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Book of Abstracts

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Abstracts

COMBINATORIAL NUCLEAR LEVEL DENSITY MODEL

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Structure of level densities in the energy region between the ground state and the neutron separation energy is studied. A recently developed microscopic model for the level density is reviewed [1]. The level density is constructed from a microcanonical approach with single-particle states obtained from a well established deformed mean field model. We explicitly account for pairing, rotational and vibrational enhancements for each state, and include a schematic residual interaction. Detailed structure effects of the level density function, parity enhancement and structure of the spin distribution function will be discussed and compared to other models. In particular, the vibrational enhancement is suggested to be considerably smaller than is usually adopted.
The model is compared to level densities obtained from observed low-lying discrete states, and a global comparison to data is made at the neutron separation energy. For a few measured cases (Osla data) we compare to full level density functions. Calculated parity enhancements are compared to available data, and cases with extreme enhancements of one parity at high excitation energy are discussed.

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Level densities of rare-earth nuclei in the shell model Monte Carlo approach: the crossover from vibrational to rotational collectivity

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The shell model Monte Carlo (SMMC) method enables us to calculate microscopically level densities in the presence of correlations [1]. These calculations can be carried out in shell model spaces that are many orders of magnitude larger than spaces that can be treated with conventional diagonalization methods.

A recent major development has been the extension of the SMMC approach to heavy nuclei [2,3]. Applications to heavy nuclei, such as rare-earth nuclei, have been a major challenge. On the conceptual level, a crucial question is whether a truncated spherical shell model Hamiltonian can describe the proper collectivity observed in such heavy nuclei and, in particular, the rotational character of strongly deformed nuclei. On the technical level, the low excitation energies make it necessary to perform calculations down to much lower temperatures. We have studied the crossover from vibrational to rotational collectivity in families of samarium and neodymium isotopes [3]. Such a crossover can be identified in the temperature dependence of $\langle \mathbf{J}^2 \rangle$ (where $\mathbf{J}$ is the total angular momentum). Both level densities and $\langle \mathbf{J}^2 \rangle$ are found to be in good agreement with experimental results.

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Reactions on Nuclei in High Energy Density Plasmas

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Stellar nucleosynthesis for nuclei with Z>26 is driven by slow (s-process) and fast (r-process) neutron capture reactions. While these models assume that the target nuclei have a thermal distribution of low-lying states, they also assume that the nuclei decay instantaneously from their entry region ($E_x \approx S_n$) following neutron capture. In this talk I will show that the rate of photonuclear interactions in high temperature plasma environments on highly excited nuclear levels populated is greater than the spontaneous photon emission rate. The critical parameter for modeling this photon-absorption is the photon strength function for $E_\gamma \approx k_B T$. The result is "pre-equilibrium" absorption and stimulated emission of photons leading to an effective increase in the excitation energy of the nucleus following neutron capture. This increased excitation energy could in turn lead to a suppression in the formation of massive (A>240) nuclei in astrophysical environments where (n,γ) competes with (n,f). The implication of this process for nucleosynthesis at the terminus of the r-process is examined and suggestions are made for studying these effects in neutron-rich inertial confinement fusion (ICF) plasmas.

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory in part under Contract W-7405-Eng-48 and in part under Contract DE-AC52-07NA27344.

The Brink hypothesis 54 year later

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Golhaber and Teller in 1948 proposed a simple collective model for the the giant dipole resonance (GDR) in which the neutrons in the nucleus oscillated out of phase with the protons. It was very successful in describing the main features of the mode. A hydrodynamical model with similar features was suggested by Steinwedel and Jensen in 1950. Photon absorbtion could excite the GDR. Because of its simple collective character, it was expected that photon absorbtion on an excited state could also excite the resonance and that the characteristics of the GDR would not be very sensitive to the detailed structure of the initial state [1], [2].

Photon emission could be related to absorbtion by the principle of detailed balance. The gamma widths of excited states were estimated by assuming a shape for the GDR and expressions for the density of states in the initial and final nucleus. The same idea has been used to study the nuclear density of states experimentaly [3] by measuring primary gamma spectra over a range of excitation energies and assuming the gamma energy and a density of states factor.

The giant dipole resonance in highly excited or 'hot' nuclei was first observed in 1981 [4]. One can imagine a thermodynamical model for photon emission from highly excited nuclei which views it as a kind of black-body radiation [5]. The excitation energy is related to a nuclear temperature and the density of states to the entropy [3]. A model for the spreading width of the resonance is needed to understand the properties of the resonances. Coupling of the collective mode to low energy complicated states leads to a nuclear friction and a width [6]. In fact the theory of the spreading width also depends on shape vibrations and is much more complicated.

The GDR is excited thermally in hot nuclei. It can also be excited directly in heavy ion collisions. The GDR excited directly would have a frequency characteristic of the compound nucleus with an enhanced strength with respect to thermal excitation.

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Level Densities and Strength Functions in Light Sc and Ti Isotopes

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Level densities and γ-ray strength functions are an important input to stellar reaction models and isotope abundance calculations. The nuclear physics group at the Oslo Cyclotron Laboratory has developed a method to extract both the level density and the γ-ray strength function below the particle-emission thresholds from particle-γ coincidence data obtained in proton- or ^{3}He-induced pickup or transfer reactions. This experimental method will be presented in the talk.

The method has recently been applied to study the nuclei ^{43}Sc and ^{44,45,46}Ti using the reactions ^{46}Ti(p,x γ)X. In ^{45}Ti, steps in the level density as a function of excitation energy have been observed. The nucleus ^{44}Ti is expected to be exclusively produced in supernovae. The abundance observed is therefore regarded as a marker for the type of supernova. The nuclear level density of ^{44}Ti is an important input for modelling the production of ^{44}Ti in the stellar environment. Preliminary results on level densities and γ-ray strength functions for ^{43}Sc and ^{44,45,46}Ti will be presented.

Micro-canonical level densities of U-234

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The micro-canonical model of level densities of non-magic nuclei [1] is applied to obtain the level density of uranium nuclei. On the assumption of adiabatic decoupling of collective and non-collective degrees of freedom, spin and parity dependent level densities of even-even nuclei are computed by folding intrinsic level densities computed by a Monte Carlo technique with collective levels generated by the interacting boson model (IBM), whose parameters are adjusted on the low-lying experimental discrete levels of both parities. In this way, different collective degrees of freedom are coupled together and the resulting enhancement of level densities cannot be reduced to a product of rotational and vibrational factors. The microscopic interpretation of the bosons of the model as collective fermion pairs open the way to a dynamical treatment of the collective enhancement as a function of excitation energy. Comparison to recently released microscopic and phenomenological RIPL-3 level densities [2] is given.

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Available online at http://www-nds.iaea.org/RIPL-3/public.html (See Densities segment).

Systematic studies of the Pygmy Dipole Resonance by means of the (α,$\alpha'\gamma$) reaction*

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In the last years investigations have been made to study the electric Pygmy Dipole Resonance (PDR), mainly in semi-magic nuclei. A number of (γ, γ') photon scattering experiments have been performed [1]. In $(\alpha, \alpha'\gamma)$ coincidence experiments at $E_\alpha = 136$ MeV a comparable energy resolution and a high selectivity of E1 transitions can be obtained by using the Big-Byte Spectrometer at KVI [2] and an array of large volume High Purity Germanium detecors. We give an overview about systematic studies on the N = 82 isotones ^{140}Ce and ^{138}Ba, the Z = 50 isotope ^{124}Sn and the off-shell nucleus ^{94}Mo. In comparison to the (γ, γ') reaction a structural splitting of the PDR could be observed which is possibly connected to the different isospin natures of the two groups of $J^\pi = 1^-$ states. There is a low energy part which can be found in $(\alpha, \alpha'\gamma)$ as well as in (γ, γ') reactions and a high energy part which can only be observed in (γ, γ').

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Cross sections for neutron capture and other compound reactions from Surrogate measurements*

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An overview of current experimental and theoretical activities in the area of *Surrogate nuclear reactions* will be presented.

The Surrogate method is an indirect approach for obtaining cross sections for compound-nuclear reactions that involve difficult-to-produce targets. Indirect methods play in general an important role in the determination of cross sections, but most indirect methods currently under consideration focus on direct-reaction cross sections. Compound-nuclear reaction cross sections are needed for nuclear energy applications and for understanding astrophysical phenomena, and the Surrogate approach addresses this need. The method has primarily been employed to determine (n,f) cross sections for various actinides, including unstable isotopes. Cross sections for other reactions, in particular (n,γ) reactions on short-lived targets, are of interest as well, but are more difficult to extract from Surrogate measurements.

This presentation will give a brief outline of the Surrogate method and the challenges involved in carrying out a complete Surrogate treatment. The primary focus of the presentation will be on the prospects for employing the Surrogate method to obtain neutron-capture cross sections. Progress made in understanding and describing the nuclear processes involved in a Surrogate reaction will be discussed; calculations will be presented that assess the validity of employing various approximate treatments in the interpretation of Surrogate measurements and insights gained from recent experiments will be summarized.

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The Influence of Nuclear Structure on Statistical Decay Properties

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Comprehensive new thermal neutron capture gamma ray cross section measurements have been performed on all stable elemental targets with guided neutron beams from the Budapest Reactor. These data are compiled in the Evaluated Gamma-ray Activation File (EGAF)[1]. The measured neutron cross sections deexciting low-lying nuclear levels have been derived from EGAF and compared with cross sections populating these levels calculated with the Monte Carlo statistical model code DICEBOX[2] and the LBNL statistical model code COSMO[3]. Calculated cross sections populating nuclear levels have been normalized to the experimental EGAF cross sections deexciting these levels in order to determine the theoretical contribution of the unresolved continuum γ-ray spectrum in order to derive total thermal neutron radiative cross sections σ_0. Measurements of σ_0 for all palladium isotopes have been completed resulting in excellent agreement with previous values. Comparisons of the theoretical and experimental cross sections populating levels have also been used to improve the palladium spin and parity assignments taken from the Reaction Input Parameter Library (RIPL)[4] that are used by the statistical model codes. Theoretical level spin and parity distribution functions and the contribution of nuclear structure to the statistical model have also been investigated. Although the importance of nuclear structure contributions to statistical model calculations for neutron capture reactions remain elusive, strong evidence for the contribution of nuclear structure to continuum nuclear beta decay strength functions has long been known. The beta decay strength functions for the $^{117-124}$Cs isotopes have been measured with the LBNL Total Absorption Spectrometer and evidence for the onset of nuclear structure effects in the cesium isotopes will be discussed.

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Instantaneous-Shape Sampling for Calculating the Electromagnetic Dipole Strength in Transitional Nuclei

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Electromagnetic dipole absorption cross-sections of transitional nuclei with large-amplitude shape fluctuations are calculated in a microscopic way by introducing the concept of Instantaneous Shape Sampling (ISS), which is based on the slow shape dynamics as compared to the dipole vibrations. The dipole strength is calculated by means of RPA for the instantaneous shapes, the probability of which is obtained by means of IBA-1 with the method suggested in Ref. [1]. For RPA part, we adopt the quasiparticle version of RPA (QRPA) described in [2, 3], which combines a triaxial potential with separable interaction. The IBA parameters are obtained in the standard way by fitting the energies and B(E2) values of the lowest collective quadrupole excitations. Shape coexistence is taken into account by combining two IBA probability distributions.

The method has been applied to ^{88}Sr, ^{90}Zr and $^{92-100}$Mo. Fig. 1 depicts the probability distribution of the ground state of ^{94}Mo, which demonstrates that the resulting instantaneous shapes are widely distributed over the $\beta - \gamma$ plane, consistent with the transitional nature of the nucleus. Figs. 2 compares the results of ^{94,96,98,100}Mo with the data for the energy range around the neutron emission threshold, in comparison with the RPA results for the equilibrium deformations calculated by means of the micro-macro method. ISS well describes the experimental σ_γ. Taking into account the collisional damping does not enhance the strength near neutron emission threshold. Hence, the dipole strength in this energy region is controlled by the Landau fragmentation of the instantaneous shapes.

Our version of RPA can be replaced by more sophisticated versions based on modern density functionals, which are expected to provide reliable dipole strength functions for instable nuclei. Likewise,the IBA-1 phenomenology can be extended in a systematic way or it can be replaced by any large-amplitude description for the collective shape degrees of freedom. This holds the promise that the concept of ISS-RPA will improve the prediction of the dipole strength for the instable nuclides passed in the stellar events.

This work was supported by the German DFG project KA2519/1-1 and the US DOE grant DE-FG02-95ER4093. vspace-0.5cm

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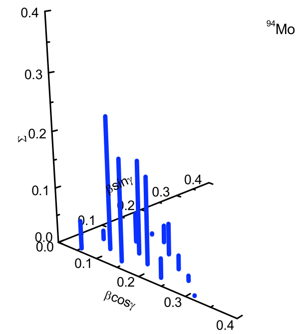

FIG. 1: Probability distributions of the instantaneous nuclear shapes over the $\beta - \gamma$ plane.

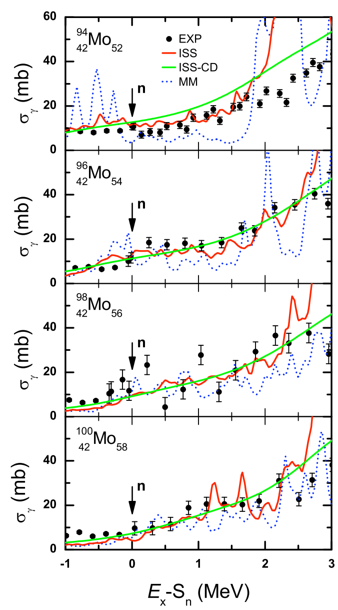

FIG. 2: Absorption cross section for Mo isotopes for the energy range around the neutron emission threshold, where S_n = 9.68, 9.15, 8.64, 8.29 MeV for N = 52, 54, 56, 58, respectively. Micro-Macro: RPA for the equilibrium deformation, ISS: RPA averaged over the probability distributions for shapes, ISS-CD: ISS folded with a Lorentzian with an energy dependent width $\Gamma = 0.025E^{1.8}$ to include the collisional damping.

Surrogate Ratio Methodology for the Indirect Determination of (n,γ) Cross Sections

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The Surrogate Ratio Method (SRM) has been developed as an indirect technique for the determination of neutron-induced reaction cross sections on both stable and radioactive nuclei, whereby surrogate reactions, using stable beams and targets, are used to populate the same compound systems as the neutron-induced reactions of interest. The relative decay probability for two different compound nuclei is then measured and the unknown cross section is extracted relative to one that is well known. The recent extension of this method to the determination of neutron capture cross sections showcases the effects of the nuclear structure of the two compound nuclei employed in the ratio on the extracted surrogate cross sections. Experimental data for the ^{170}Yb(n,γ) and ^{161}Dy(n,γ) cross sections, both obtained using the SRM via two different surrogate reactions, (^{3}He,^{3}He') and (^{3}He,α), are presented. The desired characteristics of the two compound nuclei employed in the ratio are demonstrated and a methodology for overcoming the limitations of the technique is suggested.

Recent results in quantum chaos and its applications to nuclei and particles

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A survey of chaotic dynamics in atomic nuclei is presented, using on the one hand standard statistics of quantum chaos studies, as well as time series analysis methods. We emphasize the energy and isospin dependence of nuclear chaoticity, based on shell-model energy spectra fluctuations in Ca, Sc and Ti isotopes, which are analyzed using standard statistics such as the nearest level spacing distribution $P(s)$ and the Dyson-Mehta Δ_3 statistic [1].

We also discuss quantum chaos in general using a new approach based on the analogy between the sequence of energy levels and a discrete time series. Considering the energy spectrum fluctuations as a discrete time series, we have shown that chaotic quantum systems such us ^{24}Mg and ^{32}Na nuclei, quantum billiards, and random matrix theory (RMT) ensembles, exhibit $1/f$ noise in their power spectrum [2]. Moreover, we show that the spectra of integrable quantum systems exhibit $1/f^2$ noise [2]. Therefore we suggest the following conjecture:

The energy spectra of chaotic quantum systems are characterized by $1/f$ *noise.*

We have also derived an analytic expression for the energy level fluctuations power spectrum of RMT ensembles, and the results confirm the above conjecture [3].

The order to chaos transition has been studied in terms of this power spectrum for several intermediate systems, such as the Robnik billiard [4], the quartic oscillator or the kicked top [5]. A power law $1/f^\alpha$ is found at all the transition stages, and it is shown that the exponent α is related to the chaotic component of the classical phase space of the quantum system.

This approach has also been applied to study the possible existence of chaos remnants in nuclear masses [6], and to characterize the spectral fluctuations of imperfect spectra, with missing or misassigned levels [7].

Finally, we present a recent study of the low-lying baryon spectrum up to 2.2 GeV which has shown that experimental data exhibit a $P(s)$ distribution close to GOE and, on the contrary, quark models predictions are more similar to the Poisson distribution [8]. This result sheds light on the problem of missing baryon resonances.

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Nuclear level densities and γ-ray strength functions for astrophysics applications

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(Dated: April 20, 2009)

Important effort has been devoted in the last decades to measure reaction cross sections. These measurements are fundamental to put the nuclear astrophysics models on a sound basis. However, despite such efforts, many nuclear applications, and most particularly nuclear astrophysics, still require the use of theoretical predictions to estimate experimentally unknown cross sections. The nuclear ingredients in the calculations of reaction cross sections, including in particular level densities and γ-ray strength functions, need to be extrapolated in an energy or/and mass domain out of reach of laboratory simulations. In addition, some applications often involve a large number of unstable nuclei, so that only global approaches can be used. For these reasons, when the nuclear ingredients to the reaction models cannot be determined from experimental data, it is highly recommended to consider preferentially microscopic or semi-microscopic global predictions based on sound and reliable nuclear models which, in turn, can compete with more phenomenological highly-parametrized models in the reproduction of experimental data. The latest developments and improvements made in the prediction of nuclear level densities and γ-ray strength functions within global microscopic models are reviewed. The direct as well as indirect experimental data available to test these models are discussed. It is shown to what extent previous and future experiments can bring new insights or constraints on the existing models.

Nuclear Level Densities

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ABSTRACT

Nuclear level density studies have been concentrated on nuclei in or near the valley of stability. Some recent investigations have looked for systematic differences in level densities off of the stability line compared to those along the valley of stability. We present the results of some theoretical and experimental studies of this question. Evaporation spectra produced by ^{6}Li and ^{7}Li bombardment of targets with A ~ 55 have allowed information to be inferred about nuclear level densities for nuclei with A about 60. An additional measurement program involved formation of the compound nuclei ^{82}Kr, ^{82}Sr and ^{82}Zr and observation of the decay gamma rays corresponding to the population of specific final nuclei. Both measurement programs have yielded results which support a reduction in level density parameters as we reach nuclei away from the line of stability.

A parallel effort is underway to calculate these effects. Moment methods have been used to make one-body Hamiltonian calculations of nuclear level densities including the decay width. These calculations support the results obtained experimentally. Further efforts are underway to make two-body calculations of these level densities.

Level densities from neutron resonance parameters in evaluated nuclear data libraries

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Evaluated nuclear data libraries are a precious source of neutron induced reaction information, including evaluated resonance parameters. These libraries, like JEFF, ENDF, JENDL, BROND, CENDL and others are intended to contain a consistent and complete set of nuclear reaction information obtained from an evaluation of available experimental data and theoretical models.

From the resolved resonance parameters the level spacing for a spin-parity sequence in the excitation energy region just above the neutron binding energy can be obtained. Nuclear level density models are in general calibrated to the level spacing D_0 in this region. It is therefore important that this level spacing, and therefore the level density, is correctly derived. In this contribution we will demonstrate that for many nuclei improvements can be made to obtain a more accurate value for D_0.

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Optical Model Potentials and Nuclear Level Densities for the nucleosynthetic p process: an experimentalist's point of view

Abstract: The study of capture reactions at energies well below the Coulomb barrier is quite challenging both in terms of scientific motivation and experimental approach. These reactions are interesting as they are associated with a long-standing astrophysical problem, i.e. how certain heavy-isotopes (p nuclei) observed, so far, only in the solar system, are formed in the Universe (p process). The most favored scenarios proposed for the p process involve a series of photodisintegrations of intermediate and heavy elements at high temperatures (2-3 billion degrees Kelvin) that can be achieved only during the explosive burning phases of massive stars. Moreover, p-nuclei abundances are the signatures of the creation mechanism(s) of our solar system. It is widely accepted, that this issue still remains open and that there is much research work left to be done. Existing p-process models are still unable to reproduce the observed p-nuclei solar abundances and certain nuclear physics models describing global parameters such as Optical Model Potentials (OMP) and Nuclear Level Densities (NLD) entering the calculations are inaccurate and unreliable. It is therefore of paramount importance, on top of any astrophysical model improvements, to check the reliability of nuclear physics predictions related to the understanding of the p-nuclei abundance pattern. In this direction, a new method was developed by the groups of ``Demokritos", and Bochum that is based on the use of a large volume NaI(Tl) detector covering a solid angle of almost 4π for photons emitted by a target placed at its center. Using this new method, angle-integrated cross sections of more than 20 proton and alpha-particle capture reactions were determined at energies well-below the Coulomb barrier. The present paper presents a review of recent theoretical and experimental developments including some first attempts to measure cross sections of capture reactions in inverse kinematics using the JUROGAM array. Finally, the question of whether there is sufficient experimental information to put constraints on the theory of nucleon-nucleus, alpha-particle-nucleus potentials and nuclear level densities and draw final conclusions will be discussed.

Combinatorial level densities for pratical applications

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New developments have been brought to our energy-, spin- and parity-dependent nuclear level densities based on the microscopic combinatorial model [1]. Indeed, the vibrational contributions now explicitly take the phonon excitations into account using a vibrational partition function instead the previously adopted phenomenological enhancement factor. This new model predicts the experimental s- and p-wave neutron resonance spacings with a degree of accuracy comparable to that of the best global models available and provides reasonable description of low energies cumulative number of levels. Our predictions are also in good agreement with experimental data obtained by the oslo group [2]. When used in actual cross section calculation, these non statistical level densities provide reasonable predictions, both for fissile and non fissile nuclei. Total as well as partial level densities for more than 8500 nuclei are made available in a table format for practical applications, and for the nuclei for which experimental s-wave spacings and enough low-lying states exist, renormalization factors are also provided to reproduce simultaneously both observables.

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Neutron resonance densities and neutron strength functions for RIPL-3

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Abstract: The recent comprehensive compilation of neutron resonance parameters [1] was used to update the average resonance parameters contained in the Reference Input Parameter Library (RIPL-3) widely used for evaluations of nuclear reaction cross sections. Various methods for statistical analysis of missing resonances are considered for the purpose to obtain some objective estimation for uncertainties of recommended parameters. Effects of the resonance spacing modifications on the systematics of level-density parameter are briefly discussed for the most typical examples.

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Role of Multiphonon Configurations on Nuclear Spectra and Giant Resonances

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The quasiparticle-phonon model (QPM) is adopted to study the low-energy spectroscopic properties of medium-heavy spherical and heavy deformed nuclei. Multiphonon spectra in spherical nuclei in proximity of N=50 and N=82 shell closures are investigated with special attention at the so called mixed symmetry states. Intriguing effects induced by the shell structure are disclosed [1]. As regards deformed nuclei, the QPM study is concentrated mainly on the investigation of monopole and hexadecapole excitations in Os isotopes [2]. The analysis makes an important step toward settling the long debated issue about the phonon structure of the third 4^+ states in these nuclei and shows a close correlation between the properties of the 0^+ states and the evolution of the nuclear shape of those isotopes. Finally, a new multiphonon method which extends the old fashioned equation of motion method and is as accurate as shell model [3] is implemented numerically on O^{16}. The study points out the crucial role of multiphonon configurations on the nuclear responses of different multipolarity [4]. In particular, the phonon coupling is shown to be essential for reproducing shape and magnitude of the giant dipole resonance cross section.

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STRUCTURE OF EXCITED NUCLEAR STATES*

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In the study of nuclear structure, the bulk of research is performed on discrete states near the yrast line. Therefore, the properties of hot states remain unexplored in most of the spin-energy "landscape" -- despite many interesting questions. Do predicted temperature-induced shape fluctuations occur? Are signatures of phase transitions smeared out in a mesoscopic system? How fragile are superheavy nuclei when they are heated and spun? What is the nature of the transition from order to chaos as the nuclear temperature increases? This talk will address some of these questions. Remanent signatures of phase transitions are seen in the E2 spectrum as γ cascades traverse the phase boundary in the spin-energy plane. Some superheavy nuclei (e.g. ^{254}No) are found to be surprisingly robust, surviving up to at least $E^* = 8$ MeV and $\ell = 32\hbar$. The feeding and decay of superdeformed bands exhibit a unique double cycle of chaos-to-order transition, revealed by switches of the gamma spectrum from quasicontinuous to discrete. In the superdeformed well of ^{194}Hg, the chaos-to-order transition proceeds through a new ergodic regime. Aided by motional narrowing, the E2 γ flow is channeled along bands, appearing ordered, although the underlying states are chaotic.

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The two-step cascade method as a tool for studying γ-ray strength functions

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The method of two step γ cascades following the thermal and resonance neutron capture appears to be a powerful method for studying γ-ray strength functions. The experimental methods together with the interpretation of measured data in medium-weight and heavy nuclei using the DICEBOX algorithm will be described. Recent results obtained from data measured at Řež near Prague from thermal neutron capture and at Los Alamos with help of the DANCE detector for resonance neutron capture will be presented.

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Warm superdeformed nuclei: probes of nuclear structure and tunneling processes at the onset of chaos

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The properties of the atomic nucleus in the order-to-chaos transition region, namely a few MeV of internal energy above the yrast line, are discussed in connection with the γ-decay from the warm superdeformed (SD) nuclei ^{151}Tb and ^{196}Pb, representative of the mass regions A=150 and A=190. Several independent experimental quantities related to the γ-decay flux in the SD well are extracted, for the first time, from two high statistics experiments performed with the EUROBALL IV array. In particular, the analysis of double and triple coincidence γ-spectra is discussed, both in terms of spectrum intensities and fluctuations, providing a stringent test of nuclear structure properties in the warm rotating SD nucleus up to few MeV above yrast.

The experimental findings are compared to prediction from a newly developed Montecarlo simulation of the γ-decay flow in the SD well, based on microscopic cranked shell model calculations at finite temperature, including also a tunneling decay probability into the ND well [1]. This allows for a quantitative and microscopic description of the γ-decay flow over the whole spin range relevant for the SD nucleus, namely from the feeding region at the highest spins, down to the decay-out region in the ND-well. It is found that the simulation is able to reproduce rather well all the experimental quantities in both mass regions only including an enhancement of the E1 strength in the region up to 1.0-1.5 MeV above yrast. This can be related to the experimental observation of enhanced octupole vibrational states in both SD wells [2-4]. These results demonstrate that exclusive studies of quasi-continuum can shed light on important nuclear structure effects, still playing a role in the region next to the chaotic regime.
In addition, quasi-continuum studies are found to probe the basic ingredients of the physical process, such as the strength of the two-body residual interaction and the potential barriers as a function of spin and excitation energy.

Future perspectives with advanced detector arrays (such as AGATA) and radioactive beams will be finally discussed.

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Nuclear Level Density and Photon Strength Function Measurements at n_TOF.

S. Marrone on behalf of n_TOF Collaboration

In this contribution, we review results of Nuclear Level Densities (NLD) and Photon Strength Functions (PSF) measured at the neutron Time-of-Flight facility (n_TOF) at CERN. Accurate knowledge of these quantities is important to nuclear structure and nuclear astrophysics. Characteristics of the n_TOF neutron beam such as the very high instantaneous neutron flux, wide energy range, and good energy resolution have allowed collection of new and accurate data on a variety of nuclides, many of which are radioactive. The n_TOF experimental program is focused mainly on measurements of neutron capture and neutron-induced fission cross sections. However, these same sets of data allow NLDs and PSFs, near the neutron binding energy of the compound nucleus, to be determined. After a short description of the facility, detectors, and data analysis procedures, we will report published results of NLDs for isotopes of La, Sm, Os, Pb, Bi, Th, U, Np, and Am, and, particularly, the study of PSFs of ^{152}Sm and ^{197}Au. Finally, we will describe future upgrades of the facility and plans for new measurements to be performed at n_TOF beginning in spring 2009.

Single particle level densities in tetrahedral and octahedral nuclear shapes.

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New islands of nuclear stability are the consequence of particularly strong microscopic effects which are obtained in the calculation with application of high rank symmetries in definig the deformation. Microscopic energies are obtained with the Strutinsky shell energies and PNP pairing energies in multidimensional space of deformation parameters, especially the tetrahedral and octahedral ones. Single particle energies are calculated with the Woods-Saxon potential and the level densities have direct consequence on the shell effects and prediction of new stable nuclei.

Neutron Capture Experiments at DANCE

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The Detector for Advanced Neutron Capture Experiments (DANCE) is a very highly segmented γ-ray calorimeter that consists of 160 BaF_2 crystals. It was designed to measure neutron capture cross sections on very small stable or radioactive targets. Our initial measurements focused on Mo isotopes (^{94,95}Mo targets measured, ^{097}Mo proposed). Our recent emphasis is on Gd. We have data on ^{152,154,155,156,157,158,160}Gd targets. These isotopes are interesting for a variety of pure and applied reasons. The odd isotopes have very large capture cross sections and have numerous applications from reactors to medical therapy. The even isotopes have a range of deformations and thus may provide insights concerning e.g., behavior of scissors mode resonances as a function of deformation. Even for isotopes such as ^{152}Gd for which it is impossible to procure a very highly enriched target one can obtain very clean γ-ray spectra by gating on isolated resonances. The high degree of segmentation permits the separate study of different γ-ray spectra for different multiplicities, thus providing more sensitive comparison between experimental data and calculations with various strength function and level density models. The multiplicity distributions provide detailed information about the quantum numbers of the neutron resonances, even when the resonances overlap. Sample results will be presented.

*On behalf of the DANCE Collaboration

Spin- and isospin-projected nuclear level densities in the shell model Monte Carlo methods

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The microscopic calculations of nuclear level densities require the inclusion of both shell effects and collective two-body correlations. Whereas the interacting shell model gives a suitable framework for such calculations, required size of the model space is beyond the reach of the conventional computational method of diagonalizing the Hamiltonian matrix. By applying the shell model Monte Carlo (SMMC) method [1, 2], we have successfully described state densities of medium-mass nuclei [3–5] and of several heavy deformed nuclei; *e.g.* ^{162}Dy [6].

The spin distribution of level densities is important for the calculation of statistical nuclear reaction rates such as those in thermal stellar reactions [7]. However, the microscopic calculation of the spin distribution of level densities in the presence of correlations is a difficult problem, and the spin-cutoff model [8] is often assumed for the spin distribution. We introduce spin projection methods in the SMMC approach and apply them to calculate the spin distribution of level densities for iron-region nuclei using the complete $(pf + g_{9/2})$-shell [9]. Comparing the calculated distributions with the spin-cutoff model, we find significant deviation in densities of even-even nuclei at low excitation energies.

Analogously to the spin projection, we have also developed an efficient isospin projection method in the SMMC approach for isospin-conserving Hamiltonians [10]. For isoscalar observables this projection method has the advantage of being exact sample by sample. The isospin projection method allows us to take into account the proper isospin dependence of the nuclear interaction, thus avoiding a sign problem that such an interaction introduces in unprojected calculations. We apply our method in the calculation of the isospin dependence of level densities in the complete $(pf + g_{9/2})$-shell. We find that isospin-dependent corrections to the total level density are particularly important for $N \sim Z$ nuclei. It is noted that the perturbative correction employed in earlier works [11, 12] does not work well for those nuclei.

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Level densities and the γ-ray strength functions of ^{163,164}Dy

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The Oslo group have developed a technique in which it is possible to extract both the level density and the γ-ray strength function simultaneously from one and the same experiment [1]. The rare earth nuclei ^{163,164}Dy have been analyzed through this method from an experiment preformed at the Oslo cyclotron laboratory (OCL). The experiment was carried out using a 38 MeV beam of ^{3}He particles, and the $^{164}\mathrm{Dy}(^{3}\mathrm{He},\alpha)^{163}\mathrm{Dy}$ and $^{164}\mathrm{Dy}(^{3}\mathrm{He},^{3}\mathrm{He})^{164}\mathrm{Dy}$ reaction channels have been studied.

The experimental level densities and γ-ray strength functions will be presented. The pygmy resonance found around 3 MeV in the γ-ray strength function, also referred to as the scissors mode, was studied, see Fig. 1. The question whether the width of the pygmy resonance is reaction dependent is addressed. In addition thermodynamical properties of the nuclei have been extracted from the level density within the micro-canonical ensemble.

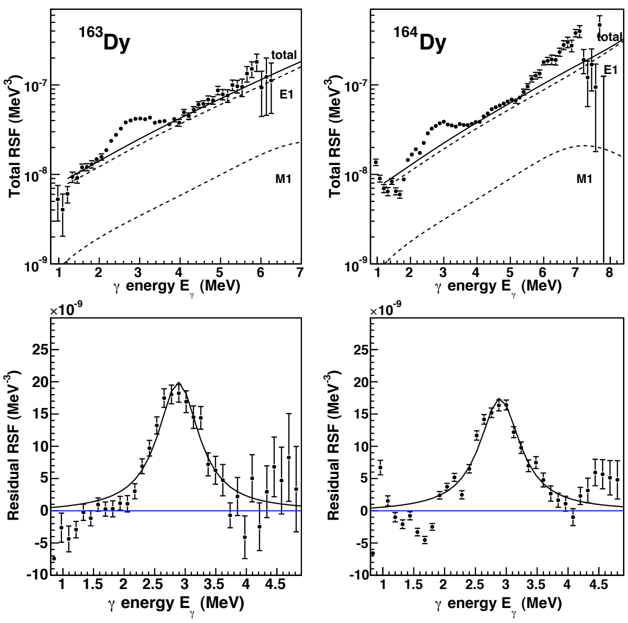

Figure 1: Experimental γ-ray strength functions for ^{163}Dy, left panel, and ^{164}Dy, right panel. The dashed lines in the uppermost panels represent the giant M1, and the extrapolated tail of the giant E1, as indicated in the figure. The solid line makes up the sum of the giant dipole resonances. The fit to the experimental datapoints in ^{164}Dy is performed up to γ-energy 5.3 MeV. The difference between the experimental data and the fit without the $M1$ pygmy resonance is shown in the lower panels.

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CLOSED-FORM E1 RADIATIVE STRENGTH FUNCTIONS FOR GAMMA-DECAY AND PHOTOABSORPTION

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Gamma-emission is one of the most universal channels of the nuclear de-excitation processes , and accompanies most nuclear reactions. The average probabilities both gamma decay and photo-absorption can be described through the use of the radiative strength functions (RSF). The calculations of nuclear reaction ingredients within statistical approach are as a rule rather time consuming procedure and simple closed-form expressions are as a rule used for the RSF[1,2].

In this contribution, different models of the dipole radiative strength functions (RSF) are discussed. Photoabsorption cross sections and isovector E1 gamma-decay strength functions are calculated for the middle-weight and heavy atomic nuclei within the Lorentzian-type models with asymmetric and symmetric shapes and with allowance for dependence on excitation energy ([1,2], and Refs. therein). The theoretical calculations are compared with experimental data to test the RSF models.

It is also shown that asymmetric shaped RSF with dependence on excitation energy, that leads to violation of the Brink's hypothesis, provide the most reliable simple methods to estimate the dipole RSF both for gamma-decay and for photoabsorption in spherical and axially-deformed nuclei over a relatively wide energy interval ranging from zero to slightly above the GDR peak, at least, when GDR parameters are known or their systematics can be safely applied to. A new ready-to-use table and systematic of the giant dipole resonance (GDR) parameters are are obtained from fitting the theoretical calculations for photoabsorption cross sections to the experimental data. The errors of the GDR parameters are estimated too.

The modified Lorentzian approach(see [1,2] for Refs.), that is based on general relations between the RSF and the nuclear response function, can potentially lead to more reliable predictions among simple models. However, the energy dependence of the width is governed by complex mechanisms of nuclear dissipation and is still an open problem. Reliable experimental information is needed to better determine the temperature and energy dependence of the RSF, so that the contributions of the different mechanisms responsible for the damping of the collective states can be further investigated. This should help to discriminate between the various closed-form models describing the dipole RSF.

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Enhanced dipole strength below particle threshold

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Dipole-strength functions up to the neutron-separation energies S_n of the N=50 isotones ^{88}Sr, ^{89}Y, ^{90}Zr, and the even-mass Mo isotopes from ^{92}Mo to ^{100}Mo have been studied in photon-scattering experiments using the bremsstrahlung facility at the superconducting electron accelerator ELBE of the Forschungszentrum Dresden-Rossendorf.
To estimate the distribution of inelastic transitions from high-lying levels at high level density to low-lying levels, simulations of γ-ray cascades were performed. On the basis of these simulations intensities of inelastic transitions were subtracted from the experimental intensity distributions, including the resolved peaks as well as a continuous part formed by unresolved transitions, and the intensities of elastic transitions to the ground state were corrected for their branching ratios. The photoabsorption cross sections obtained in this novel way are combined with (γ, n) and (γ, p) data and give detailed information about the dipole-strength functions in the energy range from about 4 MeV up to the giant dipole resonance (GDR).
In all nuclides extra strength in excess to simple Lorentzian-like approximations of the tail of the GDR is found in the energy range from about 5 MeV up to about the respective particle thresholds. Calculations in the framework of the quasiparticle-random-phase approximation (QRPA) underestimate the dipole strength at low energy because they do not take into account the coupling of two-quasiparticle to multi-quasiparticle excitations. A new approach is presented that calculates the dipole strength for nuclei with shape fluctuations by combining the interacting boson model (IBA) with QRPA. Based on the slow shape dynamics and the fast dipole vibrations an Instantaneous Shape Sampling (ISS) is performed that describes the photoabsorption at a fixed shape with QRPA with probabilities given by IBA. The ISS-QRPA improves the description of the experimental photoabsorption cross sections.
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Experiments with photon-induced reactions

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Photon-induced experiments play an important role in the solution of the puzzle about the production of the heavy elements in different nucleosynthesis scenarios. At the superconducting electron linear accelerator S–DALINAC, Darmstadt, Germany, the High Intensity Photon Setup (HIPS) is available [1]. The monoenergetic electron beam is converted into a continuous energy bremsstrahlung spectrum which can be used for photon-scattering or photoactivation experiments according to the chosen energy. Due to the high intensities systematic studies on spin, width, and absolute strength of resonance levels are possible in a broad energy range. The determination of parities is also enabled using Compton polarimetry at a second setup. However, parities are more likely determined using linearly polarized photon beams from Laser Compton Scattering facilities like *e.g.* the High Intensity Gamma Source (HIγS), TUNL/DFELL, Durham, NC, USA [2].

If the energy of the photon beam is above the particle threshold photoactivation experiments are enabled. Using bremsstrahlung at HIPS the predicted energy dependence of a cross section can be tested experimentally and yields information about the input of the prediction like *e.g.* the photon-strength function. In contrast, monoenergetic beams from Laser Compton Scattering allow the direct determination of the cross section with resolutions of about 100 keV. First activation experiments at HIγS showed very promising results [3].

In addition, the high-resolutive low-energy photon tagger NEPTUN allows direct measurements of photodesintegration cross sections $\sigma(E_\gamma)$ [4]. An energy resolution of less than 40 keV for $E_\gamma = 2 - 12$ MeV was achieved during test beam-times. The detection of neutrons from lowest energies up to several MeV will be realized with a detector array consisting of liquid scintillator detectors enriched with ^{10}B combined with standard neutron detectors to permit the required neutron-to-photon discrimination in the full energy range.

Recent studies on astrophysically relevant isotopes below and above the neutron separation threshold will be presented.

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Level Densities and γ-Ray Strength Functions in $^{116,118,119}Sn$

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The so-called γ-ray strength function and the energy level density characterize average decay properties of excited nuclei. These quantities are indispensable for calculating nuclear reaction cross sections and reaction rates relevant for, e.g., astrophysical applications. The strength function is also very important for describing the γ-emission channel in nuclear reactions.

The nuclear physics group at the Oslo Cyclotron Laboratory (OCL) has developed a unique method where both level density and γ-ray strength function below the neutron separation energy can simultaneously be extracted. The method is based on particle γ-ray coincidences obtained in single nucleon transfer and inelastic scattering reactions.

In this talk, preliminary results for the level densities for $^{118,119}Sn$ are presented. In ^{119}Sn, steps in the level density as a function of excitation energy are observed. This is a verification of the pair-breaking processes recently published for $^{116,117}Sn$ (Phys. Rev. C **79**, 014320 (2009)).

Also, preliminary results for the γ-ray strength functions of the isotopes $^{116,118,119}Sn$ are presented. The data clearly show an increase in γ-ray strength function for γ-energies above 4 MeV. Interpreting this as the left part of a resonance, the estimate of the resonance peak energy is localized at around 9 MeV. The position, strength and width indicate that this structure is due to the neutron-skin oscillation mode. The findings are in agreement with results recently seen in ^{117}Sn (PRL **102**, 162504 (2009)).

Study of the Nuclear Dipole Response using the Monoenergetic and Polarized Gamma Beams at HIγS

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The present experimental activity at High-Intensity-Gamma-Ray Source (HIγS) is focused on the study of dipole states in spherical nuclei where large, mostly electric dipole transitions to the ground state, have been observed. This concentration of dipole states in the $E_x \sim$ 4 - 9 MeV energy region, has been dubbed "Pygmy Dipole Resonance" (PDR) in comparison to the Giant Dipole Resonance that dominates the E1 response. The dipole strength distributions at the particle separation energies might affect reaction rates in astrophysical scenarios where photo-disintegration reactions are important, i.e., in hot stars and stellar explosions. The HIγS facility, utilizing intra-cavity back-scattering of free electron laser photons, allows one to produce a unique beam of high-flux-γ-rays with 100% linear polarization and selectable energy resolution which is ideal for low-energy scattering experiments. The dipole-strength distribution of the PDR has been studied in the N = 50 and 82 isotones and novel information about the character of these low modes of excitations has been obtained. In addition to the dominant E1 strength in this low-energy region, the polarized HIγS beam allows one to study the fine structure of the M1 distribution with high resolution and sensitivity. An unambiguous determination of spin and parity of the dipole excitations below the neutron threshold will be presented. The observations will be compared with calculations using statistical and quasiparticle random-phase approximation (QRPA) codes with multiphonon extension.

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Pigmy E1 and giant M1 resonances in the nucleosynthesis of heavy elements

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The γ–ray strength function (γSF) is a fundamental statistical quantity in the Hauser-Feshbach model calculation of radiative neutron capture cross sections. The γ-decay of a compound nuclear state populated immediately above neutron threshold by neutron capture is sensitive to the γSF in the low-energy tail of GDR. Recent investigations of the γSF with photon and baryon probes have revealed a concentration of extra γ-ray strengths known as pigmy E1 and giant M1 resonances near neutron threshold. The extra strengths increase radiative neutron capture cross sections in the statistical model and direct/semi-direct model calculations. Therefore, it is of growing importance to quantitatively understand the γSF for the nucleosynthesis of heavy element in terms of the decomposition of the γSF into three components of GDR, PDR and giant M1 resonance.

We present results of recent measurements of photoneutron cross sections for all zirconium stable isotopes including ^{96}Zr with laser-Compton-scattering γ-ray beams at the National Institute of Advanced Industrial Science and Technology. The γSF for the zirconium isotopes is systematically formulated as a combination of the Skyrme HFB+QRPA model calculation of low-lying E1 γSF of GDR and giant M1 resonance. Based on the systematic γSF, radiative neutron capture cross sections are deduced for ^{93}Zr ($T_{1/2} = 1.5 \times 10^6$ y)and ^{95}Zr ($T_{1/2}$ = 64 d) in the statistical model calculation.

Photoneutron cross sections were also measured for ^{116}Sn and ^{117}Sn. The result is indicative of the presence of pigmy E1 resonance which strongly enhances (γ,n) cross sections near neutron threshold.

The present study includes the result of "Study on nuclear data by using a high intensity pulsed neutron source for advanced nuclear system" entrusted to Hokkaido University by the Ministry of Education, Culture, Sports, Science and Technology of Japan (MEXT).

Level Densities and γ-strength functions from compound nuclear reactions

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We study nuclear level density and γ-strength functions experimentally with compound nuclear reactions. Level density is obtained from particle spectra measured at backward angles. We measure neutrons, protons and α-particles from reactions with d, ^{3}He, $^{6,7}Li$ projectiles. Experimental techniques and methods are discussed. One of the last finding is the unusual level density functional dependence for ^{60}Ni and ^{60}Co. The level densities for these nuclei exhibit the constant temperature energy dependence up to about 20 MeV of excitation energy. This feature contradicts modern theoretical models. Experimental results and comparison with theory are presented.

We started to study γ-strength functions by using proton radiative capture reactions. In particularly two-step γ-cascades have been measured from $^{59}Co(p,2\gamma)$ and $^{55}Mn(p,2\gamma)$ reactions. Results are presented. Experimental perspectives of such type of reactions and comparison with (n,2γ) reactions are discussed.

Measuring lifetimes in the quasi-continuum*

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The density of energy levels in nuclei increases rapidly as the excitation energy increases towards the particle separation energy, creating a quasi-continuum. The density of states (entropy) in a given system depends on excitations across shell gaps and the number of broken nucleon pairs. In contrast to regions of excitation energies within a few MeV of the ground state, it is not possible to identify all energy levels in this quasi-continuum experimentally. Instead, average quantities such as the entropy and γ-ray strength functions are used to describe "gross" nuclear properties, critical in calculating nuclear reaction rates in astrophysical processes.

Lifetimes near the particle separation energies are difficult to measure directly and are often inferred from resonance width measurements. The average lifetimes of nuclear states at the separation energies vary somewhat with mass number but are generally between 1 and 10 fs. As the excitation energy decreases the lifetimes of states in the quasi-continuum increase significantly. If lifetimes of quasi-continuum states are long enough lived to allow for photon absorption after being populated in astrophysical capture processes the nucleus may be excited above the particle separation energy. Consequently, the captured particle may be emitted suppressing the astrophysical reaction rate.

I will discuss experimental efforts underway at the 88-inch cyclotron at Berkeley National Laboratory within the LLNL, LBNL, and University of Oslo collaboration to measure lifetimes of quasi-continuum states using (d,p) transfer reactions in inverse kinematic. In particular I will focus on inverse kinematic reactions of Mo beams on a ^{2}H ion implanted layer on a thick stopper foil. The protons and γ-rays from the reactions are detected using the STARS-LIBERACE detector array. Particle energies of detected charged particles will be used to infer the "entrance" excitation energy of the residual nucleus. These "entrance" energies will be binned and lifetimes of γ-ray transitions in coincidence will be measured. Lifetimes of lower lying discrete states are partly dependent on the feeding of statistical γ-decays from these quasi-continuum states. Measuring differences in the lifetimes of a state using incremental particle gates will provide information on the average lifetimes of the gated region of the quasi-continuum.

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The Gamma Decay of the GDR Under Extreme Conditions

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The study of the gamma decay from the giant dipole resonance (GDR) at finite temperature and far from stability allows to obtain information on the properties of nuclei in different regimes. Exclusive measurements of gamma-decays with fusion reactions were made at LNL (INFN) in order to address different physical problems. First, the measurement of the temperature dependence of the GDR width up to T = 4 MeV in the mass region A=130 will be shown together with its interpretation in terms of thermal shape fluctuation calculations. Secondly, a measurement of the isospin mixing for nuclei in the mass region A = 80 at temperature around T=2 MeV is described. Finally the search for the pygmy dipole resonance in the neutron rich 68Ni nucleus, produced by fragmentation at GSI, will be presented. Coulomb excitation at 600 MeV/nucleon was employed and the gamma-rays were detected with the RISING array.

Nuclear data for reactor physics: Cross sections and level densities in the actinide region

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Abstract

Nuclear data in the actinide region are particularly important because they are basis behind all simulations of nuclear reactor core behaviour over both long time scales (fuel depletion and waste production) and short time scales (accident scenarios). Nuclear reaction cross sections must be known as precisely as possible so that core reaction rates can be accurately calculated. Although cross section measurements in this region have been widely performed, for certain nuclei, particularly those with short half lives, direct measurements are either very difficult or impossible and thus reactor simulations must rely on theoretical calculations or extrapolations from neighbouring nuclei. The greatest uncertainty in theoretical cross section calculations comes from the lack of knowledge of level densities, for which predicted values can often be incorrect by a factor of two or more. Therefore there is a strong case for a systematic experimental study of level densities in the actinide region for the purpose of a) providing a stringent test of theoretical cross section calculations for nuclei where experimental cross section data are available and b) for providing better estimations of cross sections in nuclei for which no experimental data are available.

In this presentation I will discuss possible level density measurements in the actinide region with a particular emphasis on the thorium cycle and the results of simulations of the potential use of the thorium in future light water reactors.

CHAOS, THERMALIZATION AND STATISTICAL FEATURES OF COMPLEX NUCLEI

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Huge amount of literature exists concerning thermal description of excited nuclei, its relation to standard thermodynamics and to level densities and reaction cross sections. We have also other finite (mesoscopic) fermionic systems - complex atoms or molecules, quantum dots, atoms in traps etc. (Hypotetical many-qubit quantum computers also would belong to this class). Such systems are far away from a theoretical thermodynamic limit. Moreover, s self-bound system, as the nucleus, is not interacting with the environment or a heat bath, so that many thermodynamic concepts seem to hang in the air. Nevertheless they usually work and it would be nice to understand the underlying physics. We argue that the driving force behind applicability of thermodynamical ideas is many-body quantum chaos. At high level density, all residual interactions become effectively strong so that the energy eigenstates are extremely complicated superpositions of many "simple" states. This efficient mixing and averaging is responsible for the validity of statistical approaches. Then the thermodynamic language and the language of individual chaotic wave functions become essentially equivalent. This will be illustrated by the results of exact diagonalization of realistic Hamiltonians in the shell-model approach. The pairing phase transition properties in such a system will be shown as well.

NUCLEAR LEVEL DENSITIES OF ^{208}Bi AND ^{209}Po FROM NEUTRON SPECTRA IN (p,n) REACTION ON NUCLEI OF ^{208}Pb AND ^{209}Bi.

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Abstract

Neutron spectra from (p,n) reaction on nuclei of ^{208}Pb, ^{209}Bi have been measured at proton energies between 8 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. The high resolution and stability of time-of-flight spectrometer allowed to identify reliably the discrete low-lying levels together with continuum part of neutron spectra. Analysis of the measured data have been carried in the framework of statistical equilibrium and pre-equilibrium models of nuclear reactions. The calculations are done using the exact formalism of the statistical theory as given by Hauser-Feshbach with generalized superfluid model of nucleus and back-shifted Fermi-gas model for nuclear level density. The nuclear level densities of ^{208}Bi, ^{209}Po, their energy dependences and model parameters have been determined. The obtained results have been discussed in totality with existing experimental and model systematics data.

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