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Contents

The shape distribution of nuclear level densities in the shell model Monte Carlo method

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In modeling nuclear shape dynamics, e.g., fission, it is necessary to determine the dependence of the nuclear level density on intrinsic deformation.

The probability density of the axial quadrupole deformation in the laboratory frame at finite temperature can be calculated in the framework of the configuration-interaction (CI) shell model using the shell model Monte Carlo (SMMC) method, and was found to exhibit model-independent signatures of deformation [1].

However, since intrinsic deformation is a concept introduced via a mean-field approximation that breaks rotational symmetry, it is a challenge to determine the probability density of the intrinsic deformation within a framework that preserves rotational symmetry, such as the CI shell model. We overcome this difficulty by parametrizing the probability density of the quadrupole shape by a Landau-like expansion with an analytic dependence on the intrinsic deformation coordinates (β, γ) [2]. This enables us to calculate deformation-dependent level densities within the SMMC method. We demonstrate our method for the heavy nuclei ^{148}Sm,^{150}Sm, and ^{154}Sm, which represent, respectively, spherical, transitional, and strongly deformed nuclei in their ground states.

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On deuteron interactions in surrogate $(d, p\gamma)$ reactions

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The validation test of the deuteron surrogate method by comparing well known (n, γ) reaction cross sections with those obtained by analysis of surrogate $(d, p\gamma)$ reaction showed large discrepancies (e.g., [1]). However, less considered was the specific noncompound processes that should be considered in the case of deuterons, making them substantially different from other incident particles. Thus, the deuteron breakup (BU) is particularly important due to the large variety of reactions initiated by the breakup nucleons along the whole incident energy range. Actually, an update of the theoretical analysis of deuteron-nuclei interaction within an unitary and consistent account of the related reaction mechanisms is highly requested not only by the use of deuteron surrogate reactions for (n, γ) and (n, f) cross sections, of interest for breeder reactors studies, but also by strategic research programs (ITER, IFMIF, SPIRAL2-NFS) [2] and medical investigations using accelerated deuterons [3]. Nevertheless, the complexity of deuteron interactions may still motivate the use of various Pade approximations of measured deuteron-reaction cross sections [3] at variance with the FENDL recommended advance of theoretical analysis [4].

Moreover, the role of deuteron BU increases with the target-nucleus mass and charge, so that it becomes dominant for heavy target nuclei and deuteron incident energies around the Coulomb barrier [5] as it is the case of the above mentioned studies [1]. At the same time, the consistent analysis of protons-induced reactions [3] may support the suitable evaluation of the BU-proton enhancement of various outgoing channels of deuteron-induced reactions on the same nucleus, which could not be accounted for by Pade approximations. This is why a comparative assessment [6] of measured data and results of BU microscopic description as well as current parametrization already involved within recent systematic studies [7] and present work is equally useful to basic objectives and improved nuclear data calculations.

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Realistic radiative strength functions within fast neutron-induced reactions in the mass range $A \sim 90$

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The recently improved cross sections for reactions induced by reaction-in-flight (RIF) neutrons with energies up to 30 MeV produced in warm, dense deuterium-tritium plasma [1], with thresholds above 15 MeV, reopen questions underlined by an widespread study of the fast-neutron induced reaction on Zr isotopes [2]. Consistent statistical model (SM) calculations of all competitive reaction channels are needed in this respect, using no empirical rescaling factor of the γ and/or particle widths but a consistent input parameter set, either established or validated by analyzing various independent data. The γ-ray strength functions are the most important among them in connection with the capture modeling and population of so many isomeric states in fast neutron-induced induced reactions on Zr. We took in this respect the opportunity of high accuracy measurements of the radiative strength function (RSF) performed especially at lower energies [3, 4] through the Oslo method [5, 6], leading to the RSF models progress. Thus, it has been useful to continue [7] a comparation of these data with predictions of the former Lorentzian (SLO) model for the electric-dipole γ-ray strength functions, as well as the generalized Lorentzian (GLO) model [8] and generalized Lorentzian (EGLO) model [9, 10] with a constant temperature T_f parameter. A small resonance (SR), as lastly used for ^{89}Y [3] to get a reasonable agreement withe the measured strength, has been also involved but to describe the low-energy enhancement of the RSF data. Similar assumptions involved within data cross-section calculations for fast neutron-induced induced reactions on Zr isotopes prove the usefulness of realistic radiative strength functions.

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Application of Oslo Method on Heavy Nd Isotopes

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The nuclear level densities are useful ingredients for statistical model calculations to estimate reaction cross sections. These quantities have many applications such as transmutation of nuclear wastes, astrophysics and test of nuclear models. The nuclear level densities were determined via the Oslo Method for ^{145,149,151}Nd isotopes below the neutron separation energies. In order to obtain the nuclear level densities ^{144,148,150}Nd(d,p) reactions were studied. The results from these reactions will be presented.

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Gamma strength function and level density of ^{120}Sn

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The gamma strength function (GSF) and level density of 1^- states in ^{120}Sn was extracted from polarised inelastic proton scattering data taken at the Research Center for Nuclear Physics (RCNP), Osaka, Japan [1, 2]. The results are compared to those from Oslo-type measurements for several neighbouring tin isotopes [3, 4] and theoretical models for the GSF and level density. First results from a systematic study of the even-mass stable tin isotopes are also presented.

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Preliminary results on photon strength functions of ^{195}Pt from resonance neutron radiative capture measured by DANCE experiment

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The ^{195}Pt (n,γ) reaction was measured by the γ calorimeter DANCE (Detector for Advanced Neutron Capture Experiments) consisting of 160 BaF_2 scintillation detectors at the Los Alamos Neutron Science Center. The cascades of gammas for describing the reaction were simulated by the DICEBOX statistical model code. The shapes of the experimental spectra for different multiplicities were compared with simulations. The preliminary results on photon strength functions of ^{196}Pt and the comparison with other similar analysis are presented in the work.

Update on (n, γ) studies of photon strength functions at Budapest

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^{113}Cd is an important nucleus for shielding or absorption of low energy neutrons due to its extremely high neutron capture cross section. The (n,γ) reaction populating the ^{114}Cd decay-scheme shows interesting nuclear structure and its neutron capture gamma-ray spectrum can be described rather well using the extreme statistical model. Using this tool the decay scheme can be constructed up to about 3.2 MeV. Feeding from the quasi continuum shows systematics, as a function of spin and parity, which help construct the decay-scheme. The unfolded gamma-ray spectrum indicates the need for an up-bending photon strength function (PSF) at low energy. Shell model calculations are still running may explain the nature of this up-bending. There also appears to be an enhanced group of gamma-ray peaks at about 5.5 MeV, which was also mentioned in old PFS studies that cannot be explained.

In addition the ^{238}U(n,γ) has been measured and the analysis of the gamma-ray spectrum of ^{239}U has started. Preliminary results will also be presented

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Constraining the low energy limit of the strength function through nuclear-plasma interactions

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Electron-mediated nuclear-plasma interactions (NPIs) such as Nuclear Excitation by Electron Capture (NEEC) or Transition (NEET) are expected to cause significant changes in reaction cross sections in High Energy Density Plasmas such as nuclear tests, National Ignition Facility (NIF) shots, and astrophysical settings. However, NPIs remain largely unobserved due to the extreme narrowness of nuclear transitions. We proposed to overcome this challenge with an experiment at the NIF[1] by inducing NPIs on highly-excited (∼1-5 MeV) nuclear states produced by nuclear reactions *prior* to their decay by spontaneous gamma-ray emission. The large density of nuclear states at these excitation energies increases the probability that the energy from the atomic transition will resonantly match an available nuclear transition. Neutrons from deuterium-tritium fusion in an indirect-drive exploding pusher capsule produce highly-excited ^{133}Xe nuclei in both the imploding plasma and a control sample located outside the plasma. NPIs are expected to alter the angular momenta of excited nuclei in the plasma, thus affecting the subsequently-populated isomer fraction. Any difference in the ^{133}Xe isomer-to-ground state population ratio between the in-plasma and control samples, measured in the same high-purity germanium detector, is indicative of plasma-induced effects.

Predictions of NPI probabilities are extremely uncertain due, in part, to the dependence on the low-energy (keV) photon transition strength, characteristic of the xenon M-, L-, and K-shell atomic binding energies. While the strength function in similar-mass nuclei has exhibited an unexpected dipole enhancement at low energies [2], deviating dramatically from the Lorentzian models, no measurement has ever been made below about an MeV. The observation, or lack thereof, of NPIs therefore may set limits on the low-energy photon transition strength, where no measurements are currently possible and theoretical estimates vary by orders of magnitude.

Preliminary findings from our first attempt to measure NPIs in ^{133}Xe at the NIF will be presented.

Work performed by LLNL and LBNL under Contracts DE-AC52-07NA27344 and DE-AC02-05CH11231, the UCOP under Award No. 12-LR-238745, and the NRF of South Africa.

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Valence particle-core excitations couplings: new experimental investigations and novel theoretical approaches

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We present a new microscopic model aimed at describing the structure of nuclear systems with one- to few-valence particles outside a doubly-magic nucleus, in the medium-heavy mass regions [1, 2]. The model accounts for both collective phonons and non-collective configurations and it includes couplings between valence nucleons and core excitations, in a self-consistent way, by means of Hartree-Fock (HF) and Random Phase Approximation (RPA) calculations with the Skyrme effective interaction. The theoretical outcomes will be discussed and compared with experimental results on nuclei in the region of the ^{132}Sn and ^{40,48}Ca doubly-magic cores, populated in neutron-induced fission, neutron-capture and multi-nucleon transfer reactions, in different experimental campaigns. The agreement between theory and experiment will be outlined, along with possible future developments.

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Resonances in odd-odd ^{182}Ta

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Relatively small resonances on the low-energy tail of the giant electric dipole resonance such as the scissors or pygmy resonances can have significant impact on reaction rates. These rates are important input for modelling processes that take place in astrophysical environments and nuclear reactors. Recent results from the University of Oslo indicate the existence of a significant enhancement in the photon strength function for nuclei in the actinide region due to the scissors resonance [1]. Further, the M1 strength distribution of scissors resonances in rare earth nuclei has been studied extensively over the years [2]. In order to investigate the extent and persistence of the scissor resonance in other mass regions, an experiment was performed utilizing the NaI(Tl) gamma-ray detector array (CACTUS) and silicon particle telescopes (SiRi) at the cyclotron laboratory at the University of Oslo. Particle-gamma coincidences from the ^{181}Ta(d,p)^{182}Ta reaction were used to measure the nuclear level density and photon strength function of the well-deformed ^{182}Ta system, to investigate the existence of resonances below the neutron separation energy. In this talk I will present and discuss the results of this investigation and place our findings in the context of previous work.

This work is based on the research supported in part by the National Research Foundation of South Africa Grant Number 92600.

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Statistical vs. direct γ-decay of ^{64,65}Ni

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Several analytical techniques in nuclear physics are based on the generalized Brink-Axel hypothesis (gBA), since it considerably simplifies calculations. In general terms, the gBA hypothesis implies that the dipole γ-strength is independent on the structure of the initial state, having no explicit dependence on the excitation energy, spin or parity, besides the selection rules for dipole transitions [1, 2]. Therefore, when the gBA hypothesis is valid, the γ-Strength Function (γSF) depends solely on the γ-ray energy for dipole radiation [3].

Given the extensive application of the gBA hypothesis, it is of great importance to determine the circumstances under which this hypothesis holds. This is often a difficult task, specially for nuclei in which strong Porter-Thomas fluctuations are observed. As shown in Ref. [5], the heavy odd-odd nucleus ^{237}Np presents a extremely high level density ($\approx 10^7$ levels/MeV). Averaging over many γ-transitions can be then performed and Porter-Thomas fluctuations are less significant. In contrast, lighter nuclei such as ^{64,65}Ni present a much lower level density ($\approx 10^3$ levels/MeV) and strong Porter-Thomas fluctuations are seen. Extracting conclusions regarding the validity of the gBA hypothesis becomes then more difficult and the role of Porter-Thomas fluctuations needs to be investigated in more detail.

In this talk, the validity of the gBA hypothesis in ^{64,65}Ni is discussed. The analysis of particle-γ coincidences on the ^{64}Ni$(p, p'\gamma)^{64}$Ni and ^{64}Ni$(d, p\gamma)^{65}$Ni reactions [6, 7] is here presented together with a further study of the γSF of ^{64,65}Ni. The dependence of the γSF with initial and final excitation energy is investigated and the role of Porter-Thomas fluctuations estimated.

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Investigating the surrogate method via the simultaneous measurement of fission and gamma probabilities

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Fission and gamma decay probabilities of ^{237}U and ^{238,239}Np have been measured, for the first time simultaneously in dedicated experiments, via the surrogate reactions ^{238}U(^{3}He,^{4}He), ^{238}U(^{3}He,t) and ^{238}U(^{3}He,d), respectively. While a good agreement between our data and neutron-induced data is found for fission probabilities, gamma decay probabilities are several times higher than the corresponding neutron-induced data for each studied nucleus. We study the role of the different spin distributions populated in the surrogate and neutron-induced reactions. Our results indicate a strong sensitivity of the gamma probability to the compound nucleus angular momentum distribution and, contrary to statistical model predictions, a much weaker sensitivity of the fission probability. Preliminary results from a Hauser-Feshbach calculation, coupled with a DWBA-deduced spin and parity distribution for the ^{238}U(^{3}He,^{4}He) reaction, well reproduce, for the very first time, both measured fission and decay probabilities, helping to gain an insight into the origin of the weaker sensibility of the fission probability to the angular momentum. This finding is highly relevant because it implies that the Hauser-Feshbach calculation, tuned on decay probabilities measured in surrogate reactions, can provide reliable predictions for neutron-induced cross sections of short-lived nuclei that cannot be directly measured.

In the contribution we will present the mentioned results and possible future developments using inverse kinematics at ion storage rings.

Updating the Photonuclear Data Library and Generating a database for Photon Strength Functions

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Photon nuclear data describing interactions of photons with atomic nuclei are of importance for a variety of applications including radiation shielding and radiation transport analyses, calculation of absorbed does in the human body during radiotherapy, safeguards and inspection technologies, nuclear waste transmutation, fission and fusion reactor technologies, and astrophysical nucleosynthesis.

The IAEA Photonuclear Data Library (1999) includes photon absorption data, total and partial photoneutron reaction cross sections for 164 isotopes, primarily for structural, shielding, biological and fissionable materials. Although this database has been extremely useful to a broad user community, it has become evident that it needs to be revised especially since some of the data are unreliable and discrepant, there exist data that have not been evaluated, improved evaluation techniques are available, and many new data have been published in recent years.

In addition to the many applications mentioned above, photon strength functions describing the average response of the nucleus to an electromagnetic probe, are important for the theoretical modelling of nuclear reactions. In the past two decades, there has been considerable growth in the amount of reaction data measured to determine integrated photon strength functions. Quite often the different experimental techniques lead to discrepant results and users are faced with the dilemma of trying to decide which (if any) amongst the divergent data they should adopt. It is therefore important that all these experimental data are evaluated by experts who will recommend the most reliable data for use in the various applications.

To address the above mentioned data needs, the IAEA is coordinating an international research project on Updating the Photonuclear Data Library and Generating a Database for Photon Strength Functions[1, 2]. I will discuss the objectives of this project, present the recent progress that has been achieved and show some aspects of the preliminary version of the photon strength function database.

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Simultaneous Microscopic Description of Nuclear Level Density and Radiative Strength Function

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We propose, for the very first time, a microscopic approach, which is able to simultaneously describe the nuclear level density (NLD) and radiative γ-ray strength function (RSF). This approach uses the exact solutions of the pairing problem to construct the partition function to calculate the NLD and thermal pairing gap at finite temperature. The latter is included in the Phonon Damping Model (PDM)[1] to calculate the RSF. The good agreement between the results obtained within this approach and the experimental data for NLD and RSF in $^{170-172}$Yb shows that exact thermal pairing is indeed very important for the description of both NLD and RSF in the low and intermediate region of excitation and γ-ray energies. Moreover, to have a good description of the RSF the microscopic strength function with the temperature-dependent width for the giant resonances should be used instead of the Brink-Axel hypothesis. The merits of this approach are its microscopic nature and the absence of parameter fitting at different excitation and γ-ray energies. It does not consume much computing time either as the calculation takes less than 5 min even for a heavy nucleus, and therefore can be performed on a PC.

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Rotational enhancement of the level density in deformed nuclei

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Breaking of the spherical symmetry of the nuclear wavefunction, and the associated generation of rotational bands, implies a gain in the level density by a substantial factor, as was pointed out by Bjørnholm, Bohr and Mottelson[1]. This factor is often referred to as the *rotational enhancement* of the level density. We shall address this enhancement from different perspectives.

Our starting point will be Fermi-gas expressions, for spherical nuclei as given by Bethe, and for deformed nuclei as given by Ericsson, emphasizing that the rotational enhancement is present at all angular momenta, even for bandheads at angular momentum $I = 0$. The rotational enhancement also emerges as the ratio between the intrinsic state density and the total state density.

The nature of the rotational enhancement can be illustrated by counting the number of states in finite spaces, such as for example four particles in a j-shell - on their own for the Bethe scenario - and combined with a rotor for the Ericsson scenario.

Finally, we discuss experimental and calculated enhancement factors evaluated as the ratio between the intrinsic state density and the total state density. The intrinsic state density is the level density of bandheads, which is difficult to access experimentally, except at the lowest excitation energies, where discrete rotational bands can be identified. We shall give a critical discussion of the information on the rotational enhancement one can extract from data, and compare to theoretical level densities based on the folded Yukawa potential with a monopole pairing. For an ensemble of even-even rare earth nuclei, at excitation energies around 1.7 MeV, and odd-odd nuclei around 0.6 MeV, we find experimental enhancement factors approximately equal to ~ 15, and theoretical enhancement factors approximately equal to ~ 30.

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The 3α process studied through pair conversion transitions from the Hoyle state in ^{12}C

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Stellar formation of carbon occurs when three alpha particles fuse to form ^{12}C in the excited 7654-keV 0^+ "Hoyle" state. Stable carbon is only formed if the excited nucleus decays to the ground state. This, however, is very unlikely since the Hoyle state is above the 3α break-up threshold, meaning that the excited carbon nucleus disintegrates ~99.96% of the time. The process is therefore a bottleneck in stellar nucleosynthesis, and precise knowledge of the reaction rate is imperative for proper stellar modelling. Since the formation of stable carbon depends on electromagnetic decay from the Hoyle state, the 3α rate is directly related to its radiative transition probabilities [1]. The radiative decay occurs either by a 7654-keV $E0$ transition to the 0^+ ground state, or by a 3215-keV $E2$ transition to the first excited 2^+ state. The total radiative width currently has an uncertainty of ~12.5%. A new approach for deducing the radiative width has been proposed at the ANU [2], and is expected to lower the uncertainty to ~5%. It proceeds by combining the $E0/E2$ pair-emission ratio from the Hoyle state, with the theoretical pair-conversion coefficient [3] and the $E0$ pair width from electron-scattering experiments [4]. The $E0/E2$ pair-emission ratio is currently unknown, but our aim is to obtain a direct measurement by measuring the $E0$ and $E2$ pair transitions from the Hoyle state in the same experiment. In order to achieve this, the superconducting electron spectrometer setup [5] at the ANU has been upgraded and optimized for pair spectroscopy. Furthermore, the Hoyle state is easily populated via ^{12}C(p,p') @ 10.5 MeV in the laboratory. Current results, from an experiment in April 2016, clearly exhibit the 7654-keV $E0$ pair transition, and also indicate the 20 times less likely 3215-keV $E2$ transition. To obtain more statistics, additional measurements were performed in November 2016, and are currently under analysis. A detailed description of the experimental setup, new method and preliminary results will be discussed in this presentation.

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Capture Reactions on Unstable Isotopes: Connecting Indirect Measurements to the Desired Cross Sections*

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Cross sections for compound-nuclear reactions involving unstable targets are important for many applications, but can often not be measured directly. Several indirect methods have recently been proposed to determine neutron capture cross sections for unstable isotopes. These methods aim at constraining statistical calculations of capture cross sections with data obtained from the decay of the compound nucleus relevant to the desired reaction. Each method produces this compound nucleus in a different manner (via a light-ion reaction, a photon-induced reaction, or β decay) and requires additional ingredients to yield the sought-after cross section. This contribution focuses on the process of determining capture cross sections from inelastic scattering and transfer experiments. Specifically, theoretical descriptions of the (p,d) and (d,p) transfer reaction have been developed to complement recent measurements in the Zr-Y-Mo region. The procedure for obtaining constraints for unknown capture cross sections is illustrated. Indirectly extracted cross sections for both known (benchmark) and unknown capture reactions are presented. The main advantages and challenges of this approach are compared to those of the proposed alternatives.

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Particle-number projection in finite-temperature mean-field approximations to level densities

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Finite-temperature mean-field theories, such as the Hartree-Fock (HF) and Hartree-Fock-Bogoliubov (HFB) theories, are formulated in the grand canonical ensemble. However, their applications to the calculation of statistical properties of nuclei such as level densities require a reduction to the canonical ensemble. In a recent publication that benchmarked the accuracy of mean-field theories against shell model Monte Carlo results [1], it was found that ensemble reduction methods based on the commonly used saddle-point approximation are not reliable in cases in which rotational symmetry or particle-number conservation is broken. In particular, the calculated HFB canonical entropy can be unphysical as a result of the inherent violation of particle-number conservation. In my presentation, I will introduce a general formula for exact particle-number projection after variation in the HFB approximation, assuming that the pairing condensate preserves time-reversal symmetry [2]. This formula reduces to simpler known expressions in the HF and Bardeen-Cooper-Schrieffer (BCS) limits of the HFB. In our work, we applied this formula to calculate the thermodynamic quantities needed for level densities in the heavy nuclei ^{162}Dy, ^{148}Sm, and ^{150}Sm. The exact particle-number projection gives better physical results and is much more computationally efficient than saddle-point methods. However, fundamental limitations caused by broken symmetries in the mean-field approximation are still present. I will also discuss a general symmetry projection method for the case in which the finite-temperature mean-field solution violates time-reversal symmetry. This novel projection method would be useful for finite-temperature mean-field studies of odd-mass nuclei.

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Photoneutron reactions studies at ELI-NP using a direct neutron multiplicity sorting method

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Reliable measurements of total and partial photoneutron reactions cross sections in the Giant Dipole Resonance region provide a better understanding of the photoabsorption process and of the excited nuclear collective states decay, which is necessary for obtaining a good model description of observed cross sections over the complete range of nuclei.

The Extreme Light Infrastructure - Nuclear Physics (ELI-NP) [1] team plans to provide new and reliable experimental (γ, 1–2n) cross sections using the very brilliant ELI-NP γ-ray beam source (20 MeV maximum photon energy, up to 0.5 % relative energy resolution, $\sim 10^8$ photons per second flux within the bandwidth [2]).

For this, a direct neutron multiplicity sorting technique [3] will be used to obtain (γ, xn) cross sections, where x = 1 − 2. The method has been applied for the first time for the case of ^{209}Bi at the NewSUBARU synchrotron radiation facility [4]. This is the first of a series of experiments dedicated to partial photoneutron cross section measurements for the IAEA-CRP F41032 which make use of the new neutron multiplicity sorting method. We report here on the experimental technique, data analysis and preliminary results on ^{209}Bi(γ, 1–4n) cross sections.

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A new formulation of the nuclear level density by spin and parity

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The Constant Temperature (CT) and Back Shifted Fermi Gas (BSFG) formulations are the most commonly used level density models. Both models rely on a separable spin distribution function that is clearly insufficient at low level excitation energies, and neither model explicitly considers parity. Each model has two fitting parameters that can be determined from the low level energy distribution and the s-wave level spacing, *D0*, at the neutron separation energy. In this fit *D0* must be converted to a total level spacing using the spin distribution function which contains the elusive spin cutoff parameter, σ_c. The CT and BSFG formulations describe the “total level density” with a set of fitting parameters that have little physical meaning. All nuclear reaction experiments populate only a subset of level spins and parities that cannot adequately be described by the total level density.

In this paper I propose the CT-JPI formulation that can describe the level densities, $\rho(J^\pi)$, for a broad range of spins and parities with only a single free parameter, temperature $T(J^\pi)$. The CT-JPI formulation is given by,

$$\begin{aligned} N(E^{J^\pi}) &= \exp\left[\frac{E^{J^\pi} - E_0^{J^\pi}}{T(J^\pi)}\right] \\ \rho(J^\pi) &= \frac{N(E)}{T(J^\pi)} \end{aligned} \tag{1}$$

where $E_0^{J^\pi}$ is the Yrast energy for each J^π. The experimental temperatures, $T(J^\pi)$, for each J^π are fit by Equation 1 to the experimental neutron resonance energies, E^{J^π}, where $N(E_0^{J^\pi})$=1 and $N(E^{J^\pi})$ are the resonance sequence numbers. When no resonance data are available $T(J^\pi)$ is determined by normalizing its level spacing to the experimental level spacings with the spin distribution function. The spin cutoff parameter, σ_c, is varied to obtain a constant temperature for all J^π.

I have applied the CT-JPI formulation to two very different isotopes, ^{57}Fe and ^{236}U. In both cases constant temperatures can be obtained for σ_c=2.5 although $T(J^\pi)$ diverges to nonphysical values for $J > 11/2$. In ^{57}Fe the level densities can be determined by three temperatures,

$$\begin{aligned} T(\pi=-) &= 1.664 \pm 0.016 \text{ MeV} \\ T(1/2^+, 5/2^+, 9/2^+) &= 1.13 \pm 0.03 \text{ MeV} \\ T(3/2^+, 7/2^+, 11/2^+) &= 1.28 \pm 0.03 \text{ MeV} \end{aligned} \tag{2}$$

For ^{236}U, a single temperature, $T(J^\pi) = 0.443 \pm 0.005)$ MeV, can describe the level densities for all spins and parities. Total level densities are determined by summing the individual J^π level densities. The CT-JPI formulation gives comparable total level densities to conventional CT and BSFG calculations. The level density parity ratio at the neutron separation energy is $\rho(\pi=+)/\rho(\pi=-)$=0.88 for ^{57}Fe and $\rho(\pi=+)/\rho(\pi=-)$=0.75 for ^{236}U, which are contrary to a common assumption that they should be equal.

Interaction dependence of the nuclear level density calculated using Hartree-Fock-Bogoliubov theory

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While Fermi Gas type phenomenological models are widely used to calculate the nuclear level density (NLD) of stable nuclei, it is important to develop a microscopic method to achieve reliable NLD for unstable nuclei.

One of microscopic methods to calculate NLD is that based on the microscopic nuclear structure calculation using Hartree-Fock-Bogoliubov (HFB) theory. Since an effective nuclear interaction is basically the only input in HFB calculation, we investigated how the calculated NLD depends on it with special attention to the adopted pairing interaction, to discuss about the reliability of this method.

Adding to SkM* force that was used in our previous study [1], SLy4, SkP, and UNEDF1 forces were used in HFB calculations of the present study. The statistical method [2] was applied to derive NLD based on HFB calculation.

We compared the s-wave resonance spacing D_0 derived from the calculated NLD with experiments, and found fair agreement with the results obtained using SkP and UNEDF1 forces. Figure 1 (a) shows calculated D_0 normalized to the experimental values for 66 even-even nuclei. We adopted two pairing strength parameter sets P1 and P2 for SkP force. They were adjusted to reproduce the experimental neutron pairing gaps around Sn and Pb, respectively, as shown in Fig. 1 (b). The better reproduction was achieved with P2. D_0 calculated using UNEDF1 and SkP P2 forces were similar despite they give different results for other nuclear properties.

Acknowledgement

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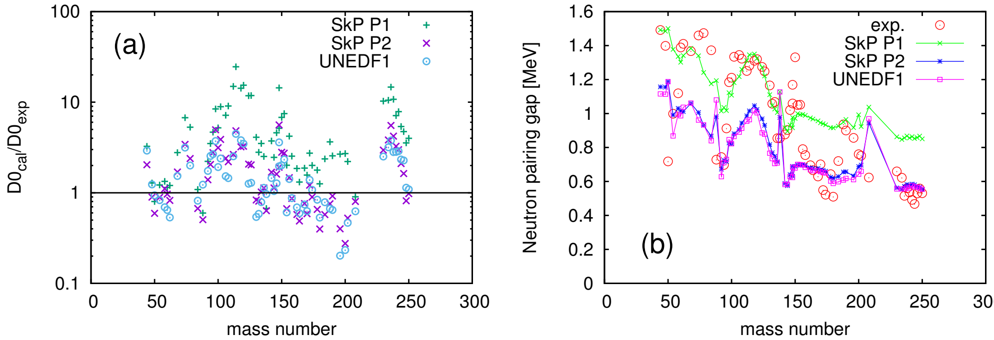

Figure 1: Calculated D_0 normalized to the experimental values and neutron pairing gaps for 66 even-even nuclei.

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Experimental evidence of chaos in the bound states of ^{208}Pb

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We study the spectral fluctuations of the ^{208}Pb nucleus using the complete experimental spectrum of 151 states up to excitation energies of 6.20 MeV recently identified at the Maier-Leibnitz Laboratorium at Garching, Germany. For natural parity states the results are very close to the predictions of random matrix theory (RMT) for the nearest-neighbor spacing distribution. A quantitative estimate of the agreement is given by the Brody parameter ω, which takes the value $\omega = 0$ for regular systems and $\omega = 1$ for chaotic systems. We obtain $\omega = 0.85$ which is, to our knowledge, the closest value to chaos ever observed in experimental bound states of nuclei. By contrast, the results for unnatural parity states are far from RMT behavior. We interpret these results as a consequence of the strength of the residual interaction in ^{208}Pb, which, according to experimental data, is much stronger for natural than for unnatural parity states. In addition, our results show that chaotic and nonchaotic nuclear states coexist in the same energy region of the spectrum.

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QRPA E1 and M1 strengths and their impact on reaction rates

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The γ-ray strength function plays a fundamental role in the description of radiative captures as well as photodisintegrations, two reaction channels of fundamental importance for the heavy element nucleosynthesis. While the γ-ray strength function has been traditionally described through phenomenological models, new systematic large-scale calculations of the E1 and M1 strength based on the consistent HFB+QRPA approach are now available. The latest development in such calculations will be described together with a comparison with existing experimental data. Such a microscopic description of the E1 and M1 strengths is also used to estimate radiative neutron capture and photodisintegration rates of astrophysical interest. The low-energy strength found in the HFB+QRPA description either due to the so-called pygmy resonance or to deformation effects are highlighted and their impact on reaction rates discussed. Similar low-energy effects linked to the so-called upbend character of the M1 strength and its impact on nuclear and nucleosynthesis observables will also be discussed.

Studies of spin cutoff parameters for Pt isotopes

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A recent large-scale survey of spin cutoff parameter σ variations with mass number A and excitation energy [1] suggests that at energies below 8 MeV nuclei near A=200 have a minimum in σ relative to slightly lighter and slightly heavier nuclei. We present microscopic calculations of σ for Pt isotopes. We examine the possibility that σ values might have a parity dependence at energies below 10 MeV.

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The measurement programme of the n_TOF facility at CERN

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Neutron-induced reaction cross sections are important for a wide variety of research fields. Applications of nuclear data are related to research fields as the study of nuclear level densities, stellar nucleosynthesis, and nuclear technology.

CERN's neutron time-of-flight facility n_TOF has produced an considerable amount of experimental data since it has become fully operational with the start of its scientific measurement programme in 2002. For a long period a single measurement station (EAR1) located at 185 m from the neutron production target was available. Since 2014 a second beam line at 20 m (EAR2) is operational.

An outline of the experimental nuclear data activities at CERN's neutron time-of-flight facility n_TOF will be presented as well as a description of the facility with the two beamlines.

Large scale QRPA predictions of gamma ray strength functions based on the D1M Gogny interaction

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Within the framework of a global microscopic approach, all the nuclear input required for nuclear reaction predictions are being, step by step, derived from a sole nucleon-nucleon effective interaction, namely the D1M Gogny force [1]. Nuclear masses [1], deformations, radial densities and level densities [2] have already been obtained and have shown a rather good agreement with experimental data either directly or when used, for instance, to derive optical models [3]. We now focus on the radiative strength functions within the QRPA approach [4], and in particular, aim at producing tables of gamma-ray strength functions, first for E1, and then for M1 transitions. The current status of this project will be discussed and perpectives will be drawn.

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The Oslo Method in Inverse Kinematics

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The Oslo Method[1] have for more than a decade been the "go-to" method for extracting γ-ray strength functions (γSF) and nuclear level density (NLD) below the neutron separation energy. The method relies on having knowledge of the distribution γ-rays emitted at different excitation energies. Traditionally this have been measured in experiments where a light ion beam (p, d, ^{3}He, α) hits a target which induce reactions. The γ-ray spectrum and excitation energy is then found by recording particle-γ coincidences. The nuclei that can be measured with this experimental technique is unfortunately limited to nuclei close to stability and by it's chemical properties, due to the lack of suitable targets.

In this presentation we will present a different approach to the experimental setup that allows for measurements of γ-ray strength functions and nuclear level densities of virtually any nuclei. By employing a heavy ion beam together with a deutrated target we are able to achieve the same type of results obtained in the traditional setup. The results from the proof-of-principle experiment done at iThemba LABS will be presented, reviling the γSF and NLD of ^{87}Kr. Difficulties arising from the change of kinematics will also be discussed.

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Photonuclear Reaction Methods and Needs for Global Security Applications

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There is some interest from a variety of agencies to use γ-ray sources for detection and assay of materials in a wide array of global security applications, including cargo container screening and fuel-assembly assay. γ-ray sources provide a means to non-destructive detection and assay, which is important to nuclear safeguards and non-proliferation. The biggest challenge for γ-ray source-driven detection and assay is the ability to extract small signals in large backgrounds for heavily shielded materials. Critical to this challenge is the requirement for a more complete understanding of γ-ray strength functions and more empirical data in the nuclear libraries. Nuclear data libraries are used for simulations that are necessary for application studies. For example, applications with sparse (unstable) nuclei in a large matrix such as spent nuclear fuel assemblies, it is essential to know the γ-ray strength function to determine the absolute and relative abundances of certain isotopes. γ-ray strength function data for most unstable nuclei does not exist. Practical applications that could use γ-ray source-driven methods will be discussed in this presentation in addition to some of our cross-section and demonstration measurements. We will also discuss some of the data needs.

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Understanding the Nature of the Low-energy Enhancement in the Photon Strength Function of ^{56}Fe

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The discovery of a low-energy enhancement in the photon strength function (PSF) of medium mass nuclei in the Fe and Mo region [1] as well as nuclei in the rare-earth region [2], has recently attracted great experimental and theoretical attention. The presence of an enhanced decay probability of low-energy gammas rays below the neutron threshold may represent a new decay-mode [3], and has the potential to greatly affect a broad range of applications including the astrophysical r-process and nuclear reactors [4, 5]. Recent shell model calculations on ^{56,57}Fe, ^{94,95}Mo and ^{90}Zr show that the enhancement could be due to a large B(M1) strength for low energy γ-rays caused by orbital angular momentum recoupling of high-j orbits [3, 6], while other mechanisms suggest an enhanced $E1$ strength [7].

A recent experiment designed to confirm the multipolarity and determine the electric or magnetic character of transitions in the region of the PSF enhancement in ^{56}Fe was performed at ATLAS/ANL using GRETINA and the Phoswich Wall

[8]. A 16 MeV proton beam was used to inelastically excite an ^{56}Fe target to the quasicontinuum where it promptly decayed by γ-ray emission. The PSF can be extracted using two-step cascades from the quasicontinuum to specific low-lying levels by a model independent method first employed in ^{95}Mo [9]. This method is being extended to take advantage of GRETINA as a polarimeter to obtain angular and polarization information in the region of the low-energy enhancement of the PSF. Preliminary results will be discussed.

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[2] A. Simon *et al.* Phys. Rev. C 93, 034303 (2016).

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Microscopic calculations of the photon strength functions in magic and semi-magic nuclei.

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The photon strength functions (PSF) in many magic and semi-magic nuclei are calculated and predicted within the microscopic self-consistent version of the extended theory of finite Fermi systems in the quasiparticle time blocking approximation. In addition, the microscopic PSFs are calculated within the fully self-consistent method with exact accounting for the single-particle continuum which has been developed recently for double-magic nuclei. Both methods are of great predictive power and take into account the phonon coupling (PC) and usual quasiparticle random phase approximation effects. The Skyrme forces with known universal parameters are used so that both the HFB mean field and effective interaction between nucleons are calculated self-consistently. The characteristics of nuclear radiative reactions are calculated with our microscopic PSFs. Our main conclusion is that the contribution of the PC effects turned out to be significant both in magic and semi-magic nuclei and is found necessary to explain available experimental data [1, 2, 3].

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The Radiative Width of The Hoyle State From Cascading γ-Ray Measurement

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The excited state of the ^{12}C nucleus known as the “Hoyle state”, constitutes one of the most interesting, difficult and important challenges in nuclear physics, as it plays a key role in the production of carbon via fusion of three alpha particles in red giant stars. In this paper we report on a new measurement of the Γ_γ/Γ ratio of the 7.654 MeV 0^+ state, which together with the world data on $\Gamma_\pi(E0)/\Gamma$ and $\Gamma_\pi(E0)$ was used to determine the radiative width, Γ_{rad}, of the Hoyle state.

The experiment was carried out at the Oslo Cyclotron Laboratory. The Hoyle state was populated using the $^{12}C(p,p')^{12}C$ reaction at 10.7 MeV energy using a 180 $\mu g/cm^2$ thick natural carbon target. Cascade gamma-rays of E2 multipolarity and at energies of 3.215 MeV and 4.439 MeV were observed using the CACTUS array [1], consisting of twenty-six 5” by 5” NaI detectors. Scattered protons in singles and in coincidence with γ-ray cascades were recorded with the Silicon Ring (SiRi) array [2] consisting eight DE-E telescopes, where the front detector is segmented into eight strips. A total of 2.56×10^8 singles proton events leading to the excitation of the Hoyle state were observed in an 11 day run. The number of $p\gamma\gamma$ events involving the 3.215 MeV and 4.439 MeV γ-rays was 529(23). The observed angular correlation of the events is consistent with a 0-2-0 cascade.

This talk will focus on the analysis of the data and will compare our results with the only previous measurement performed by Obst and Braithwaite more than 35 years ago [3]. This study complements our project to determine the radiative width from pair conversion measurement of the E0 and E2 transitions de-exciting the Hoyle state [4].

We thank the Oslo Cyclotron laboratory for the support and hospitality during the experiments. We also thank Hilde-Therese Nyhus (University of Oslo) for her help. TK and AES would like to acknowledge the financial support of the Australian Research Council, grant number DP140102986.

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Nuclear Level Density and Gamma Strength from Quasi-Continuum Lifetimes with GRETINA

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This talk explains a new experimental method to determine the absolute magnitude and energy dependence of the $\gamma-$strength function employing an extension of the doppler shift attenuation method in ^{56}Fe(p,p') using the GRETINA array coupled to a fast phoswich particle detector. The Gamma Ray Energy Tracking Inbeam Nuclear Array (GRETINA) is an 1152-segmented germanium detector array that has the capabilites to extract quasicontinuum lifetimes (QCτ) from miniscule shifts in doppler shift as a function of outgoing particle energy.

High resolution $\gamma-$ray spectroscopy provides access to lifetimes of discrete nuclear excited states via changes in $\gamma-$ray energy with angles respect to the intial nuclear recoil vector. Gates on the outgoing particle energy isolate events where decay from the QC precedes a low lying discrete transistion. This gives the recoiling excited nucleus more time to slow down and reduces doppler shift of subsequent $\gamma-$rays. The relationship between QCτ and $\gamma-$strength complements both the traditional Oslo method [1] and the two-step cascade method developed by Wiedeking et al. [2].

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Improved Neutron Capture Cross Sections, Level Densities, and γ-ray Strength Functions via Total-Cross-Section Measurements at the Los Alamos Neutron Science Center

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Neutron total-cross-section (σ_t) measurements are feasible on a much wider range of radioactive samples than (n,γ) cross-section measurements, and information extracted from the former can be used to set tight constraints on the latter. In addition, when level densities and γ-ray strength functions derived from, for example, the Oslo technique exist, they can be more accurately calibrated using average level spacings and total γ-ray widths resulting from σ_t data. Taken together, the σ_t and Oslo data can even more tightly constrain (n,γ) cross sections. There are many (n,γ) cross sections of great interest to radiochemical diagnostics, nuclear forensics, and nuclear astrophysics which are beyond the reach of current direct measurement that could be obtained in this way. Our simulations [1, 2] indicate that measurements on at least 40 high-interest nuclides can be made at the Manuel Lujan Jr. Neutron Scattering Center at the Los Alamos Neutron Science Center (LANSCE) for samples as small as 10 μg. Exploratory measurements were made at LANSCE in February 2016 and, with an improved apparatus, in December 2016 – January 2017. I will describe the technique, proof-of-principle simulations, and the first test data.

[1] P. E. Koehler, *Total Cross Sections as a Surrogate for Neutron Capture: An Opportunity to Accurately Constrain (n,γ) cross Sections for Nuclides Beyond the Reach of Direct Measurements*, Los Alamos National Laboratory report LA-UR-14-21466;

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Radiative strength functions and population of isomers in deformed nuclei from (n,γ) reaction

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Gamma-ray spectra from radiative neutron capture serve as important source of information on radiative strength functions. The information on these quantities is deduced from comparison of experimental spectra with simulations based on statistical model of γ decay under different assumptions on radiative strength functions and level density. This approach does not necessarily finds the best models but serves as a verification of validity of different models.

In this contribution the application of the above-described approach is applied on getting information on radiative strength functions in well-deformed nuclei ^{162,164}Dy and ^{168}Er. Experimental γ-ray spectra from s-wave individual neutron, that are compared to simulations, were measured with the DANCE detector at Los Alamos National Laboratory.

In ^{168}Er there is an isomeric state (K-isomer) with its half-life of about 100 ns. Similar isomeric states can be found also in other deformed nuclei (like ^{236}U). Population of these isomeric states from radiative neutron capture can be often well checked with the DANCE detector. It shows up that actual population of such isomeric states in ^{168}Er and ^{236}U is significantly higher than the population predicted by the statistical model calculations. This fact indicates that some features of the γ decay are not correctly treated in simulations. The observed deficiency in simulation likely comes from complete ignoring the quantum number K in deformed nuclei, especially at relatively low excitation energies.

Experimentally constrained ^{73}Zn(n,γ)^{74}Zn reaction rate

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Modeling astrophysical processes, such as the r-process, requires information about both the location of where the process is taking place and the nuclear physics that govern the reactions. Neutron capture rates are important inputs in astrophysical models but are not well known for the very neutron-rich nuclei that are involved in the r-process. Theoretical predictions of neutron capture cross sections for these nuclei can vary by orders of magnitude, and the ability to experimentally constrain these values is limited to indirect methods due to the short half-lives of the nuclei of interest. Cross sections can be obtained by using statistical properties of the compound nucleus of interest—the nuclear level density (NLD) and gamma strength function (γSF)—extracted from experiments and used as input in a Hauser-Feshbach statistical model. The indirect Oslo method was developed to extract these properties from reaction-based experiments. It was followed by the more recent β-Oslo method, which extends our experimental reach to short-lived nuclei by using β decay to populate highly excited levels in the nuclei of interest. Experiments at the National Superconducting Cyclotron Laboratory use a segmented total absorption spectrometer (the Summing NaI (SuN) detector), which provides information on both total excitation energy and individual gamma-ray energy of the daughter nucleus. The β-Oslo method has been used to reduce the uncertainty in neutron capture cross sections for the nuclei ^{50}Ti, ^{75}Ge, and ^{68,69}Ni from orders of magnitude to under a factor of two. Recently the NLD and γSF of ^{74}Zn were extracted from the β decay of ^{74}Cu and used to constrain the ^{73}Zn(n,γ)^{74}Zn cross section.

Validating the β-Oslo technique for neutron capture rates far from stability

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Neutron capture rates on short-lived rare isotopes are required input into a number of physical processes; one such example is the astrophysical r-process. Our inability to directly measure a neutron capture rate for exotic isotopes stems from the lack of both a sufficiently large target of short-lived decaying nuclei and a suitable neutron beam. These deficiencies necessitate the development of indirect approaches. One such indirect approach, the so-called β-Oslo method, an adaptation of the traditional Oslo method, seeks to simultaneously infer the nuclear level densities and γ-ray strength functions of a particular nucleus following beta decay to highly excited states. The two quantities are then used as an input into statistical reaction model calculations to constrain the neutron capture rate in exotic nuclei. A number of nuclei have been studied using the β-Oslo technique including ^{51}Ti, ^{69,70}Ni [2, 1], ^{76}Ge [3], and ^{74}Cu. The β-Oslo technique will be described and the validation measurement on ^{51}Ti will be discussed along with comparisons between the results obtained from beta-decay and reactions..

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Nuclear level densities and gamma-ray strength functions of ^{180,181,182}Ta and neutron capture cross sections

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Most stable and extremely low abundance proton-rich nuclei with A>110 are thought to be produced by the photodisintegration of *s*- and *r*- process seed nuclei. However, this so-called *p*-process is insufficient to explain the observed low abundance (0.012%) of the ^{180}Ta isotope. Hence combinations of several processes are considered to reproduce the observed abundance of ^{180}Ta in the cosmos, provoking debates and making it a unique case study. Significant uncertainties in the predicted reaction rates in *p*-nuclei arise due to large uncertainties in nuclear properties such as the nuclear level densities (NLD) and gamma-ray strength functions (γSF) [1], as well as the actual astrophysical environments. An experiment was performed in October 2014 to extract the γSF and NLD below the neutron threshold in ^{180,181,182}Ta isotopes which provide important input parameters for nuclear reaction models. In the present case study, these parameters were measured using the ^{181}Ta(^{3}He, ^{3}He'γ) and ^{181}Ta(^{3}He, ^{4}Heγ) reactions with 34MeV beam, ^{181}Ta(d, d'γ) and ^{181}Ta(^{3}He, tγ) reactions with 15MeV beam , and ^{181}Ta(d, d'γ) and ^{181}Ta(d, pγ) reactions with 12.5 MeV beam at the Oslo Cyclotron Laboratory. Using the SiRi array at backward angles (64 silicon particle telescopes) and the CACTUS array (26 NaI(Tl) detectors), the NLD and γSF were simultaneously extracted below the neutron separation energy from particle-γ coincidence matrices through iterative procedures using the Oslo method [2]. The experimental results have been used to determine the corresponding neutron capture cross sections, which in turn were utilized to extract Maxwellian averaged cross sections. The latter can be used in astrophysical network calculations to investigate the galactic production mechanism of ^{180}Ta. In this talk I will present results of this investigation of statistical properties for ^{180,181,182}Ta and the corresponding (n,γ) cross sections.

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Addressing Nuclear Data Needs with FIER

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The Fission Induced Electromagnetic Response (FIER) code has been developed to predict delayed gamma-ray spectra following fission of nuclei with evaluated independent yield libraries. FIER calculates the time-dependent populations of fission products arising from a user-specified irradiation of a fissionable isotope using evaluated nuclear data libraries and solutions to the Bateman equations. The resulting populations provide the beta-delayed gamma-ray activity of each fission product. The predictions of FIER were benchmarked against an experiment performed where a U-235 sample was irradiated in the Godiva critical assembly. While FIER generally agrees with the experimental results, discrepancies between the time-dependent FIER output and the experimental data show the utility of the code to highlight deficiencies in the underlying nuclear data. Methods by which to improve existing nuclear data libraries are explored.

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Statistical nuclear reaction uncertainties important for the astrophysical *rp* and α processes

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Explosive astrophysical phenomena often involve complex networks of thousands of nuclear reactions which impact the energy release and nucleosynthesis of these scenarios. Many of these reactions are presently beyond the capabilities of direct measurement techniques, but are believed to be in the regime of validity for statistical nuclear reaction rate calculations. However, reaction rate predictions from statistical models can vary by an order of magnitude or more depending on adopted input parameters, leading to large changes in astrophysics model calculation results. Here I will focus on uncertainties in reaction rate calculations of (p, γ) reactions for the astrophysical *rp*-process and of (α, n) reactions for the astrophysical α-process. I will discuss the implications these uncertainties have for astrophysics model calculations of Type-I X-ray bursts and of core collapse supernova nucleosynthesis. I will also discuss near-future measurement plans to remedy some of the most pressing uncertainties and highlight where future measurements are needed.

Studies of Nuclear Statistical Properties with the Nuclear Shell Model

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In recent years, an unexpected increase in the γ strength function for low E_γ has been observed experimentally in several fp shell [1, 2, 3] and medium-mass [4, 5] nuclei. Since its initial discovery more than ten years ago [1], it remained controversial until it was verified with independent experimental techniques a few years back [5]. It is known that the radiation forming the *upbend*, as it has been dubbed, is of dipole character. However the electromagnetic nature (*i.e.* E1 or M1) of the radiation, and thus the underlying physical explanation for it, remains elusive.

Successful attempts have been made using the nuclear shell model to reproduce the experimentally observed upbend in ^{56,57}Fe [6] and ^{94,95,96}Mo [7] as M1 transitions. It remains to see if this explanation holds also for other nuclei, including exotic, neutron-rich ones. In this talk we will present our work on using the shell model to study the M1 transitions in ^{70}Ni, a neutron-rich nucleus where the upbend has recently been found experimentally to be present [8].

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Absence of rotational collectivity in a large number of fission excitation functions

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We have looked for collective rotational enhancement and its disappearance in a large number of fission excitation functions of spherical and deformed ground state nuclei. All nuclei at the saddle point are substantially deformed and their level density should present collective rotational enhancement, while nuclei after neutron emission should present collective rotational enhancement only if they are deformed in their ground states.

The corresponding fission excitation functions, which depend on the ratio of fission and neutron widths, should manifest a difference between spherical and deformed ground state nuclei.

We have measured the fission excitation functions of many nuclei near the Pb doubly magic region and in the deformation region immediately below it, from about 3MeV above the barrier to about 100 MeV. This range of excitation energies should allow for the appearance and disappearance of collective enhancement. A detailed analysis of the data does not show any difference between deformed and spherical nuclei, casting doubts on the very existence of collective enhancements.

Level densities and γ strength functions in modeling neutron interactions with iron isotopes

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We discuss the role and experimental constraints of level densities and gamma strength functions on the modeling of neutron induced reactions on isotopes of iron. We demonstrate that exceptionally high sensitivity of the ^{56}Fe(n,p) reaction to level densities can be used to test various formulations of level densities used in the Hauser-Feshbach model. Different level-density models and parametrizations were tested, including microscopic models that simulate experimentally-measured level densities. The role of spin and parity distributions in level-density modeling is also investigated. After careful analyses we compare the different levels of agreement of calculated cross sections with experimental data corresponding to such models. Additionally, we compare our calculated gamma cross sections following inelastic neutron scattering with experimental results. We point out that such data are sensitive to the details of decay schemes, which may often be unknown. At the same time these data can be used to extract strength of the direct reaction contribution to specific high lying levels. We present such comparisons as means to extract nuclear structure information, such as level spin, parity and deformation, directly

from cross-section data [2]. This study is a part of the major international effort CIELO, which aims to reevaluate the five most important isotopes including ^{56}Fe [1].

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Investigation of Scissors Resonance in ^{145,149,151}Nd

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γ-ray strength functions (GSFs) are essential ingredients of statistical nuclear reaction theory with many applications in astrophysics, reactor design, and waste transmutation. The γ-ray strength functions have been obtained via the Oslo method for ^{145,149,151}Nd isotopes below the neutron separation energies with the ^{144,148,150}Nd(d,p) reactions, by using the least square method on primary gamma matrix. The properties of the scissors resonance parameters in neodymium isotopes will be discussed using the experimental γ-ray strength functions.

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Investigating the Pygmy Dipole Resonance in deformed nuclei

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The study of the Pygmy Dipole Resonance (PDR), the low energy part of the electric dipole response in nuclei, is particularly relevant to investigate the nuclear structure and for its connections with photo-disintegration reaction rates in astrophysical scenarios [1, 2, 3].
Studies of the PDR are currently almost exclusively focused on spherical nuclei. Only a few measurements have been performed in deformed nuclei so far [4, 5]. These measurements showed the presence of a double-hump structure of the PDR similar to the one observed in the GDR for these deformed nuclei.
To investigate in more detail what is the contribution of the deformation to this excitation mode, an $(\alpha,\alpha'\gamma)$ experiment was performed at iThemba LABS in October 2016. The pygmy states in the deformed ^{154}Sm nucleus were excited by inelastic scattering of α-particles at 120MeV. The scattered particles were detected by K600 magnetic spectrometer, while the subsequent gamma decay was measured by the BaGeL (Ball of Germanium and LaBr detectors) array. This experiment was the first measurement that made use of this particle-γ coincidence setup at iThemba LABS. Preliminary results of the analysis will be presented.

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Test of Recent Expressions for Photon Strength Functions

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The global semiphenomenological models (SLO- Standard Lorentzian, MLO-Modified Lorentzian, TLO - Triple (triaxial) Lorentzian)[1-5] for the calculations of the E1 photon strength functions (PSF) in atomic nuclei are tested. The photon strength functions are calculated using renewed GDR parameters and are compared with all data for gamma-absorption and gamma-decay presented in the EXFOR database. New analytical approach with excitation of two states (TSE model)[6] for calculation of electric dipole PSF is discussed and tested. The TSE expression of the PSF includes response of two coupled nuclear states - low-energy state (LES) and GDR. In spherical nuclei, the LSE corresponds to the pygmy dipole resonance (PDR). Expression for the nuclear response function on electromagnetic field is based on model of excitation of two coupled damped states. The calculations within this approach (TSE model) are compared with that for microscopic calculations and available experimental data for photoabsorption cross-sections in the spherical atomic nuclei. The input parameters for the calculations were fixed by the use of the experimental data. It was shown, that TSE model much better describes the microscopic calculations then SLO approach. On the whole, TSE model is a simple approach to account for low energy enhancement due to LES excitation. Allowance for coupling between low and high energy modes leads to better description of the experimental data and microscopic calculations, specifically at energies below the neutron threshold, in comparison with situations of independent modes. Therefore, TSE approach can also provide more accurate determination of the resonance parameters (both PDR and GDR). The work is supported in part by the IAEA (Vienna) under IAEA Research Contract within CRP No.F41032.

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Fission Dynamics with Microscopic Level Densities

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Within the Langevin framework of nuclear shape dynamics, we study the dependence of the fission evolution on the degree of excitation. As the energy of the fissioning system is increased, the pairing correlations and the shell effects diminish and the effective potential-energy surface grows ever more liquid-drop like. This feature can be included in the treatment in a formally well-founded manner by using the local (*i.e.* shape-dependent) level densities as a basis for the shape evolution. This is particularly easy to understand and implement in the Metropolis treatment [1] where the evolution is simulated by means of a random walk on the five-dimensional lattice of shapes for which the potential energy has been tabulated [2]. Because the individual steps between two neighboring lattice sites are decided on the basis of the ratio of the associated statistical weights, what is needed is the ratio of the level densities for those shapes, evaluated at the appropriate local excitation energies.

For this purpose, we have adapted a recently developed combinatorial method for calculating nuclear level densities [3] which employs the same single-particle levels as those used for the extraction of the pairing and shell contributions to the macroscopic-microscopic potential-energy surfaces. For each nucleus under consideration, the level density (for a fixed total angular momentum) is calculated microscopically for each of the over five million tabulated three-quadratic-surface shapes. This novel treatment [4], which introduces no new parameters, provides detailed insight into the effects of the shape-dependent nuclear structure on the fission paths and it is illustrated for fragment mass distributions from fission of several thorium, uranium, and plutonium isotopes.

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Isomeric ratio measurements for the radiative neutron capture ^{176}Lu(n,γ) at DANCE

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Neutron capture cross sections are of high interest in nuclear astrophysics to investigate the s-process in which the synthesis of heavy elements is dominated by neutron induced reactions. In this context, partial cross sections feeding the ground states or isomers are particularly crucial in certain cases of the s-process nucleosynthesis. From first studies on isomeric states, the isomeric ratio, defined as the ratio of isomeric over total cross sections, was always seen as a pertinent parameter to characterize the gamma-ray cascade following the decay of the compound nucleus state. Parameters required to evaluate the neutron capture cross sections as the spin distribution of the compound nucleus, the level density, the gamma strength function can be set by means of isomeric ratio measurements. The isomeric ratios for the neutron capture reaction ^{176}Lu(n,γ) on the $J^{\pi}=5/2^{-}$, 761.7 keV, $T_{1/2}=32.8$ ns and the $J^{\pi}=15/2^{+}$, 1356.9 keV, $T_{1/2}=11.1$ ns levels have been measured using the DANCE array at LANL [1]. The detection efficiencies were determined with GEANT4 simulations and γ-cascades obtained with the Hauser-Feshbach code EVITA, based on the TALYS code and developed at CEA. To reproduce the experimental γ-ray spectra, it was needed to add a resonance at low energy in the photon strength function using in EVITA. This is a confirmation of a recent result [2, 3]. A discussion will be done about the nature of the resonance. The effect of this added resonance was studied using the TALYS code. We found that with a coherent radiative width and this resonance in the gamma strength function, the evaluated capture cross section reproduces well the experimental one with any normalization as it was found for ^{238}U[4]. The experimental isomeric ratios are also compared with calculated ones with the TALYS and EVITA codes. In these calculations, we have tested several models of nuclear level density and optical potential in order to reproduce the data. Discrepancies are found and will be discussed. Finally, these important results for nuclear data stimulate us to look at this effect for several neutron resonances. Some preliminary results on this second experiment performed at DANCE will be presented.

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Investigation of radiative proton-capture reactions using high-resolution g-ray spectroscopy

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Nuclear reaction cross sections are one of the main ingredients for the understanding of nucleosynthesis processes in stellar environments. For isotopes heavier than those in the iron-peak region, reaction rates are often calculated using the Hauser-Feshbach statistical model. The accuracy of the predicted cross sections strongly depend on the uncertainties of the nuclear-physics input-parameters. These are nuclear-level densities, γ-strength functions, and particle+nucleus optical-model potentials.

The precise measurement of total and partial reaction cross sections at sub-Coulomb energies are used to constrain or exclude different nuclear-physics models. Especially the comparison of partial cross-section to predictions from the statistical-model can yield valuable information on the γ-ray strength function [1].

This talk is going to present recent experiments performed at the Cologne 10 MV FN-Tandem accelerator and the high-efficiency HORUS γ-ray spectrometer. Results for cross-section measurements of ^{92}Mo(p,γ) [2] and ^{107}Ag(p,γ) reaction will be presented.

More over, preliminary results of proton-capture studies applying the method of two-step cascades [3, 4] for the ^{63}Cu(p,$\gamma\gamma$) and ^{65}Cu(p,$\gamma\gamma$) reactions will be shown.

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E1 and M1 excitations in ^{54}Fe and low-energy M1 strength in open-shell Fe isotopes

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We present data for dipole excitations in the $N = 28$ nuclide ^{54}Fe studied in photon-scattering experiments using bremsstrahlung at the γELBE facility of Helmholtz-Zentrum Dresden-Rossendorf and using quasi-monoenergetic, polarized γ beams at the HIγS facility of the Triangle Universities Nuclear Laboratory in Durham. We identified intense E1 as well as M1 transitions to spin-1 states up to about 10.6 MeV. The relation between the E1 and M1 strength distributions differs from that observed in heavy nuclei [1, 2].

In the second part, we present low-energy M1 strength functions of ^{60,64,68}Fe determined on the basis of large-scale shell-model calculations with the goal to study their development from the bottom to the middle of the neutron shell [3]. We find that the zero-energy spike, which characterizes nuclei near closed shells [4, 5], develops toward the middle of the shell into a bimodal structure composed of a weaker zero-energy spike and a scissorslike resonance around 3 MeV, where the summed strengths of the two structures change within only 8% around a value of 9.8 μ_N^2. The summed strength of the scissors region exceeds the total γ absorption strength from the ground state by a factor of about three, which explains the discrepancy between total strengths of the scissors resonance derived from (γ, γ') experiments [6] and from experiments using light-ion induced reactions [7, 8].

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Magnetic and electric dipole strength at low energy.

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A low energy enhancement of radiative strength functions has been deduced from recent experiments in several mass regions of nuclei [1, 2], which is believed to alternate considerably the resulting neutron capture cross sections [3]. The nature of this enhancement is not well understood and theoretical models (shell-model and QRPA) do not agree in their predictions of the behavior of the low energy strength [4, 5, 6].

In this contribution I will present large-scale shell model calculations for the low energy magnetic and electric dipole strength in several nuclei, calculated consistently in the same theoretical framework. The nature of the enhancement will be discussed and the results compared to existing global models of radiative strength functions. The differences between SM and QRPA results will be also addressed.

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A pygmy quadrupole resonance in the stable Sn isotopes

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An extensive experimental study of the recently predicted pygmy quadrupole resonance (PQR) in the stable even-even Sn isotopes [1] will be presented. In this study, $(\alpha,\alpha'\gamma)$ and (γ,γ') experiments were performed on ^{124}Sn [2] as well as lifetime measurements in ^{112,114}Sn using the recently established $(p,p'\gamma)$ Doppler-shift attenuation (DSA) coincidence technique [3]. In all experiments, $J^\pi = 2^+$ states below an excitation energy of 5 MeV were populated. The $E2$ strength integrated over the full transition densities could be extracted from the (γ,γ') and the $(p,p'\gamma)$ DSA experiments, while the $(\alpha,\alpha'\gamma)$ experiment at the chosen kinematics strongly favors the excitation of surface modes because of the strong α-particle absorption in the nuclear interior. The excitation of such modes is in accordance with the quadrupole-type oscillation of the neutron skin predicted by a microscopic approach based on self-consistent density functional theory and the quasiparticle-phonon model (QPM). The newly determined γ-decay branching ratios hint at a non-statistical character of the $E2$ strength, as it has also been recently pointed out for the case of the pygmy dipole resonance (PDR). This allows us to distinguish between PQR-type and multiphonon excitations and, consequently, supports the recent first experimental indications of a PQR in ^{124}Sn [2, 4].

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Neutron captures far from stability and astrophysical applications

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Approximately half of the isotopes of the heavy elements are created by the rapid neutron-capture process (r process). The r process was proposed more than 60 years ago, and although its general characteristics are well understood, there are still major questions associated with it. Probably the most important question has to do with the astrophysical site of the r process, which has not yet been determined. This is partly due to uncertainties related with the astrophysical modeling itself, but also due to uncertainties in the nuclear input. Masses, β-decay half-lives, β-delayed neutron emission probabilities, and neutron capture reaction rates are the main nuclear properties needed in r-process calculations. Of these, neutron capture reactions are the least constrained due to the complete lack of experimental data along (or even close to) the r-process path. This talk will present first results using the newly developed β-Oslo method far from stability. This method combines β-decays with the traditional Oslo method to populate the compound nucleus of interest and extract nuclear level densities and γ-ray strength functions. These experimental quantities are then used as input in statistical model calculations to extract the (n,γ) reaction cross section and investigate their impact in r-process calculations.

Relativistic Quasi-particle Random Phase Approximation (RQRPA) and Photon Strength Functions (PSF)

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It has been shown in several applications that Relativistic Quasiparticle Random Phase Approximation (RQRPA) provides an excellent tool for the description of the multipole response of stable as well as of unstable and weakly bound nuclei far from stability. These investigations have been devoted to low-lying collective excitations [1], to giant resonances [2], to spin-isospin resonances [3], and to new exotic modes in stable [4] and unstable nuclei [5]. In this article, We have computed dipole strength distributions for Zirconium(Zr) and Tungsten(W) isotopes within RQRPA. In the ph-channel we use effective RMF Lagrangian. In the pairing channel we use a separable pairing interaction [6, 7]. These calculations provide a good description of data.

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Recent developments in neutron capture on actinides using the DANCE detector

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Neutron-capture cross sections and cascade gamma-ray spectra have been measured for several actinide nuclides, including ^{233,234,235,236,238}U(n,γ) and ^{238,239,242}Pu(n,γ), using the DANCE 4π gamma-ray detector at Los Alamos. Neutron energies ranged from thermal to approximately 100 keV. A fission-tagging parallel-plate avalanche counter was used to identify fission events for fissile nuclides. Calculations of the gamma-ray cascade spectra were made using the DICEBOX code, and can be used to constrain the photon strength function. Calculations of the capture cross section were made using the CoH$_3$ code. For ^{234,236,238}U(n,γ), a structure consistent with the M1 scissors-mode resonance was required to reproduce the gamma-ray spectra. This is consistent with results from Oslo and other measurements. Using this photon strength function, the calculated cross sections in the continuum region were in very good agreement with our measurements. We will present additional results of current measurements and data analysis.

Statistical Properties of Nuclei Far from Stability for National Security Applications

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The yields of fission products can be altered by neutron capture in the high neutron flux of a nuclear device explosion. In this work, the neutron capture cross section of the short-lived fission product ^{92}Sr will be determined from a measurement of statistical nuclear properties. These data represent the first measurement of this quantity and provide a constraint on regional systematics to guide predictions of the ^{95}Sr capture cross section, an important diagnostic tool for supporting the stockpile stewardship mission. Since ^{93}Sr can not be measured from the neutron capture reaction experimentally, it will be produced by the β decay of ^{93}Rb. The γ-ray cascade from ^{93}Sr excited states will be studied to determine the initial excitation energy using the Summing NaI (SuN) detector. From the measurement of the γ-ray cascade, the nuclear level density (NLD) and γ-ray strength function (γSF) can be extracted using the β-Oslo method, which was first successfully applied to infer the ^{75}Ge(n,γ) [1] and the ^{69}Ni(n,γ) cross sections [2].

At the National Superconducting Cyclotron Laboratory (NSCL), a low-energy beam of ^{93}Rb will be delivered onto a moving tape collector in the borehole of SuN. In addition, a simulated data set of γ rays emitted by the ^{93}Sr nucleus was generated with the Monte Carlo code DICEBOX so as to predict the experimentally-observed behavior. The simulated data set was generated with an *a priori* NLD and γSF model combination to verify if the γSF obtained agrees with the predetermined behavior.

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Gamma-ray strength functions and a new dimension of partial GDR cross section measurements

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The γ-ray strength function (γSF) is directly connected to the photo-absorption cross section. The upward γSF determines (γ, n) cross sections, while the downward γSF determines (n, γ) cross sections. Thus, one can apply the γSF method to isotopic chains based on the Brink hypothesis of the equality of the upward and downward γSFs to determine (n, γ) cross sections for radioactive nuclei [1, 2].

The (γ, n) cross section provides an absolute normalization to the γSF below neutron threshold. Putting together experimental data acquired with different methods like the nuclear resonance fluorescence and the Oslo method, one can investigate γSF. Research along this line constitutes a new CRP (Coordinated Research Project) F41032 of generating a reference database of photon strength functions by the IAEA (International Atomic Energy Agency) [3].

Having faced the *historical discrepancy* between the Livermore and Saclay data of partial GDR cross sections, the IAEA CRP-F41032 was launched to update the photonuclear data library (IAEA-TECDOC-1178) published in 2000 [4]. Our mission in the CRP is to resolve the discrepancy by providing new experimental data with a novel methodology of direct neutron-multiplicity sorting [5].

The latest develpments are presented.

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Study of Photon Emission with the Fission Event Generator `FREYA`

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The event-by-event fission model `FREYA` [1] is employed to study photon observables. The model has been expanded beyond the simple statistical photon emission reported in Ref. [2] to include the discrete RIPL-3 lines. We update the results of Ref. [2] and discuss the sensitivity of the results to the `FREYA` input parameters.

We also show calculations of the photon energy and multiplicity as a function of excitation energy for ^{233}U(n,f) and ^{239}Pu(n,f).

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Spin cutoff studies from ^{6,7}Li and α-induced reactions

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The spin cutoff parameter determining the spin distribution in nuclei appears to be a central problem in the level density studies and it is also the key parameter used for absolute normalization of level density and γ-strength functions deduced from Oslo experiments. Therefore it is important to study it experimentally using a technique which would be independent from the technique of level density studies used in Oslo.

In this work measurements of proton and neutron evaporation spectra have been analyzed from (^{6,7}Li, p) and (α, n) reactions on iron isotopes. These lead to information on $^{57,59-64}$Ni isotopes. Both level density parameters and spin cutoff values (σ) have been inferred. σ values have been deduced from both (α, n) angular distributions and from comparing total level densities with binding energy resonance counts. These will be compared with compilations and with new microscopic calculations.

Tests of the Brink-Axel Hypothesis with High-Resolution Small-Angle Inelastic Proton Scattering

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Polarized proton scattering at energies of a few 100 MeV and extreme forward angles including 0° has been established as a tool to extract the complete $E1$ response in nuclei up to excitation energies of about 20 MeV. In particular, this method provides information on the poorly determined $B(E1)$ strength below and around neutron threshold in heavy nuclei [1-4]. One can also extract the spin-$M1$ resonance and the analog $B(M1)$ strength [5] and from the combined information on $B(E1)$ and $B(M1)$ the gamma strength function [6]. The high energy resolution achieved in the experiments additionally allows to extract level densities in the energy region of the GDR with a fluctuation analysis [7]. The combined information allows tests of the Brink-Axel hypothesis in the astrophysically relevant energy region of the pygmy dipole resonance by comparison with results of Oslo-type experiments in the same nucleus.

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Spin Distribution of Excited Nuclear States in $^{\mathrm{nat}}$Fe(p,αn)

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A series of stacked target thin-foil activation experiments have been conducted at the LBNL 88-Inch Cyclotron, as part of a larger campaign to address deficiencies in cross-cutting nuclear data needs. While these efforts have been targeted towards the production cross section of the ^{51,52}Mn PET isotopes (as well as other emerging medical radionuclides), these measurements offer insight into the spin distribution of excited nuclear states, in the 10 - 55 MeV range.

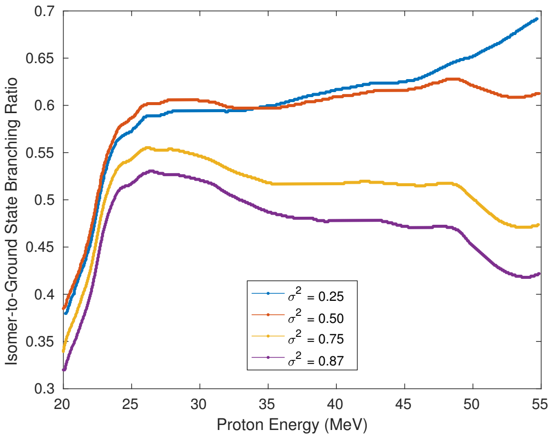

Figure 2: ^{52m}Mn (2^+) / ^{52g}Mn (6^+) for ^{56}Fe(p,αn). These curves have been calculated using TALYS-v1.8, for various values of the spin cut-off parameter σ^2.

Figure 2 shows the ^{52m}Mn (2^+) / ^{52g}Mn (6^+) isomer-to-ground state branching ratio for the ^{56nat}Mn(p,αn) reaction, calculated using TALYS-v1.8 over the 20 - 55

MeV range spanned by the foil stack. It is thus possible to infer the spin cut-off parameter σ^2, the width of the angular momentum distribution of the level density, and, by extension, measure the level density parameters a and $\tilde{a}$ [1, 2].

In addition, the isomer-to-ground state ratio provides insight into the validity of various level density models predict the observed branching ratios. Lastly, measurements of the branching ratio from our foil stacks can be used to infer the angular momentum imparted to the reaction products, thereby lending insight into the equilibrium / pre-equilibrium nature of reactions in this energy region.

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Evaluation of Photonuclear Reaction Cross Sections for ^{90}Zr

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The photonuclear data are very important for radiation damage, radiation safety, reactor dosimetry, accelerator shielding and radiation therapy etc. A new program has been developed at CNDC to perform the photonuclear reaction. In this work, the avilable experimental data of photonuclear reaction cross sections for ^{90}Zr were analysed, and the theoretical calculation were performed. The recommended photonuclear data for ^{90}Ze were obtained on analysed and calculated data, and compared with the existing measured data.

Spectroscopy of prompt fission decay processes induced with fast directional neutrons

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At the IPN Orsay we have recently developed an unusual kind of neutron source which produces high fluxes of directional fast neutrons. The directionality is achieved by using nuclear reactions which produce neutrons in inverse kinematics assuring that neutrons are emitted in focussed cones. Standard neutron sources emit neutrons almost isotropically and so the natural directionality of the source, which we call LICORNE, opens up a whole range of new scientific opportunities. This presentation will describe the kind of fundamental and applied physics that can be performed with such a source – a physics program under development at the IPN. These include the high resolution spectroscopy of fast neutron induced nuclear reactions, the study of nuclear fission, the production and study of exotic neutron-rich nuclei. Of particular relevance are the recent results obtained on prompt gamma ray emission in the fission process, where models which reproduce the statistical neutron and gamma decay of the hot fission fragments require accurate level density information to reproduce spectral shapes.

Photonuclear data evaluation at China Nuclear Data Center

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The new program is developed at CNDC to perform the assignment of photonuclear data evaluation in the recent Co-ordinated Research Project (CRPF41032) ”Updating the photonuclear data library and generating a reference database for Photo Strength Functions”. Firstly, the GMEND code is updated recently to calculate the contribution of pre-equilibrium and compound nuclide process for the gamma induced reactions. The present maximum of E_γ in GMEND reaches 200 MeV to fulfill the requirement of CRPF41032. Besides, we have developed the optimization codes based on Miniut by CERN to get the good parameters automatically. In order to achieve the reasonable gamma absorption cross sections, we incorporate several approaches including the microscopic QRPA calculation and other empirical formula based on the Lorentz functions to consider the E1 giant dipole resonance contribution to the desired (γ, abs) cross sections. In addition, the experimental data are also evaluated a little to guide the present calculations. So far, we have performed the photonuclear data evaluation for isotopes of W, Zr and Cr, and parts of the results and analysis will be presented in this presentation.

A new approach to estimate spin distributions & fitting the gSF: Finally the end of the many parameter nightmare?

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Nuclear level densities (NLD) and γ-ray strength (γSF) functions are essential quantities in various fields of basic and applied research involving nuclear matter. From microscopic calculations and structure research to nuclear reactor models and astrophysical applications a good knowledge of these parameters determines fundamental properties of the systems.

The current state of approaches to two challenges encountered in the extraction of the NLD and γSF using the Oslo Method will be presented. We will focus on the extraction of the results for ^{240}Pu in the quasi-continuum, that have been extracted from the (d,p) reaction – however it is expected that the approaches are of general applicability and interest.

Aspect 1: Spin Distributions

The Oslo Method used data from surrogate reactions, oftentimes (d,p), to simultaneously extract the nuclear level density (NDL) and gamma-ray strength function (gSF) of the residual nucleus. In the extraction procedure we need to make an assumption on the spin distribution of the nucleus. This is a challenge in itself. However, with light ion reactions, and in particular (d,p) we may not populate the high spins present in the nucleus. We attempt to estimate and quantize the effect of this. The calculations of the spins populated in the (d,p) are based on the non-elastic part of the deuteron breakup cross section, using within the distorted-wave Born approximation. We will present the current states of the calculations and problems we still face in the implementation.

Aspect 2: Fitting the γSF

Whenever we try to determine a function with many free parameters it is challenging to determine the best parameters, let alone the connected statistical uncertainties and covariances. In the parametrization of the γSF extracted for ^{240}Pu below the particle separation threshold we face this situation. We will present the first results using a minimum χ^2 method that is approximately independent of the input estimate.

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