1st RCM on Updating and Improving Nuclear Level Densities for Applications

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IAEA Headquarters

Book of Abstracts

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Improving Nuclear Level Densities within the combinatorial and QRPA plus boson expansion method

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The determination of the nuclear level densities is of particular importance in a large number of nuclear applications. Most of existing theoretical estimates of nuclear level densities rely on empirical or phenomenological models essentially fitted to experimental data. Although such adjustments respond to the high accuracy needs of some nuclear applications, their predictive power remains poor due to the large number of free parameters and often non-physical approximations considered. Nowadays microscopic models can provide nuclear level densities with a degree of accuracy comparable with the best phenomenological models. In the present contribution, we propose to estimate nuclear level densities on the basis of two distinct sound and reliable models, namely the combinatorial model and the QRPA plus Boson Expansion model. Both models make use of nuclear ingredients estimated within the non-relativistic Hartree-Fock-Bogolyubov model (HFB), the first one is based on triaxial-deformed HFB model with the Skyrme effective interaction and the second one on the axially deformed HFB+QRPA approach with the Gogny effective interaction.

Experiments (45' talks, 30' coffee) / 2

Constraining Nuclear Level Densities Using the Shape Method and Related CRP Research Activities

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Knowledge of nuclear level densities (NLD) is essential for applications in nuclear astrophysics, reactor physics, and nuclear security. The Oslo Method, a widely used technique for extracting NLDs, typically requires neutron resonance spacing data, which is unavailable for many nuclei of interest. In this presentation, I will review the novel Shape Method, which provides a model-independent approach to constraining NLDs even in the absence of neutron resonance data. Through the relative energy dependence of primary γ-ray transitions, the Shape Method enables constraints on NLDs, improving their reliability.
Additionally, I will briefly discuss the US Nuclear Data Program-funded quasi-continuum data evaluator training, which supports expertise development relevant to this coordinated research project (CRP). Finally, I will outline the key NLD tasks planned for this CRP, including the collection of experimental NLD data, their assessment and evaluation.

Experiments (45' talks, 30' coffee) / 3

Level densities from high-resolution spectra

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I present the extraction of level densities from a fluctuation analysis of high-resolution spectra. In cases where the spectral fluctuations arise from the incoherent overlap of a single class of states with given quantum number J^π, a connection can be made between the magnitude of the signal in an autocorrelation analysis and the level spacing. This condition is best fulfilled in experiments selectively enhancing a single giant resonance. The resulting level densities are complementary to most other experiments: they provide data in the excitation energy region of giant resonances (typically $10-20$ MeV) and they are spin-parity resolved facilitating direct comparison with microscopic calculations.

I then discuss our research plans for the period of the CRP: (1) a comprehensive analysis of data on the ISGMR, IVGDR and ISGQR for a set of key nuclei with a newly developed code providing a systematic uncertainty treatment, (2) studies of the spin dependence based on the set of derived $J = 0, 1, 2$ level densities, (3) extension to cases with two or more classes of states (e.g. 1^- and 1^+) and test with coincident γ-decay experiments for resolved final states, and (4) exploration of a novel technique to determine level densities in nuclear resonance fluorescence self-absorption experiments.

Discrete levels, Resonances (45' talks, 30' coffee) / 4

Average spacing and total radiative widths of neutron resonances

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Average resonance spacing and total radiative widths derived from experimental data are key quantities used in many nuclear physics applications, including testing of level density models and normalization of many experiments. The previous compilation of average resonance spacing and radiative width was a part of the RIPL-3 IAEA project about 15 years ago. The way how the compilation was made is largerly undocumented. The consultants meeting for this CRP recommended updating this database. Work towards updating the compilation will be presented.

Theory (45' talks, 15' coffee) / 5

Microscopic investigation on the nuclear level densities of medium and heavy nuclei with shell model

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Abstract: Nuclear level densities (NLD) are fundamental input parameters in nuclear reaction cross-section calculations and evaluations. Those for medium and heavy nuclei are significant to nuclear energy and non-energy applications. At present, investigations on NLD are mostly performed through empirical formulas. Many important properties are based on simple assumptions like parity and angular momentum distribution. This talk will introduce how to use the configuration-interaction shell model (CISM) to evaluate the NLD. I will introduce a unified nucleon-nucleon interaction for medium and heavy nuclei and a truncation method, which are crucial for NLD investigations with CISM. The model is tested specifically in two nuclear regions, around A=100 and 150, by comparison with standard databases. The spin and parity distributions will be analyzed to give a

microscopic view. The contribution of different interaction components, such as central, spin-orbit, and tensor parts, will be derived to understand the underlying physics deeply. The cluster-related level-density problem will also be expected using the spectroscopic factors of one-, two-, three-, and four-nucleon.

Theory (45' talks, 15' coffee) / 6

Status of the QRPA Boson expansion method

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The determination of the nuclear level densities is of particular importance in a large number of nuclear applications. They indeed govern the decay process from the compound nucleus and are mandatory when dealing with capture cross sections. For decades, theoretical estimates of nuclear level densities have relied on phenomenological models whose parameters are fitted to experimental data. Such adjustments respond to the high accuracy needed for many nuclear applications, but their predictive power is questionable in particular for nuclei far from the mass regions where data are available.

Microscopic approaches, in particular the combinatorial ones, have shown their ability to provide nuclear level densities with a degree of accuracy comparable with the best phenomenological models. In the present project, we propose to estimate nuclear level densities on the basis of two distinct sound and reliable models, namely the combinatorial one and the QRPA-Boson Expansion approach. Both models make use of nuclear ingredients estimated within the non-relativistic Hartree-Fock-Bogolyubov model (HFB). The first one is based on triaxial-deformed HFB solutions obtained using a Skyrme effective interaction and the second one on QRPA predictions based on axially deformed HFB solutions using the D1M Gogny effective interaction.

The status of the developments around the QRPA-Boson Expansion approach will be presented.

Discrete levels, Resonances (45' talks, 30' coffee) / 7

Status and plan for the theoretical research of nuclear levels related to CRP Contract

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We will present three research topics related to the theoretical part of our CRP Contract.
The first topic aims to improve the resolved nuclear levels scheme. To this end, we firstly demonstrate that how the discrete levels can influence the nuclear reaction cross sections and astrophysical reaction rates. Such calculations are performed with both Hauser-Feshbach model and Breit-Wigner formula. Then we propose a procedure to build a dataset of the discrete levels. This includes (1) the compilation of new experimental resonance properties (energy, spin/parity, width), (2) the generation of energy level with the properties derived from known (Porter-Thomas and Wigner) distributions for experimental unknown cases, and (3) the results obtained with the help of machine-learning

method. We will also show the preliminary results for this procedure.
For the second topic, we develop a simple method to constrain the nuclear level density (NLD) by using the evaluated cross section data and the recommended database of nuclear structure. In particular, this method is preliminarily demonstrated by using the neutron capture cross sections and the IAEA photon strength function database to constrain the NLD within TALYS calculation. The necessity to continue this study needs to be discussed in accordance with the CRP's goals.
For the third topic, we will show some results of the determination of the most relevant energy range of NLD. The combination of this study and the existing CRP contents can be discussed.
We also want to discuss the necessity to perform the theoretical study of NLD using Nilsson-BCS model, which was present in our CRP Contract. We are open to accept other tasks for the CRP after the discussion of the meeting.

Experiments (45' talks, 30' coffee) / 8

Nuclear level density from the Oslo method

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The Oslo method has been applied to a double-digit number of experiments at the Oslo Cyclotron Laboratory (OCL) and other facilities. The method allows for extraction of nuclear level densities (NLD) and γ-ray strength functions (γSF) from excitation tagged γ spectra. Due to the large number of experiments performed, the nuclear physics group at the University of Oslo has a database of NLD data for more than a hundred different nuclei ranging almost the entire nuclear chart, from Si to Pu. In addition, the group has engaged in theoretical studies of statistical properties through large-scale shell model calculations.

The Oslo method itself yields the relative shape of the NLD and relies on other external data to obtain physical values. The reliance on external data means that the quality of the result also depends on the quality of the external data. I will discuss the different types of data often used, the potential systematic errors introduced and how they are handled. I will also give an overview of the NLD data from Oslo method experiments available/published and current ongoing projects.

Experiments (45' talks, 30' coffee) / 9

Can we use isomeric ratios to study impact of level densities?

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The Uppsala group has been measuring isomeric yields ratios (IYR) from fission for several years now. This work is done in collaboration with the IGISOL group of the University of Jyväskylä. The IYR are obtained using mass measurement techniques (Penning traps and multi-reflection time-of-flight), i.e., the results are not dependent on current information on, e.g., nuclear level schemes. However, the population of isomeric states with different spins is dependent on the angular momentum of the fission fragment and the de-excitation path. Therefore IYR can be used to study the question of angular momenta in fission and also the impact on level density models in de-excitation calculations (see e.g. [1-3]).

In this talk I will present the experimental work that has been done so far as well as our future plans for measuring IYR at IGISOL and other facilities. I will also present a global study that compared experimental isomeric ratios from other nuclear reactions (extracted from the EXFOR database) with predictions from model calculations using TALYS [4].

[1] V. Rakopoulos et al., Phys. Rev. C 98, 024612 (2018).
[2] A. Al-Adili et al., Eur. Phys. J. A 55, 1 (2019).
[3] Z. Gao et al., Phys. Rev. C 109, 064626 (2024).
[4] S. Cannarozzo et al., Eur. Phys. J. A 59, 295 (2023).

Evaluation/validation (45' talks, 30' coffee) / 10

Work plan for validating nuclear level densities with CCONE

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The nuclear reaction model code CCONE will be used to validate the nuclear level density updated and improved in the CRP. The work plan will be presented.

Experiments (45' talks, 30' coffee) / 11

Neutron Spectroscopic Measurement for Studying Nuclear Level Density via the Fusion Evaporation Route

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Nuclear level density (NLD) can be determined through various experimental techniques, including nuclear level counting, neutron capture reactions (via nuclear resonance widths), gamma-ray spectroscopy in the OSLO method, and particle spectroscopy in the fusion evaporation method.
NLD is strongly influenced by nuclear structure effects such as shell corrections, pairing interactions, deformation, and isospin. In deformed nuclei, numerous rotational states contribute significantly to NLD at low excitation energies, leading to values much higher than those predicted by the single-particle Fermi Gas model. The ratio of total NLD to the single-particle estimate at a given excitation energy is referred to as the collective enhancement factor. As excitation energy increases, collective contributions gradually diminish and eventually vanish beyond a certain threshold known as the critical energy. This energy is associated with nuclear shape transitions and varies across different nuclei. While recent experiments have focused on measuring both the collective enhancement factor and the critical excitation energy [1–8], further measurements across the nuclear chart are needed to obtain conclusive data on these quantities.
Another key challenge in NLD studies is understanding its isospin dependence. The conventional approach to NLD in exotic nuclei with extreme neutron-to-proton (N/Z) ratios assumes behavior similar to that of stable nuclei, which may not always be valid. Experimental observations suggest a

reduction in NLD for neutron-deficient nuclei compared to their neighboring stable isotopes, particularly in the mass regions around 60 and 120 [9–11]. Further investigations are needed to gain deeper insights into NLD trends in exotic nuclei. Al-Quraishi et al. proposed two empirical relations for NLD parameters—one based on (N-Z) and another on (Z-Z_0), where Z_0 represents the atomic number of the nucleus at the bottom of the mass parabola for a given mass [12–13].
For excited nuclei with mass above 100, neutron emission is predominantly influenced by the large Coulomb barrier. Consequently, fast-neutron spectroscopy at backward angles provides a valuable tool for NLD measurements. In this talk, I will present recent experimental results on the fadeout of collectivity and the isospin dependence of NLD. Additionally, I will discuss future experimental plans under the IAEA-CRP project F41034 to further investigate these aspects. Plans for the compilation and evaluation of measured NLDs using the fusion evaporation reaction will also be outlined.

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[4] M. Guttormsen et al., Phys. Lett. B 816, 136206 (2021).
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Evaluation/validation (45' talks, 30' coffee) / **12**

Validation of level densities for and with TALYS

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The current beta version (2.1) of TALYS contains 8 level density models.
The latest version of the RIPL discrete level database and the RIPL-3 database for D0 values have been used to assess the global quality of these models and to perform a new consistent parameterization for all nuclides with these models.
Further validation with adjusted level density models have been done for average radiative widths, MACS, and (n,gamma) cross sections in the whole fast neutron range, obviously accounting for the additional model dependence of photon strength functions.
The constant temperature model (Gilbert-Cameron) and the new BSKG3 microscopic model come out as the best 2 models, with the BSKG3 model seen as superior for a description all open reaction channels up to 20 MeV when compared to experimental data.
A template for new databases of D0, D1, Gamma_gamma and MACS, all in YANDF format, is proposed to allow for validation of current and future level density models.

Discrete levels, Resonances (45' talks, 30' coffee) / **13**

A Nuclear Data perspective for Nuclear Level Densities

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Nuclear level densities (NLD) impact directly many aspects of nuclear data evaluations, from Hauser-Feshbach calculations to
decay spectra. Therefore, accurate description of NLD are essential to ensure reliability of nuclear applications. Despite its
importance, however, proper extraction of NLD as a function of excitation energy, spin and parity from experimental
measurements has historically encountered significant challenges. Recent developments of experimental methods such as the
Oslo, beta-Oslo and shape methods have produced a wide breadth of experimental information on NLD. This is
normally obtained with many model assumptions, since what is actually measured is not the NLD but rather a convolution of
NLD with gamma strength functions. Additionally, experimental assumptions are also made in the sense that the measured
reaction may not necessarily populate a complete range of spins and parities.

Our research plan involves performing a complete investigation of the data directly measured through the Oslo method and
carefully determine what are, in each case, the spin and parity coverage in the level population for each excitation energy in a
model-independent way. That will impact the total NLD estimation and redefine their corresponding uncertainties. Additionally, we intend to investigate the normalization at separation energy coming from resonance spacings to provide realistic
uncertainties to total NLD. Resonance spacings only constrain, in a model-independent way, the NLD for specific spins and
parities, therefore a careful uncertainty propagation to total NLD is crucial. Both approaches will potentially lead to
more realistic, experimentally-constrained, uncertainty bands in NLD, potentially providing more realistic NLD data to
applications and helping microscopic NLD model developers to know precisely what are the actual relevant experimental
constraints.

In this talk we will discuss the nuclear data sources of uncertainties associated with the determination of NLD and how these uncertainties can impact the extraction of NLD from measurements and the constraints assumed in NLD models. We will also explore the creation of a database of directly-measured experimental information to assist the identification of the true data constraints.

Experiments (45' talks, 30' coffee) / 14

Nuclear Level Density Analysis Using Combined Data Sets from Different Techniques

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Knowledge of nuclear level densities remains significantly limited due to the scarcity of experimental data needed to constrain level density models. Current models rely heavily on limited experimental information derived from s-wave neutron resonance spacings. These data are only available within narrow excitation energy and spin ranges, resulting in poorly constrained models.
Alternative experimental techniques are being developed to measure nuclear level densities, offering a potential solution. Experimental findings on nuclear level densities obtained through the particle evaporation technique will be presented, along with comparisons to existing models.

Potential improvement of level density modeling is suggested to be based on an extended set of experimental data, which should include reliable data from available experimental techniques.

Evaluation/validation (45' talks, 30' coffee) / 15

The Level Density study in the future Chinese Nuclear Reaction Model-UNF

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This report outlines the future research plans for level density studies in the Chinese nuclear reaction model. First, China Nuclear Data Center (CNDC) aims to implement global phenomenological level density models, including the Constant Temperature Fermi Gas model and the Enhanced Generalized Superfluid model, into the Chinese UNF code for nuclear reaction calculations, particularly for medium-heavy and fission nuclei. Additionally, efforts will be made to incorporate the IAEA-recommended level density parameters into the UNF framework and systematically compare the resulting calculations. Second, CNDC plans to develop a global microscopic level density model based on the Relativistic Hartree-Bogoliubov (RHB) approach and the combinatorial model. These investigations will focus on nuclear reaction systems involving isotopes such as Nb, Sn, and U. The ultimate goal is to enhance the accuracy and applicability of nuclear reaction models, providing a more robust theoretical foundation for both fundamental research and practical applications.

Introduction - CRP (Dimitriou) / 16

Introduction to new CRP

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The goals and research objectives of the new CRP on Updating Nuclear level Densities for Applications will be presented.

Evaluation/validation (45' talks, 30' coffee) / 17

Fission Cross Sections and Nuclear Level Densities

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Minimum requirements for developing NLD for fission.

Experiments (45' talks, 30' coffee) / 18

Experimental Nuclear Level Densities at ELI-NP and IFIN-HH

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The ELI-NP facility in Romania will consist of two different types of beamlines: The high-power laser system and the high-brilliance γ-ray beams. Such γ-ray beams are very selective when used for exciting atomic nuclei, as the narrow bandwidth provides a very well-defined excitation energy window, and usage of polarised photons provides clean spin-parity selectivity for $J^P = 1^-$ states. This provides the European community with a unique opportunity to develop complementary methods for measurements of nuclear level densities in model-independent ways with a well-defined ensemble of states based on spin and parity. During the construction period of the ELI-NP γ-ray beam facility, we have undertaken a complementary evaluation of these methods using well-established charged-particle methods for nuclear level densities at the Tandem accelerators of IFIN-HH. Here we will present the status of ELI-NP facility, and our ongoing and planned work on nuclear level densities, with a special focus on how we can contribute to the topical CRP.