@dfi.uchile.cl
Muhammad Naveed Aslam  naslamgc@yahoo.com
Marilena Avrigeanu  m_avrig@yahoo.com
Vlad Avrigeanu  v_avrig@yahoo.com
Rajni Bansal  rajnibansl@gmail.com
Rubina Bansal  rubinabansal98@gmail.com
Alexey Barabanov  a_i_barabanov@mail.ru
Bayarbadrakh Baramsai  bayar@lanl.gov
Frantisek Becvar  becvarfrank@aol.com
Remi Bernard  remi.bernard@cea.fr
Emil Betak  fyzibeta@unix.savba.sk
Emil Betak  betak@savba.sk
Chitra Bhatia  chitraphy@gmail.com
Guillaume Blanchon  guillaume.blanchon@cea.fr
Olivier Bouland  olivier.bouland@cea.fr
Guillaume Boutoux  boutoux@cenbg.in2p3.fr
Roberto Capote  rcapotenoy@yahoo.com
Giuseppe Cardella  cardella@ct.infn.it
Nicolae Carjan  carjan@cenbg.in2p3.fr
Brett Carlson  brettvc@gmail.com
Iulia Companis  companis@cenbg.in2p3.fr
Anthony A. Cowley  aac@sun.ac.za
Ron Dagan  dagan@inr.fzk.de
Airton Deppman  adepman@gmail.com
Frank Dietrich  fsdietrich@sbcglobal.net
Jan Dobes  dobes@ujf.cas.cz
Junfeng Duan  junfeng.duan@physics.uu.se
Marc Dupuis  marc.dupuis@cea.fr
Jutta Escher  escher1@llnl.gov
Imrich Fabry  imrich.fabry@gmx.de
Rick Firestone  rbfirestone@lbl.gov
Forozani Ghasem  forozani@basu.ac.ir
Supriya Goyal  ashuphysics@gmail.com
Carlos Granja  carlos.granja@utef.cvut.cz
Eckart Grosse  e.grosse@hzdr.de
Oleg Grudzevich  grudzevich@iate.obninsk.ru
Pallavi Gupta  guptapalli@gmail.com
Cecilia Gustavsson  cecilia.gustavsson@fysast.uu.se
Magne Gutormsen  m.s.gutormsen@fys.uio.no
Franz Josef Hambisch  franz-josef.hambisch@ec.europa.eu
Sotirios V. Harissopulos  sharisop@inp.demokritos.gr
Milan Honusek  honusek@ujf.cas.cz
Aaron Hurst  amhurst@lbl.gov
<table>
<thead>
<tr>
<th>Name</th>
<th>Email</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mazhar Hussain</td>
<td><a href="mailto:mazharhussain@ciitlahore.edu.pk">mazharhussain@ciitlahore.edu.pk</a></td>
</tr>
<tr>
<td>Mahir Hussein</td>
<td><a href="mailto:hussein.mahir@gmail.com">hussein.mahir@gmail.com</a></td>
</tr>
<tr>
<td>Enrico Chiaveri</td>
<td><a href="mailto:Enrico.Chiaveri@cern.ch">Enrico.Chiaveri@cern.ch</a></td>
</tr>
<tr>
<td>Yoritaka Iwata</td>
<td><a href="mailto:y.iwata@gsi.de">y.iwata@gsi.de</a></td>
</tr>
<tr>
<td>Anupriya Jain</td>
<td><a href="mailto:npryjn111@gmail.com">npryjn111@gmail.com</a></td>
</tr>
<tr>
<td>Franz Kaeppeler</td>
<td><a href="mailto:franz.kaeppeler@kit.edu">franz.kaeppeler@kit.edu</a></td>
</tr>
<tr>
<td>German Kalbermann</td>
<td><a href="mailto:hope@vms.huji.ac.il">hope@vms.huji.ac.il</a></td>
</tr>
<tr>
<td>Gurvinder Kaur</td>
<td><a href="mailto:kaurguri37@ymail.com">kaurguri37@ymail.com</a></td>
</tr>
<tr>
<td>Deepinder Kaur</td>
<td><a href="mailto:deep8894@yahoo.in">deep8894@yahoo.in</a></td>
</tr>
<tr>
<td>Toshihiko Kawano</td>
<td><a href="mailto:kawano@lanl.gov">kawano@lanl.gov</a></td>
</tr>
<tr>
<td>Arthur Kerman</td>
<td><a href="mailto:kerman@lins.mit.edu">kerman@lins.mit.edu</a></td>
</tr>
<tr>
<td>Vitaly Khryachkov</td>
<td><a href="mailto:hva@ippe.obninsk.ru">hva@ippe.obninsk.ru</a></td>
</tr>
<tr>
<td>Jiri Kroll</td>
<td><a href="mailto:kroll@ipnp.troja.mff.cuni.cz">kroll@ipnp.troja.mff.cuni.cz</a></td>
</tr>
<tr>
<td>Milan Krticka</td>
<td><a href="mailto:krticka@ipnp.troja.mff.cuni.cz">krticka@ipnp.troja.mff.cuni.cz</a></td>
</tr>
<tr>
<td>Sushil Kumar</td>
<td><a href="mailto:sushilk17@gmail.com">sushilk17@gmail.com</a></td>
</tr>
<tr>
<td>Sushil Kumar</td>
<td><a href="mailto:sushil.kumar@chitkarauniversity.edu.in">sushil.kumar@chitkarauniversity.edu.in</a></td>
</tr>
<tr>
<td>Satoshi Kunieda</td>
<td><a href="mailto:kunieda@lanl.gov">kunieda@lanl.gov</a></td>
</tr>
<tr>
<td>Lou Sai Leong</td>
<td><a href="mailto:leong@ipno.in2p3.fr">leong@ipno.in2p3.fr</a></td>
</tr>
<tr>
<td>Yury Malyshekin</td>
<td><a href="mailto:malyshkin@fias.uni-frankfurt.de">malyshkin@fias.uni-frankfurt.de</a></td>
</tr>
<tr>
<td>Kaur Mandeep</td>
<td><a href="mailto:mandeep.pu@gmail.com">mandeep.pu@gmail.com</a></td>
</tr>
<tr>
<td>Kaur Maninder</td>
<td><a href="mailto:maninder_85@yahoo.co.in">maninder_85@yahoo.co.in</a></td>
</tr>
<tr>
<td>Vladimir Maslov</td>
<td><a href="mailto:maslovat@mail.ru">maslovat@mail.ru</a></td>
</tr>
<tr>
<td>Ralph Massarczyk</td>
<td><a href="mailto:r.massarczyk@hzdr.de">r.massarczyk@hzdr.de</a></td>
</tr>
<tr>
<td>Jan Mierzejewski</td>
<td><a href="mailto:jmierz@slc.uw.edu.pl">jmierz@slc.uw.edu.pl</a></td>
</tr>
<tr>
<td>Hashem Miri Hakimabad</td>
<td><a href="mailto:mirihakim@ferdowski.um.ac.ir">mirihakim@ferdowski.um.ac.ir</a></td>
</tr>
<tr>
<td>Luciano G. Moretto</td>
<td><a href="mailto:lgmoretto@lbl.gov">lgmoretto@lbl.gov</a></td>
</tr>
<tr>
<td>Renata Moro</td>
<td><a href="mailto:moro@na.infn.it">moro@na.infn.it</a></td>
</tr>
<tr>
<td>Petr Navratil</td>
<td><a href="mailto:navratil@triumf.ca">navratil@triumf.ca</a></td>
</tr>
<tr>
<td>Antonio Di Nitto</td>
<td><a href="mailto:dinitto@na.infn.it">dinitto@na.infn.it</a></td>
</tr>
<tr>
<td>Titus Osondu</td>
<td><a href="mailto:titusosondou@gmail.com">titusosondou@gmail.com</a></td>
</tr>
<tr>
<td>Cem Ozen</td>
<td><a href="mailto:cem.ozen@gmail.com">cem.ozen@gmail.com</a></td>
</tr>
<tr>
<td>Kailash Pandey</td>
<td><a href="mailto:kaypee07@rediffmail.com">kaypee07@rediffmail.com</a></td>
</tr>
<tr>
<td>Sara Pirrone</td>
<td><a href="mailto:pirrone@ct.infn.it">pirrone@ct.infn.it</a></td>
</tr>
<tr>
<td>Giuseppe Politi</td>
<td><a href="mailto:politi@ct.infn.it">politi@ct.infn.it</a></td>
</tr>
<tr>
<td>Giuseppe Politi</td>
<td><a href="mailto:giuseppe.politi@ct.infn.it">giuseppe.politi@ct.infn.it</a></td>
</tr>
<tr>
<td>Stephan Pompl</td>
<td><a href="mailto:stephan.pomp@phys.uu.se">stephan.pomp@phys.uu.se</a></td>
</tr>
<tr>
<td>Laleh Rafat Motavalli</td>
<td><a href="mailto:rafat@ferdowski.um.ac.ir">rafat@ferdowski.um.ac.ir</a></td>
</tr>
<tr>
<td>Jorgen Randrup</td>
<td><a href="mailto:jrandrup@lbl.gov">jrandrup@lbl.gov</a></td>
</tr>
<tr>
<td>Sunniva J. Rose</td>
<td><a href="mailto:sunniva.rose@fys.uio.no">sunniva.rose@fys.uio.no</a></td>
</tr>
<tr>
<td>Ingrid Rotter</td>
<td><a href="mailto:rotter@pkp.mpg.de">rotter@pkp.mpg.de</a></td>
</tr>
<tr>
<td>Valery Rubchenya</td>
<td><a href="mailto:valery.rubchenya@phys.jyu.fi">valery.rubchenya@phys.jyu.fi</a></td>
</tr>
<tr>
<td>Roman Sagaidak</td>
<td><a href="mailto:sagaidak@nrmail.jinr.ru">sagaidak@nrmail.jinr.ru</a></td>
</tr>
<tr>
<td>Sunniva Siem</td>
<td><a href="mailto:sunniva.siem@fys.uio.no">sunniva.siem@fys.uio.no</a></td>
</tr>
<tr>
<td>Pushpendra P. Singh</td>
<td><a href="mailto:pushpendrapsingh@gmail.com">pushpendrapsingh@gmail.com</a></td>
</tr>
<tr>
<td>Brad W Sleaford</td>
<td><a href="mailto:sleaford1@llnl.gov">sleaford1@llnl.gov</a></td>
</tr>
<tr>
<td>Saeid Soheili</td>
<td><a href="mailto:soh@basu.ac.ir">soh@basu.ac.ir</a></td>
</tr>
<tr>
<td>Martin Suchopar</td>
<td><a href="mailto:suchopar@ujf.cas.cz">suchopar@ujf.cas.cz</a></td>
</tr>
<tr>
<td>Kaur Sukhjit</td>
<td><a href="mailto:sukhjitk85@gmail.com">sukhjitk85@gmail.com</a></td>
</tr>
<tr>
<td>Ondrej Svoboda</td>
<td><a href="mailto:svoboda@ujf.cas.cz">svoboda@ujf.cas.cz</a></td>
</tr>
<tr>
<td>Patrick Talou</td>
<td><a href="mailto:talou@lanl.gov">talou@lanl.gov</a></td>
</tr>
</tbody>
</table>