Book of Abstracts

9th Workshop on Nuclear Level Density and Gamma Strength

Monday 27th May – Friday 31st May

NUKLEÆRSENTERET

Code of Conduct: Oslo Workshop 2024

The organizers of the Oslo workshop are committed to enabling an event at which everyone can participate in an inclusive, respectful and safe environment. All individuals are encouraged to freely express and exchange scientific ideas. The Code of Conduct applies to all participants at the event, including all persons attending or involved in any capacity in the event.

The conference upholds principles of tolerance, equality and mutual respect, regardless of gender, ethnicity, religion, disability, age, sexual identity or any other personal attributes. Any form of bullying or harassment will be strictly prohibited and not tolerated under any circumstances. All communication should be appropriate for a professional audience of many different backgrounds. No participant should be disadvantaged, feel they are in danger or subject to repression or harassment because of these reasons or others. Treat others with kindness and avoid insulting or demeaning fellow attendees. Everyone must adhere to the UiO guidelines:

- We shall meet each other with respect and stop all forms of bullying, abuse of power, racism, harassment, discrimination and sexual harassment.
- Be open to feedback regarding your own use of language and behaviour.
- Avoid situations that may be perceived as unsafe or unwanted for others.
- Be aware of your own behaviour so that power imbalance is not exploited, for example to achieve sexual relations.
- There must be no unwelcome touching, including pinching, patting, rubbing or purposefully brushing up against a person.
- Sending sexually suggestive communications in any format is prohibited.
- Alcohol may increase the risk of harassment and sexual harassment. This implies a heightened responsibility for both organisers and participants.

How to report an incident?

If you experience or witness bullying, discrimination, or harassment, you are encouraged to immediately inform the individual that their comments and/or behaviour are unwelcome. However, direct confrontation with a person engaged in offensive behavior may not be possible or advisable in every situation. In this case you should report the incident.

If you wish to report,you may contact the contact person of the local organization committee in charge of monitoring the application of the Code of Conduct. These are:

Johannes Heines (email: j.s.heines@fys.uio.no)

Lauren Bell (email: l.t.bell@fys.uio.no)

You are also invited to write down as many relevant details as you can recall (e.g., names, dates, times, locations, behaviour or statements made, etc.), which can be helpful in assisting any future investigation of the incident.

To ensure a fair and complete investigation, we cannot accept anonymous reports. However, we will preserve confidentiality of the author's report, except where doing so would compromise another person's rights or impair a thorough investigation. Conference participants asked to stop unacceptable behavior are expected to comply immediately. We will not allow retaliation against any individual who makes a report of known or suspected code of conduct violation.

Sanctions against participants violating these rules and deliberately making false accusation about harassment are at the sole discretion of the conference organizers and may include warnings, being asked to leave the event, and notifying the relevant authorities. Sexual assaults will be reported to and investigated by the police.

	Monday	Tuesday	Wednesday	Thursday	Friday
	08:30 Registration and coffee	08:30 Coffee	08:30 Coffee	08:30 Coffee	08:30 Coffee
1st	Chair: Sunniva Siem	Chair: Luna Pellegri	Chair: Retief Neveling	Chair: Mark Spieker	Chair: Darren Bleuel
	09:00 Welcome	09:00 Stephane Hilaire	09:00 Atsushi Tamii	09:00 Jutta E. Escher	09:00 Gianluca Imbriani
	09:10 Mathis Wiedeking	09:30 Stéphane Goriely	09:30 Luna Pellegri	09:30 Adriana Sweet	09:30 Riccardo Maria Gesuè
	09:40 Peter von Neumann-Cosel	10:00 Milan Krtička	10:00 Jacob Bekker	10:00 Francesco Pogliano	09:50 Keenan Myers
	10:10 Andrea Richard	10:20 Bryn Knight	10:20 Yohei Sasagawa	10:20 Nikolaos Dimitrakopoulos	10:10 Corentin Hiver
	10:40 Vetle W. Ingeberg	10:40 Maria Markova	10:40 Thuthukile Khumalo	10:40 Mathilde Pottier	10:30 Sean Liddick
	11:00 Coffee	11:00 Coffee	11:00 Coffee	11:00 Coffee	10:50 Coffee
2nd	Chair: Lee Bernstein	Chair: Ann-Cecilie Larsen	Chair: Stéphane Goriely	Chair: Dorthea Gjestvang	Chair: Atsushi Tamii
	11:30 Lindsay Donaldson	11:30 Artemis Spyrou	11:30 Dallas DeMartini	11:30 Ramona Vogt	11:20 Wanja Paulsen
	12:00 Lauren T. Bell	12:00 Shilun Jin	12:00 Nadia Tsoneva	12:00 Jørgen Randrup	11:40 Sebenzile Magagula
	12:20 Konstantinos Bosmpotinis	12:20 Mallory Smith	12:20 Johann Isaak	12:20 Henrik Haug	12:00 Retief Neveling
	12:40 Dennis Mücher	12:40 Sivahami Uthayakumaar	12:40 Jenny Finsrud	12:40 Malia Mehdi	12:20 Pär-Anders Söderström
					12:40 Oscar Le Noan
	13:00 Lunch (group photo)	13:00 Lunch	13:00 Lunch	13:00 Lunch	13:00 Lunch
3rd	Chair: Eda Sahin	Chair: Mathis Wiedeking	Chair: Magne Guttormsen	Collaboration discussions	Chair: Andreas Görgen
	14:30 Yun-Hsuan (Abby) Lee	14:30 Sandile Jongile	14:30 Michael Weinert		14:30 Jaime Martinez-Larraz
	14:50 Eleanor Ronning	14:50 Steven Grimes	14:50 Amandeep Kaur		14:50 Beau Gregory Greaves
	15:10 Mark Spieker	15:10 Sven Åberg	15:10 Fang-Qi Chen		15:10 Sifundo Binda
	15:30 Martin Müller	15:40 Hannah Berg	15:30 Bryan Kelly		15:30 Lee Bernstein
	16:00 Posters (Origo)	16:00 Coffee	15:50 Coffee		16:00 Closing Talk + Coffee
		16:30 Discussion: Level density	16:20 Discussion: Gamma strength function	17:00 Workshop Dinner: Frognerseteren	
	19:00 UiO orchestra concert (Aula)	Chair: Sven Åberg			

The abstracts appear in the same order as the schedule

Nuclear data from the quasi-continuum

Author: Mathis Wiedeking[1]

[1] *Lawrence Berkeley National Laboratory*

The gamma-ray decay of nuclear states in the quasi-continuum provides important nuclear data for various applications, insights into nuclear structure effects and constraints on nucleosynthesis processes. In particular, measurements of Nuclear Level Densities (NLDs) and Photon Strength Functions (PSFs) have and will continue to play a central role as we have entered an era of incredible potential for novel measurements. This is due to many institutes across the world having established programs to provide enhanced, state-of-the-art research infrastructure. These range from significant increases in efficiencies for particle and gamma-ray detectors to new or upgraded radioactive ion beam facilities. In parallel, several new experimental and analytical techniques were developed, allowing for more reliable PSF and NLD studies, even on nuclei away from stability.

In this talk, I will provide an overview of the most recent and significant advances made and how these have laid the foundation for novel and ambitious measurements of PSFs and NLDs at radioactive and

stable ion beam facilities. Such measurements will address future data needs for nuclear astrophysics and various applications ranging from medical isotope production, non-proliferation efforts, as well as fission and fusion reactor technologies. This growing interest across disciplines was a major motivation for the International Atomic Energy Agency's initiative to create and disseminate the first PSF database in 2019. An overview of a major database update, which will take place in the first half of 2024, will also be presented.

Evidence for a toroidal electric dipole mode in nuclei and implications for the pygmy dipole resonance

Author: Peter von Neumann-Cosel[1]

[1] *Institut für Kernphysik, Technische Universität Darmstadt*

I present first experimental evidence for a low-energy toroidal electric dipole mode in the nucleus ^{58}Ni based on a combined analysis of high-resolution (p,p'), (γ,γ') and (e,e') experiments [1]. Large transverse electron scattering form factors are identified as an unique signature of the toroidal nature of E1 transitions. Although ^{58}Ni is a $Z \approx N$ nucleus, these results bear important implications for the pygmy dipole resonance (PDR) in heavy nuclei with neutron excess. The toroidal excitations carry the same experimental signatures as the states forming the PDR [2]: large isovector response (on the scale of low-energy E1 strength), strong isoscalar response and large ground-state branching ratios. QRPA models successfully describing the toroidal mode in ^{58}Ni predict the PDR in heavy nuclei to be of toroidal nature [3] and also reproduce the specific form of transition densities approximately isoscalar in the interior with a pronounced peak of the neutron density on the surface [4]. Furthermore, a recent study of the systematics of the low-energy dipole strength in the Sn isotope chain reveals much smaller B(E1) strengths of the PDR than previously thought [5]. These findings challenge an interpretation of the PDR as neutron skin oscillations.

[1] P. von Neumann-Cosel et al., arXiv.2310.04736.
[2] A. Bracco, E.G. Lanza and A. Tamii, Prog. Part. Nucl. Phys. **126**, 360 (2019).
[3] A. Repko et al., Eur. Phys. J. A **55**, 242 (2019).
[4] E.G. Lanza et al., Prog. Part. Nucl. Phys. **129**, 104006 (2023).
[5] M. Markova, P. von Neumann-Cosel and E. Litvinova, arXiv:2311.14525.

First Experimental Constraint of the $^{141}\mathrm{Ba}(n,\gamma)$ $^{142}\mathrm{Ba}$ Reaction Rate for the Astrophysical i-Process

Author: Andrea Richard

Co-authors: Alicia Palmisano [1]; Artemis Spyrou ; Beau Gregory Greaves [2]; Caley Harris [3]; Daniel Santiago [4]; Guy Savard [4]; Jason Clark [4]; Mallory Smith ; Paul DeYoung [5]; Sean Liddick [3]

[1] *University of Tennessee Knoxville*

[2] *University of Guelph*

[3] *Michigan State University*

[4] *Argonne National Laboratory*

[5] *Hope College*

One of the biggest questions in Nuclear Astrophysics is how elements are synthesized in stars. In the traditional nucleosynthesis picture, elements are thought to be created by one of the two traditional neutron-capture processes, namely the slow (s) and rapid (r) processes. Recent observations of carbon-enhanced metal poor stars (CEMP), however, show that observed abundance patterns cannot be reproduced by these traditional processes, and indicate that an additional process known as the intermediate neutron-capture process (i-process) is needed to describe these abundances. Occurring at intermediate neutron densities, the majority of nuclear physics properties (mass, half-life, etc.) are well constrained, however the neutron-capture cross sections and reaction rates remain largely unmeasured. In a sensitivity study by the NuGrid Collaboration, ^{141}Ba(n,γ)^{142}Ba was identified as a high-priority measurement due to its impact on the production of praseodymium in CEMP-i stars. In this talk, I will discuss the first experimental constraint of the ^{141}Ba(n,γ)^{142}Ba using the β-Oslo method. The experiment took place at Argonne National Laboratory's CARIBU facility where a ^{142}Cs beam was delivered into the SuN detector and SuNTAN tape transport system. Results on the nuclear level density and γ-ray strength function following the decay of ^{142}Cs to ^{142}Ba will be presented along with ^{141}Ba(n,γ)^{142}Ba reaction rate results.

The Oslo Method In Inverse-kinematics

Author: Vetle Wegner Ingeberg[1]

[1] *University of Oslo (NO)*

With direct kinematics the biggest challenge is the targetry, which limits us to nuclei close to stability and elements with reasonable chemical properties. To study short lived nuclei or elements such as noble gases other techniques must be used. The most obvious route is to use the inverse-kinematics. This introduces a lot of new challenges not seen in direct kinematics such as kinematics compression and Doppler shift.

In this talk I will present results from Oslo Method analysis of inverse kinematics experiments and discuss the challenges inverse kinematics poses.

The IsoVector Giant Dipole Resonance in the Neodymium Isotope Chain - Past and Future Investigations

Author: Lindsay Michelle Donaldson[1]

[1] *iThemba LABS*

The shape transition of the IsoVector Giant Dipole Resonance from the spherical ^{142}Nd to the deformed ^{150}Nd nuclei in the even-even ^{142150}Nd chain was established using proton inelastic scattering at zero degrees with the K600 Magnetic Spectrometer at iThemba LABS. The effect of deformation on the broad and the fine structure of the IVGDR was investigated. Comparisons were made to previous photo-absorption results obtained at Saclay and significant discrepancies that have implications for several applications were found. In addition to this, discrepancies between photo-absorption data from the Saclay and Livermore laboratories have been found for several nuclei. The Nd results, observed discrepancies, possible reasons for them and future investigations will be presented and discussed.

Investigating the Nuclear Level Density and γ-ray Strength Function of ^{152,154}Sm

Author: Lauren Bell[1]

[1] *University of Oslo*

The samarium isotopic chain is one of the best choices to study the evolution of the NLD and γSF as a function of deformation. This chain starts at the near spherical and stable ^{144}Sm, which has a magic number of 82 neutrons, to the well deformed isotope of ^{154}Sm. This isotopic chain have many stable isotopes which makes it one of the few isotopic chains which we can study at stable beam facilities like the Oslo Cyclotron Laboratory. This gives us a unique opportunity to investigate how the NLD and γSF evolve with deformation and increasing mass. In this talk I will focus on the results obtained for ^{152}Sm and ^{154}Sm.

In 2018, an experiment was carried out at the Oslo Cyclotron Laboratory in which 15 and 16 MeV proton beams were irradiated on targets of ^{152}Sm and ^{154}Sm, respectively, allowing the study of the ^{152}Sm(p, p γ) ^{152}Sm and ^{154}Sm(p, p γ) ^{154}Sm reactions. This work uses the Oslo method to analyze these data sets to simultaneously extract the NLD and γSF. The results from these experiments will be discussed in this talk with a specific focus on the scissors resonance.

Statistical properties of 85Rb nucleus relevant to the astrophysical p-process

Author: Konstantinos Bosmpotinis[1]

Co-authors: Alex Dombos [2]; Alicia Palmisano [3]; Andrea Richard [4]; Anna Simon [2]; Anna Simon [2]; Artemis Tsantiri [5]; Artemisia Spyrou [5]; Caley Harris [5]; Erin Good [6]; Hannah C Berg [5]; Jorge Pereira [5]; Mallory Smith [5]; O. Gomez [2]; Panagiotis Gastis [7]; Paul DeYoung [8]; Peter Mohr [9]; Remco Zegers [5]; Sean Liddick [5]; Stephanie Lyons [6]

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[7] *Los Alamos National Laboratory*

[8] *Hope College*

[9] *ATOMKI*

There are 35 proton-rich stable isotopes, known as p-nuclei. Their existence is attributed to the p-process, primarily consisting of a network of photodisintegration reactions on s- and r-process seed nuclei. The abundances of p-nuclei can be obtained based on simulations of this network, with most of the isotopes involved being radioactive. For this reason, direct measurements of these reactions are challenging, thus reaction rates are often obtained via theoretical models. Constraining theoretical models is crucial to obtain experimentally constrained cross-section values for unstable elements. 85Rb has been identified as a branching point for the p-process network. The reaction flow can proceed through two competing reactions, namely 85Rb(γ,p)84Kr or 85Rb(γ,n)84Rb photodisintegrations. Depending on which is the dominant channel, that affects the production of the 78Kr p-nucleus. Therefore, knowledge of the cross-sections for both channels is crucial to obtaining more accurate abundances for 78Kr. Typically it is preferred to study these reactions in the time-reverse direction. 84Rb is a radioactive isotope with T1/2= 32.8 days. Thus, direct neutron capture measurements on this isotope are currently unfeasible. Hauser-Feshbach theory allows for theoretical cross-section calculations when the Nuclear Level Density (NLD) and gamma-ray strength function (gSF) of the compound nucleus are given as inputs. Here we use the 84Kr(p,γ)85Rb reaction to populate the 85Rb compound nucleus, extract NLD and gSF information, and use it to constrain the 85Rb(γ,n)84Rb reaction cross section.

The 84Kr(p,γ)85Rb proton capture reaction was measured with the SuN detector at NSCL at MSU. A stable 84Kr beam was impinged onto a hydrogen gas target in the energy range of 2.7 MeV/u to 3.7 MeV/u. In the present work, a systematic investigation was performed to obtain the NLD and gSF for the 85Rb compound nucleus. The RAINIER code was implemented to

simulate the statistical de-excitation of the 85Rb compound nucleus using various combinations of NLD and gSF parameters. The resulting simulated spectra were compared to the experimental data to identify suitable combinations of NLD and gSF. These combinations were used as input in the TALYS 1.96/2.0 code to yield the experimentally constrained cross-section for the 85Rb(γ,n)84Rb reaction. These results can be used to evaluate the competition between the (γ,p) and (γ,n) reactions at the 85Rb branching point and constrain the production of 78Kr within the p process.

Constraining neutron capture rates for the intermediate neutron capture process

Author: Dennis Muecher

Co-author: Artemis Spyrou [1]

[1] *Michigan State University*

The intermediate “i” process was proposed as a plausible scenario to explain some of the unusual abundance patterns observed in metal- poor stars (Denissenkov et al, ApJ Letters 2017). The most important nuclear physics properties entering i-process calculations are the neutron-capture cross sections and they are almost exclusively not known experimentally. In this talk we demonstrate results (Spyrou et al., PRL, 2024) from an experiment using RIBs from CARIBU, Argonne National Laboratory, allowing to experimentally constraint the ^{139}Ba(n,γ)^{140}Ba reaction rate using the newly developed “Shape” method (Muecher et al., PRC 107, L011602, 2023). Our results remove the dominant source of uncertainty for the production of lanthanum, a key indicator of i-process conditions. Our results show that the observed elemental abundances in metal-poor stars are consistent with an i-process scenario at neutron densities of 10^{13} n/cm^3.
We will also discuss future plans for direct measurements of neutron capture rates at the University of Cologne, targeting i-process relevant nuclei near stability.

Measurement and modeling of nuclear quasi-continuum properties from proton irradiation of natural thallium at 30 and 50 MeV

Author: Y. Lee[1]

Co-authors: A.S. Voyles [1]; C.E. Apgar [1]; M.S. Basunia[2]; L.A. Bernstein[1,2]; J.C. Batchelder[1]; J.A. Brown [1]; C.S. Cutler [4]; J.M. Gordon [1]; T.A. Laplace [1]; D.G. Medvedev [4]; J.T. Morrell [3]; E.M. O'Brien [3]; K. Rector [3]; M. Skulski [4]; C.E. Vermeulen[3]

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^{202g}Pb ($t_{1/2} = 52.5(28) \times 10^3$ y) has been used for geochronology via thermal ionization mass spectroscopy techniques and has been proposed as a reference material for accelerator mass spectroscopy [1,2,3]. The ^{nat}Tl(p,x) reaction has been proposed as a method of production of this isotope to meet anticipated needs. However, insufficient data exist for accurate predictions of production yield and/or purity. The long lifetime and paucity of measurable gamma rays following electron capture decay make it difficult to assay the production rate for this isotope. Therefore, the Tri-Laboratory Effort in Nuclear Data (TREND) undertook an effort to determine the production of ^{202g}Pb via prompt in-beam spectroscopy of the reaction product.

An experiment was performed at the LBNL 88-Inch Cyclotron to measure the prompt gamma and neutron emissions at discrete angles (30°–110°) at different incident proton energies (30 and 50 MeV) to allow for angular- and energy-differential cross section measurements of ^{nat}Tl(p,x) reactions regardless of the lifetime of the reaction products. Information on these reaction channels will complement our group's recent ^{nat}Tl(p,x) cross sections measured via stacked-target irradiations, providing new understandings in gamma strength functions and spin-parity dependant observables.

Building on past efforts of the TREND collaboration, further parameter adjustments of reaction-modeling codes will be made via comparison between computed predictions and the results of this measurement and past stacked-target irradiations. New insights into the photon strength function and/or nuclear level density models employed in TALYS will be gained through this work in addition to the previously explored preequilibrium exciton model, optical model, etc [4,5]. This approach will greatly expand our ability to measure a range of reaction channels currently inaccessible via post-irradiation decay spectroscopy, and will offer insight into nuclear statistical properties of the wide range of additional far-from-stability nuclei populated in our group's measurements. In this talk, I will present details about the experiment, describe the progress to date on the data analysis, and discuss plans to interpret the results through comparisons to reaction modeling.

Acknowledgements: This work was supported by the U.S. Department of Energy Isotope Program, managed by the Office of Science for Isotope R&D and Production, and was carried out by Lawrence Berkeley National Laboratory (Contract No. DE-AC02-05CH11231).

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[3] A. Wallner, M. Bichler, K. Buczak, D. Fink, O. Forstner, R. Golser, M.A.C. Hotchkis, A. Klix, A. Krasa, W. Kutschera, C. Lederer, A. Plompen, A. Priller, D. Schumann, V. Semkova, and P. Steier. High-sensitivity isobar-free AMS measurements and reference materials for 55Fe, 68Ge and 202gPb. Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms, 294:374–381, 2013. Proceedings of the Twelfth International Conference on Accelerator Mass Spectrometry, Wellington, New Zealand, 20-25 March 2011.
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[5] Catherine E. Apgar, Andrew S. Voyles, Jon C. Batchelder, Eva R. Birnbaum, Cathy S. Cutler, Morgan B. Fox, Arjan J. Koning, Dmitri G. Medvedev, Jonathan T. Morrell, Ellen M. O'Brien, Michael Skulski, Christiaan Vermeulen, and Lee A. Bernstein. Inves- tigation of the production of 117mSn and 119mTe via proton bombardment on natural antimony: Implications for charged particle reaction modeling. in preparation, 2024.

Constraining the 69Zn Neutron Capture Cross-section via the Beta-Oslo Method

Author: Eleanor Ronning

Co-authors: Aaron Chester [1]; Alex Hamaker [2]; Alicia Palmisano [3]; Andrea Richard [4]; Artemis Spyrou [2]; Caley Harris [2]; Chandana Sumithrarachi [1]; Daniel Puentes [2]; Issac Yandow [2]; Jordan Owens-Fryar [2]; Katie Childers [2]; Mathis Wiedeking [5]; Paul DeYoung [6]; Rebeka Lewis [2]; Ryan Ringle [1]; Sean Liddick [2]; Stephanie Lyons [7]; Yong Chi Xiao [8]

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[8] *University of Kentucky*

The existence of the intermediate neutron-capture process (i-process) explains the observed astrophysical abundances of elements around the Z<50 region [1]. Neutron capture reactions in the A=70 mass region for Ni, Cu, and Zn isotopes are known to produce large variations in predicted i-process abundances [1]. Predicted stellar abundances of Ga are particularly affected by the ^{69}Zn(n,γ) reaction. The β-decay of ^{70}Cu offers an opportunity utilize the β-Oslo method to experimentally determine the γ-strength function (γSF) and nuclear level density (NLD) of ^{70}Zn to constrain the ^{69}Zn(n,γ) reaction rate for i-process nucleosynthesis. ^{70}Cu has three different β-decaying spin-parity states that populate different spin ranges at similar excitation energies in the daughter nucleus: the 6^- ground state, the 101 keV 3^- isomeric state, and the 242 keV 1^+ isomeric state [2]. In an experiment performed at the National Superconducting Cyclotron Laboratory the three states of ^{70}Cu was produced and delivered to the Summing NaI (SuN) Total Absorption Spectrometer [3]. Spectra from the β-decays of each state were isolated using different beam on/off periods. Preliminary results from β-Oslo analysis to obtain γSF and nuclear level densities will be presented. The preliminary constrained ^{69}Zn(n,γ)^{70}Zn reaction rate will also be presented.

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Accessing the Single-Particle Structure of the PDR

Author: Mark Spieker[1]

[1] *Florida State University*

In atomic nuclei, the term pygmy dipole resonance (PDR) has been commonly used for the electric dipole (E1) strength around and below the neutron-separation energy. It has been shown that the PDR strength strongly impacts neutron-capture rates in the s- and r-process, which synthesize the majority of heavy elements in our universe. A precise understanding of the PDR's microscopic structure is essential to pin down how it contributes to the gamma-ray strength function (γSF) often used to calculate the neutron-capture rates. In fact, the different responses to isovector and isoscalar probes highlighted the complex structure of the PDR and emphasized that different underlying structures would indeed need to be disentangled experimentally if stringent comparisons to microscopic models wanted to be made.

Featuring our recent study of ^{208}Pb 1 and ^{62}Ni 2, I will present how the neutron one-particle- one-hole structure of the PDR can be studied with high-resolution magnetic spectrographs. The data on ^{208}Pb were obtained from (d, p) one-neutron transfer and resonant proton scattering experiments performed at the Q3D spectrograph of the Maier-Leibnitz Laboratory in Garching, Germany, while the data on ^{62}Ni were measured at Florida State University with the Super-Enge Split-Pole Spectrograph. In this contribution, the new data will be compared to the large suite of complementary, experimental data available for 208Pb highlighting how we established (d, p) as an additional, valuable, experimental probe to study the PDR and its collectivity. Besides the single-particle character of the states, different features of the (d, p) strength distributions will be discussed.
To highlight future possibilities, I will also briefly present first results from a new experimental setup recently commissioned at the Super-Enge Split-Pole Spectrograph at Florida State University for particle-γ coincidence experiments 3.

References

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D. Houlihan, M. Khawaja, P. Kielb, A. Kuchera, G. McCann, A. Morelock,

E. Lopez-Saavedra, R. Renom, L. Riley, G. Ryan, A. Sandrik, V. Sitaraman, E. Temanson, M. Wheeler, C. Wibisono, and I. Wiedenhöver, The CeBrA demonstrator for particle-γ coincidence experiments at the FSU Super-Enge Split-Pole Spectrograph, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 1058,168827 (2024), https://www.sciencedirect.com/science/article/pii/S0168900223008185.

Probing nuclear level densities and γ-ray strength functions via partial reaction cross sections

Author: Martin Müller[1]

Co-authors: Andreas Zilges [1]; Benedikt Machliner [1]; Felix Heim [1]; Pina Wüstenberg [1]; Svenja Wilden [1]

[1] *University of Cologne*

Modeling the complex network of reactions that is the astrophysical γ process requires calculating tens of thousands of reaction rates. Level densities and γ-ray strength functions are key parameters in these calculations and one way to probe them is by measuring partial reaction cross sections 1. Three such experiments focusing on the iron peak region will be reported on. The ^{55}Mn(α,n)^{58}Co^{m+g} and ^{58}Fe(p,n)^{58}Co^{m+g} reactions were investigated using the activation technique. Despite being unable to directly observe the γ-ray transition from the metastable state to the groundstate of ^{58}Co, due to its low energy of 25 keV, the production of ^{58}Co via its metastable state could be disentangled from its production without populating the metastable state first. This was accomplished by identifying the feeding contribution from the metastable state in the electron capture decay of the groundstate. The ratio of the total cross section and the partial cross section associated with the production of the metastable state turns out to be very sensitive to nuclear level information. In addition, first results of an in-beam measurement of the ^{58}Fe(p,γ)^{59}Co reaction will be presented.
Supported by the DFG (ZI 510/8-2).

1 F. Heim *et al.*, *Phys. Rev. C* **103**, 025805 (2021).

Gamma strength function and nuclear level densities on the same footing

Authors: Stephane Hilaire ; S. Péru ; Stephane Goriely

The QRPA approach is a powerful method that enables to predict collective nuclear excited states both for low and high energies. It has indeed been successfully used to describe giant resonances, and it has been shown to enable a reasonable description of low energy collective states. The extension of the approach, performed to study the influence of QRPA states couplings on decay lifetimes in Gadolinium isotopes has paved the way to compute electromagnetic transitions between excited QRPA levels. Since then, a new approach for gamma strength function determination involving gamma emission between excited states in addition to traditional transitions between ground state and excited states is under investigation. A recent development has also shown that the same QRPA levels could be used as a starting point for a new level density model. I will describe these two ways of exploiting QRPA predictions, to produce within a coherent framework nuclear level densities and gamma strength functions.

Theoretical description of the photon strength function and nuclear level densities

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Reliable theoretical predictions of nuclear dipole excitations and level densities in the whole nuclear chart are of great interest for different applications, including in particular nuclear astrophysics. We present here recent and original calculations of the de-excitation E1 and M1 photon strength functions obtained in the framework of the axially-symmetric deformed quasiparticle random phase approximation (QRPA) based on the finite-range D1M Gogny force. These calculations are compared with photoabsorption strength function as well as available experimental data (including those obtained within the Oslo method). Predictions of the dipole strength function for spherical and deformed nuclei within the valley of beta-stability as well as in the neutron-rich region are discussed.

Similarly, based on the same QRPA framework but complemented by the boson expansion method, the nuclear level densities are extracted systematically for all nuclei for which experimental s-wave spacings have been measured. This new method to determine energy-, spin- and parity-dependent level densities and its capacity to reproduce experimental data will be presented. A comparison with standard nuclear level densities will also be discussed. The impact on radiative neutron capture cross sections will also be presented.

Analysis of γ-ray intensities from ^{56}Fe(n_{th},γ) reaction within the statistical model

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Decay properties of nuclear states in the region of high nuclear level density (NLD) are usually described within the statistical model of nucleus using the NLD and photon strength functions (PSFs) for transitions of different types and multipolarities. Sufficiently high NLD is reached at relatively low excitation energies in many medium-weight and heavy nuclei but in lighter nuclei (with mass $A \sim 30-100$) the NLD is still not very high even near the neutron separation energy S_n. Despite this fact the statistical model of the nucleus is used for description of decay of states near, and often well below S_n in these nuclei.

In the mentioned mass range information on PSFs for γ-ray energies well below S_n comes mainly from charged-particle induced reactions, analyzed using Oslo method [1]. Data analyzed with this method show that the PSFs should significantly decrease with E_γ for $E_\gamma \lesssim 3-4$ MeV. This feature is known as a strong low-energy enhancement (LEE) of PSFs and was for the first time reported in Fe nuclei [2]. Results from Oslo method were supported by two-step γ cascade data following thermal neutron capture measured at Budapest [2]. However, the data from this experiment can easily be contaminated by presence of soft bremsstrahlung induced by extremely intense primary transitions [3] that may mimic the effect of LEE.

In practice, the LEE has been so far reported only from a very limited number of techniques other than Oslo method, although it is supported from shell model calculations that predict it in magnetic-dipole ($M1$) transitions [4-6]. Any independent experimental confirmation of LEE is thus desired especially as data from radiative thermal neutron capture in Mo isotopes – where the LEE was also reported from Oslo data – seem inconsistent with any strong enhancement[7-9].

Almost complete decay scheme of ^{57}Fe, with more than 99% of intensity in placed transitions was published from radiative capture of thermal neutrons on ^{56}Fe several years ago [10]. In this contribution we present tests of a compatibility of these experimental data with several PSFs and NLD models. The main limitations of analysis come from expected fluctuations of individual transition intensities – they are believed to fluctuate according to Porter-Thomas distribution (PTD) around an E_γ-dependent expectation value [11]. The PTD predicts many transitions with low intensities, which may escape detection and a threshold for observation of transitions thus has to be considered in any analysis within the statistical model of nucleus.

Several different observables from ^{56}Fe(n,γ) reaction can be checked against predictions from simulations.
Special interest is paid to primary transitions, that are relevant for the radiation cross section.

In addition, a new detailed analysis of two-step γ cascade spectra from ^{56}Fe(n,$\gamma\gamma$), re-measured at Nuclear Physics Institute at Řež, has been also made. A comparison of the results from this experiment will be presented too.

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Impact of model variations for degenerate neutron capture rates within neutron star crusts

Author: Bryn Knight

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Heavy element synthesis within stellar bodies typically manifests in explosive environments such as neutron star mergers. However, at the low temperature and high density conditions of a neutron star crust, degenerate neutrons provide alternate synthesis pathways compared to conventional systems. In this work, we study the effect of this degeneracy on neutron capture rates by several rp-process ashes and neutron-rich nuclei within accreting neutron stars. We investigate variations in the nuclear physics input which constructs the absorption cross section, and their effects on the reaction rate in the context of degenerate neutron capture. This includes variations in the level density model and the γ-strength function. Our results show that degeneracy can change the capture of neutrons by orders of magnitude compared to captures under explosive conditions. This may lead to changes in the abundance evolution of rp-process ashes,and the crust's cooling following X-ray bursts.

Studying the pygmy dipole resonance in Sn isotopes with the Oslo method

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The electric dipole response of neutron-rich nuclei below the neutron threshold often reveals the presence of the pygmy dipole resonance (PDR). As this feature is commonly interpreted in relation to the neutron excess and oscillations of the neutron skin, a multifaceted experimental and theoretical study of this feature may have a significant impact on studying both the nuclear structure properties in general and heavy element nucleosynthesis via astrophysical s-, i-, and r-processes.

This work presents a systematic study of the dipole γ-ray strength functions (GSF) below the neutron threshold in eleven Sn isotopes ($^{111-113}$Sn,$^{116-122}$Sn and ^{124}Sn) with a primary goal of investigating the evolution of the pygmy dipole strength with increasing neutron number in the Sn isotopic chain. The experimental GSFs have been extracted from the particle$-\gamma$ coincidence data by applying the Oslo method [1], primarily used for a simultaneous extraction of statistical properties of nuclei, such as the GSF and the nuclear level density. The shapes of the strengths in some of the studied nuclei have been additionally constrained with the novel shape method applied to the coincidence data [2]. The previously published strengths in $^{116-119,121,122}$Sn [3] have been re-analyzed in order to provide a model-consistent analysis throughout the isotopic chain.

All experimental strengths were compared to the GSFs extracted from relativistic Coulomb excitation in forward-angle inelastic proton scattering below the neutron separation energy [4], where they were found to be in excellent agreement at least down to ≈ 6 MeV. The Oslo method strengths below and the Coulomb excitation data above the neutron threshold provide an exhaustive picture of the dipole nuclear response, covering the giant dipole resonance, the PDR, and the low-lying $M1$ strength. The evolution of parameters characterising the PDR as well as the fraction of the corresponding classical Thomas-Reiche-Kuhn (TRK) sum rule with increasing neutron number will be presented together with the study on the effect of the pygmy dipole strength on the radiative neutron capture cross-sections in these nuclei. The low-lying dipole strength appears to be almost constant ($2-3\%$ of the TRK sum rule) throughout the chain of the studied isotopes, in contradiction to the majority of theoretical approaches. Despite this, the presence of an enhancement in the strength close to the neutron threshold has a noticeable effect on the astrophysical i process in this mass region.

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Nucleosynthesis around 60Fe

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Active nucleosynthesis in our galaxy can be observed directly through the detection of long-lived radioactivities. Isotopes such as ^{26}Al, and ^{60}Fe have been observed either in solar system samples or through γ-ray observations within the galaxy. Both isotopes are predominantly produced in massive stars and ejected into the interstellar medium either via stellar winds or through the supernova explosion. Instead of only looking at absolute observational values for each isotope, the ratio of ^{60}Fe/^{26}Al can be used as a more sensitive probe since many of the observational uncertainties cancel out. In such a case, this ratio can be used to probe the production and emission of the two isotopes and the supernova mechanism itself. A long standing puzzle in our community is the fact that most theoretical models overpredict this ratio compared to the observational value. The discrepancy has been attributed to uncertainties in the nuclear reactions, and in particular the ones related to the production/destruction of ^{60}Fe. Here we report on the main reaction producing ^{60}Fe, namely the ^{59}Fe(n,γ)^{60}Fe reaction. Previous work has constrained the γ-ray strength of ^{60}Fe at energies above the neutron-separation energy (8.8 MeV). Here we will present the results of a β-Oslo measurement that extends the γ-ray strength measurement to lower energies. The presence of a significant upbend has severe implications on the reaction cross section. The impact of this result on the evolution and explosion of massive stars will be presented.

Measurement of 59Fe(n,g) reaction based on beta-OSLO method

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The experiment for measuring the 59Fe(n,g) reaction rate is performed in the Radioactive Ion Beam Line in Lanzhou, China. The beta-Oslo method is employed to obtain the level density and gamma strength function of 60Fe. This presentation will introduce the facility, detection and the preliminary results of this experiment. It also presents the impact of the 59Fe(n,g) reaction on the the r-process in the Common Envelop Jet Supernova, which jets launched by a neutron star that spirals-in inside the core of a red supergiant star in a common envelope evolution. Some novel features of different r-process scenarios are presented as well.

Determining the gamma strength function and level density in 64Fe via the beta-Oslo method

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The behavior of nuclear level densities and gamma strength functions for many regions of the nuclear landscape are not well understood, especially for and not just away from stability. For example, in the Fe-Cd region, an unexpected increase in the gamma-decay probability is seen as an up-bend in the gamma strength function below ~4 MeV. This potentially has a significant influence on extracted neutron-capture rates. It is unknown how the gamma strength function behaves for neutron-rich nuclei. Nuclear level densities and gamma strength functions are critical for constraining neutron-capture rates. Rates are often crucial missing observables for models of the r and i-processes. For the i-process in particular, sensitivity studies indicate isotopes within ~3-7 mass units of stability are often critical isotopes in determining the abundance distributions produced. Currently, facilities such as the NSCL/FRIB and ANL can produce these neutron-rich isotopes. The up-bend was first observed in iron isotopes and we populated excited states via beta-decay for the neutron-rich iron nuclei including Fe-64, a candidate for the up-bend in the gamma strength function. Gamma decays within Fe-64 were recorded with the Summing Na(I) (SuN) segmented total absorption spectrometer, which allows us to simultaneously extract the level density and strength function. We will discuss the glimpse Fe-64 provides into the evolution of these properties with increasing neutron number.

The Exploration of the Indirect Neutron-Capture Constraints of ^{87,89}Kr(n,γ)^{88,90}Kr reactions in the Astrophysical i-process using the β-Oslo method.

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The formation of heavy nuclei along the neutron-rich region of the chart of nuclides is usually explained using two main processes, namely the s- and r-processes. Recent astronomical observations have shown "strange" abundance distributions in Carbon-Enhanced Metallic Poor (CEMP) stars, which cannot be explained by these two neutron-capture processes alone, hence giving rise to additional nucleosynthesis processes. One such process is the astrophysical intermediate (i-)process.

The site at which the i-process occurs is not yet identified as one of the reasons is the associated nuclear uncertainties. The i-process occurs from 2-8 mass units away from the valley of stability, and while the structure of these nuclei along this pathway is mostly known experimentally, the neutron-capture reaction rates are almost entirely provided by theory. In particular, recent sensitivity studies of neutron-capture reactions on Kr isotopes have been identified to strongly affect Rb/Sr abundances.

To better understand the i-process, CARIBU, located at ATLAS facility at Argonne National Laboratory, was utilised to constrain the neutron-capture of the ^{87,89}Kr(n,γ)^{88,90}Kr reactions. The indirect method of β-decays from the ^{88,90}Br nuclei into ^{88,90}Kr was used to identify the resulting γ-rays using the SUmming NaI detector, SuN, and the SuNTAN moving tape system.

Nuclear level densities and γ-ray strength functions of $^{88,90}Kr$ were extracted using the β-Oslo method, of which the preliminary results will be discussed in this presentation. By exploiting the statistical properties of both $^{88,90}Kr$, the $^{87,89}Kr(n,\gamma)^{88,90}Kr$ reaction rates and cross sections will be constrained to help understand their impact on the astrophysical i-process and on the Rb/Sr production.

Development of a Photon Strength Function Database Interface

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We have developed a specialized web application with the purpose of managing, querying, and visualizing Photon Strength Function (PSF) data. This data is compiled in a well-defined format as an outcome of an IAEA Coordinated Research Project 1. This web application represents a significant advancement in accessibility and interaction with the data over existing platforms, particularly improving upon the capabilities of the prior resource noted in Ref 2.

Central to this application is the database structure, crucial for efficient data management and retrieval. Built using the Django framework, the web application's user interface is designed to present queried data and search results in an accessible format. It works seamlessly with the backend to fetch and display data (based on the data query from the user), detailing basic nuclear properties such as atomic number (Z) and mass number (A), multipolarity, energy range, and experimental method employed to produce the data. Additionally, the application offers functionalities for searching and sorting data by author names or publication years, facilitating a more refined navigation through the extensive PSF data repository. This is especially beneficial for tracking specific contributions or examining the evolution of PSF data over time.

A noteworthy feature is the dynamic data visualisation tool, which utilises Plotly to create interactive graphs displaying strength functions and other pertinent data points, thus enhancing the intelligibility of different datasets. Moreover, the platform features a comprehensive data processing pipeline. In the backend, this pipeline extracts, transforms, and loads information from data files and README files into the system, safeguarding data integrity and accessibility.

In this presentation, I will discuss and demonstrate the web application, which marks a substantial advancement in the management and dissemination of PSF data.

This work is based on research supported in part by the National Research Foundation of South Africa (Grant Number: 118846). We also acknowledge the financial support from the International Atomic Energy Agency.

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J distributions of levels for Deformed Nuclei

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The J-distribution for excited levels in the nucleus is usually calculated by a formula proposed by Bethe. His derivation assumed a spherically symmetric system. A revised formula is obtained for the spin distribution in a deformed nucleus. It is found that the average J at a given energy is raised significantly. The effect of this change on Hauser-Feshbach calculations, level densities derived from resonance counting and isomeric ratio calculations will be discussed.

Theoretical description of formation of superheavy nuclei

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The production of a superheavy element in a fusion reaction schematically proceeds through three stages: (i) the two colliding nuclei come into contact, (ii) the contact configuration evolves into a compact shape, (iii) the fused nucleus cools down by neutron evaporation. We describe the second step in a new method, utilizing the Langevin equation and random walk models. The process is schematically described in the figure below. The two fragments overcome the Coulomb barrier and come in contact (II), where the strong nuclear interaction starts to act. With a large kinetic energy, the fragments approach each other subject to a friction force as well as to a random force, where the friction strength depends on the necking of the combined object (window friction). This process is characterized by drift-dominated dynamics in the center-of- mass direction (III), and all kinetic energy dissipates into heat. With no kinetic energy several shape degrees of freedom can be explored, and the process becomes diffusion dominated (IV). The dynamics in the five shape degrees of freedom here considered is treated as Metropolis random walks. If the inner saddle is crossed a fusion event has taken place (V). Quasi-fission competes with fusion events, and we count the relative number of fusion events, constituting a formation probability. The walks are controlled by calculated angular momentum dependent potential energies as well as level-densities in a large grid in deformation space, implying that nuclear structure plays an important role. We present result of calculated formation probabilities versus excitation energy for different reactions and compare to data.

Constraining neutron-capture cross section for the i-process for the ^{151}Nd(n,γ)^{152}Nd reaction via the β Oslo method

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Nucleosynthesis of heavy elements has been traditionally attributed to two neutron-capture processes, namely the *s* and *r* processes. Recent astronomical observations have revealed stars where the abundance distributions cannot be described by the aforementioned processes and for this reason the astrophysical *i* process was introduced (*i* for intermediate between *s* and *r*). While we know neutron densities are between the *s* and *r* process, the stellar site where it can occur has not yet been clearly identified and that is largely because of the nuclear uncertainties.
The *i* process flow involves isotopes only a few steps from stability, and in this region the main nuclear physics uncertainty comes from neutron-capture reaction rates. Specifically neutron capture reactions on Nd isotopes have been identified as important for the production of Eu and Sm. With this goal in mind, an experiment was run at the ATLAS facility using the low-energy beams delivered from CARIBU to constrain neutron-capture reactions of importance for the *i* process. β-decays and their corresponding γ-rays were identified using the SuN detector and the SuNTAN moving tape system. The β-decay of $^{152-154}$Pr into $^{152-154}$Nd was measured. In this work, the

β-Oslo method was used to extract the nuclear level density and γ-ray strength function of ^{152}Nd; preliminary results will be presented. From these statistical properties, the ^{151}Nd(n,γ)^{152}Nd reaction cross section can be constrained and its significance the Eu abundance in the i process will be presented.

Gamma emission from giant dipole resonances

Author: Atsushi Tamii

Gamma decay from the giant dipole resonance to the ground state is a unique probe for studying the damping mechanism of the nuclear collective excitation. We have measured the emitted gamma rays from the giant resonances excited by proton scattering by using LaBr3 gamma-ray detectors and the Grand Riaden magnetic spectrometer. ^{90}Zr was the primary target. Similar coincidence measurement was also performed in the PANDORA project at RCNP. I plan to introduce the physics, measurement and the preliminary results.

The low-lying electric dipole strength in nuclei: the role of deformation

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The electric dipole response in nuclei is characterised at high energies by the isovector Giant Dipole Resonance (IVGDR) and, for neutron-rich nuclei, by the Pygmy Dipole Resonance (PDR) around the neutron separation energy. Even though these two excitation modes have been extensively studied, some of their characteristics are still not understood. This talk will concentrate on the discussion of the role of deformation in the excitation of the PDR. Two independent experiments were performed to study the electric dipole response of the quadrupole-deformed 154Sm nucleus. The inelastic scattering of 120-MeV alpha particles was studied at iThemba LABS while 295-MeV protons were used at RCNP. The first comparison of the isoscalar and isovector responses of the a the deformed nucleus will be presented.

The PANDORA Project: Investigating Photonuclear Reactions in Light Nuclei.

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The PANDORA (Photo-Absorption of Nuclei and Decay Observation for Reactions in Astrophysics) project is dedicated to both experimental and theoretical analysis of photo-nuclear reactions involving light nuclei with a mass below A = 60. This research is particularly significant in the context of ultra-high-energy cosmic ray investigations, where the primary mode of energy attenuation is determined by the electromagnetic interaction of the nucleus with the cosmic microwave background through the isovector giant dipole resonance(IVGDR).

Currently, propagation calculations and reaction models face challenges due to a lack of reliable experimental data sets for crucial nuclei. By utilizing virtual photon experiments conducted at iThemba LABS and RCNP, as well as real photon experiments carried out at ELI-NP, it becomes feasible to extract information such as the cross section associated with the isovector giant dipole, E1 strength and the branching ratios for particle decay for light nuclei. The first experiment of the PANDORA project that was performed at RCNP at the end of 2023 and the preliminary data analysis of ^{12}C will be presented. The Grand Raiden at RCNP spectrometer was used in conjunction with SAKRA, a backward angle silicon array for charged particle detection, and SCYLLA, a LaBr3 array.

Photonuclear excitation of 27Al and particle emission on PANDORA project.

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The PANDORA experiment, conducted in October last year in RCNP, delves into photo-nuclear reactions within the mass region below A 56. This project aims to unravel the energy loss process of ultra-high-energy cosmic rays (UHECRs) during inter-galactic propagation. The origin, acceleration mechanism, and composition of UHECRs remain mysteries. Nonetheless, cosmic-ray air-shower observatories such as Pierre Auger and Telescope Array have detected UHECRs with energies above 1020eV. Analysis of air-shower depth distributions revealed a trend to heavier in the mass composition between protons and iron at the highest energies.
UHECR nuclei are anticipated to predominantly loss their energy by emitting particles after photo-nuclear excitation induced by absorbing cosmic microwave background (CMB) photons. Consequently, understanding photonuclear reaction cross-sections and decay branching ratios assumes paramount importance in understanding the energy and mass loss process of UHECRs during inter-galactic propagation.
The experiment employed virtual photon exchange via proton scattering to excite target nuclei and determine the photo-absorption cross-sections covering the giant dipole resonance. Detection of decay particles will extract branching ratios.
I will report the experiment's setup in October 2023 in RCNP and outline the status of the analysis for 27Al.

Investigation of the character of the PDR in 96Mo via single-nucleon transfer reactions

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The pygmy dipole resonance (PDR), known as the low-lying E1 strength, is characterized by a concentration of 1− states below and around the neutron threshold. This phenomenon has been observed in neutron-rich nuclei and its investigation holds potential implications for the nuclear equation of state and nucleosynthesis. Since its initial discovery, a significant amount of research has been dedicated to comprehending the nature of the PDR, both theoretically and experimentally. An important aspect under scrutiny is the extent to which the dipole states exhibit collective behavior. This study aims to examine the nature of the PDR, specifically focusing on determining whether the 1− states are single-particle or collective in character. To achieve this, one-step transfer reactions, which possess the ability to selectively excite single-particle states, are employed as the preferred probing method. The nucleus of interest is populated using the 97Mo(p, d)96Mo reaction and its conjugate reaction, 95Mo(d, p)96Mo. The experimental investigation is carried out at the INFN-LNS facility in Catania, Italy. The resulting ejectiles are subjected to momentum analysis using the MAGNEX spectrometer and subsequently detected by its focal-plane detector. From a simplistic shell model, single-particle configurations that populate 1- and 2+ states were identified. The contribution of each configuration was determined via the use of the MDA. In this talk the results from the (p,d)

will be presented together with theoretical interpretation within the QPM framework.

This work is based on the research supported in part by the National Research foundation (NRF) of South Africa grant number 118846.

Level densities of actinides by the shell-model Monte Carlo method

Author: Dallas DeMartini

Co-author: Yoram Alhassid

Level densities are an important input to the Hauser-Feshbach theory of compound-nucleus reactions. Compound-nucleus reactions have numerous applications, including stellar nucleosynthesis and the design of next-generation nuclear reactors.

The microscopic calculation of level densities in the presence of correlations is a challenging many-body problem. The configuration-interaction shell model provides a suitable framework for the inclusion of correlations, but the large dimensionality of the many-particle model space has hindered its application in heavy nuclei. The shell model Monte Carlo (SMMC) method enables calculations in model spaces that are many orders of magnitude larger than spaces that can be treated by conventional diagonalization methods. The SMMC has been applied to nuclei as heavy as the lanthanides.

We have recently extended the SMMC method to the actinides. The actinides present several technical challenges when compared with the lanthanides: the required valence single-particle model space is larger, and the lower first excitation energy requires larger values of the imaginary time (or inverse temperature) to cool the nucleus to its ground state. Here, we present the first SMMC results for nuclear level densities up to the neutron separation energies in several even-even actinides and compare with available experimental results. This work is supported in part by the U.S. DOE grant No. DE-SC0019521.

Properties of the low-energy dipole strength of direct and cascade transitions in neutron-excess nuclei

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New results on dipole strength distributions of direct and cascade transitions in neutron-excess nuclei, obtained in a theoretical approach based on energy-density functional theory and quasiparticle-phonon model are discussed [1]. The method and its recent developments, including a reaction theory [2, 3], have been successfully applied in spectroscopic studies of different types of nuclear excitations in stable and exotic nuclei, including two-phonon states [4], pygmy and giant resonances [1-5], thus demonstrating its effectiveness and reliability. Besides the single-particle nature of the excited nuclear states from the PDR region, different properties of the low-energy dipole strength emerge from the analysis of inelastic photon- and proton-scattering spectral distributions and branching ratios, from which the role of the quasi-continuum coupling with the low-energy dipole strength can be studied [5]. Experimentally, the determination of the dipole strength function and the associated photoabsorption cross section requires knowledge of the intensity distribution of the ground state transitions and their branching ratios. These quantities cannot be derived directly from the measured spectra. However, they can be determined theoretically from our microscopic calculations, which are also important for the interpretation of the fine structure of the dipole photoabsorption cross-section in atomic nuclei.

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Recent developments in photonuclear reaction studies with quasi-monochromatic photon beams

Author: Johann Isaak

Photons provide a particularly clean probe for studying a wide range of nuclear structure phenomena 1. Their interaction with the nucleus is described by the electromagnetic interaction, so that the nuclear response can be separated almost model-independently from the details of the reaction mechanism. Hence, photon-induced reactions are important tools in nuclear physics for determining properties of low-spin excited states in atomic nuclei.

Important quantities for the modeling of nuclear and stellar reaction rates are photon strength functions (PSF) and nuclear level densities (NLD). Systematic studies of PSFs and NLDs across the nuclear chart are an important testing ground for benchmarking microscopic and macroscopic models that allow extrapolation from mostly stable isotopes to experimentally unreachable exotic neutron-rich isotopes.

Many different experimental approaches are used to study PSFs, either by studying photoabsorption cross sections or by observing the γ-decay behaviour of excited nuclear states 2. In several cases, results from complementary methods show discrepancies, in particular when comparing data from real-photon scattering and particle-induced reactions [3,4,5].

In this contribution, recent results for PSFs from coincidence experiments with quasi-monoenergetic photon beams at the High Intensity γ-Ray Source (HIGS) at Duke University are discussed [6].
Moveover, the nuclear self-absorption method offers a completely new approach to the determination of NLDs in the energy range below the neutron separation energy. For a given integrated cross section in a defined excitation energy interval, the amount of self-absorption depends on the number of levels in this interval. Hence, a pilot experiment is presented for the determination of NLD of ^{88}Sr exploiting nuclear self-absorption measurements with quasi-monoenergetic photon beams [7].

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Large-scale shell model calculations of the magnetic dipole strength in 116Sn and 120Sn

Author: Jenny Finsrud

The γ-strength function (γSF) describes the average probability of having a multipole transition that emits or absorbs a γ of energy $E\gamma$. At the lowest γ energies, a low-energy enhancement has been observed in several nuclei, but the research conducted on this area is still scarce. The low-energy enhancement may impact astrophysical neutron-capture reaction rates, which can help us understand why the distribution of heavy elements
is like it is today. Experimental results support that the the enhancement is of dipole character, but whether it is electric or magnetic remains inconclusive. I have conducted large-scale shell model calculations of 116Sn and 120Sn in order to investigate the M 1 contribution to the low-energy enhancement. It is the open-access shell model code KSHELL 1 and the supercomputer Betzy that has been used to perform the calculations.
The resulting γSFs and nuclear level density functions have been compared to experimental data obtained by M. Markova 3, where the data for 116Sn is not yet published. These results will be presented and discussed. Several additional tests have been conducted in order to explain the discrepancies seen in the experimental and numerical data. This includes the possible contribution from E2 and the effective interactions and other parameters used in the calculations.

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The Many Faces of the Pygmy Dipole Resonance in ^{120}Sn

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A concentration of electric dipole strength below the neutron separation threshold, often unified under the name Pygmy Dipole Resonance (PDR), is known to be common in medium to heavy mass nuclei and has been studied intensively in the past. As a part of the general γ-ray strength function, its generating mechanisms are of genuine interest for nuclear structure and nuclear astrophysics alike, and several complementary experiments have uncovered intricate details of this strength accumulation.
An isoscalar surface-mode character was identified in the lower-energy part of the PDR in ^{124}Sn based on the different responses observed in $(\alpha, \alpha'\gamma)$ or (^{17}O,^{17}O$'\gamma$) experiments compared to (γ, γ') data [1,2]. Conversely, the higher-energy part was attributed to a more isovector excitation taking place deeper inside the nucleus. In ^{120}Sn, access to the single-particle character of the PDR was recently gained by comparing ^{119}Sn$(d, p\gamma)$ and ^{120}Sn(γ, γ') reactions in both experiment and theory [3,4]. Although visually similar to the case of ^{124}Sn$(\alpha, \alpha'\gamma)$, the ^{119}Sn$(d, p\gamma)$ experiment is sensitive to a very different type of nuclear structure information.
This contribution gives an overview of the current experimental knowledge on the PDR in ^{120}Sn and discusses the structural comprehension based on Quasiparticle-Phonon-Model calculations. Combined with dedicated reaction theory for each population mechanism, consistent observables from experiments and theory are presented and the impact of the information gained in ^{120}Sn on the genuine low-energy E1 strength throughout the chart of nuclides is discussed.
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Impact of finite-temperature on electromagnetic dipole transitions

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Finite temperature effects in electric dipole (E1) and magnetic dipole (M1) transitions can have a significant influence on gamma strength functions [1,2]. In this work, we developed a self-consistent finite temperature relativistic quasiparticle random phase approximation (FT-RQRPA) based on relativistic energy density functional with point coupling interaction [3,4]. This study focuses on elucidating the impact of temperature (T) ranging from T=0 to 2 MeV on E1 and M1 transitions in closed- and open-shell Ca and Sn nuclei. With an increase in temperature, E1 giant resonances undergo moderate modifications, however, new low-energy excitations appear at high temperatures due to thermal unblocking effects, particularly in neutron-rich nuclei. In the case of M1 excitations, the transition strength undergoes a notable shift towards lower excitation energies in Ca and Sn nuclei, primarily ascribed to the decrease in spin-orbit splitting energies and the weakening of the residual interaction. Moreover, an interesting result is obtained for 40,60Ca nuclei at higher temperatures, i.e., the appearance of M1 transitions, which are forbidden at zero temperature due to fully occupied (or fully vacant) spin-orbit partner states. Thus, these considerable temperature effects on E1 and M1 transitions are crucial in accurately modeling gamma strength functions, with potential applications in astrophysically relevant nuclear reaction studies.

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Enhancement of low-energy magnetic dipole radiation arising from the scissors motion

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The low-energy-enhancement in the γ strength function is investigated in an angular-momentum-projected approach with the neutrons and protons projected respectively to account for the scissors motion. The rare earth nucleus 144Nd is studied as an example for which the enhancement is reproduced to a quantitative level. It is suggested that the low-energy-enhancement arises from near-degenerate sequences connected by strong M1 transitions, as a result of the approximately free scissors motion in weakly deformed nuclei.

Studying Low-Lying E1 Strength & Neutron Capture Rates in A 50 Nuclei via (d,p) and (d,pγ) experiments at FSU

Authors: Bryan Kelly[1]; Mark Spieker[1]

Co-authors: Alex Conley [1]; Dennis Houlihan [1]

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We have started an experimental program at Florida State University's John D. Fox Superconducting Accelerator Laboratory to study the single-particle structure of the Pygmy Dipole Resonance (PDR) and to inform models that use (d,pγ) as a surrogate reaction for (n,γ) neutron capture. In our program, we focus on fp-sd shell nuclei as Inakura et al. predicted a significant strength increase of the PDR beyond N=28 and connected it to a specific nuclear structure effect. The same E1 strength increase is expected at N=50, which could directly influence (n,γ) rates at the beginning of the r process path. We, therefore, chose to study the microscopic structure of the PDR around N=28 as these nuclei are accessible for detailed stable beam (d,p) experiments. In addition, we recently commissioned the CeBrA (Cerium Bromide Array) demonstrator, which can be used to perform (d,pγ) experiments at the SE-SPS (Super-Enge Split-Pole Spectrograph). In this talk, I will report initial results of our (d,p) and (d,pγ) experiments on the even-even 48,50Ti and 62Ni nuclei, as well as usefulness of particle-gamma coincidences, with emphasis on how to constrain (n,γ) rates from surrogate (d,pγ) reactions.

Predicting and constraining level densities and gamma-ray strength functions

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Level densities and gamma-ray strength functions are critical inputs for statistical reaction calculations of (n,g), (n,n'), (n,2n), and multiple other reactions. Ideally, we predict these Hauser-Feshbach inputs, along with suitable optical potentials, for the vast number of isotopes of interest to applications. More realistically, we will have to pursue a combination of theoretical predictions, indirect approaches, and direct measurements to achieve our objectives. I will describe ongoing work to combine microscopic structure and reaction theories to predict and constrain level densities and gamma-ray strength functions needed for Hauser-Feshbach calculations of neutron-induced reactions on isotopes near and away from the valley of stability.

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Strolling through strontium: Approaching the neutron drip line

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Addressing gaps in nuclear data for thousands of radioactive isotopes is a daunting challenge. We focus on the need for cross sections for neutron-induced reactions involving short-lived fission products relevant for non-proliferation and forensics applications, supporting the science-based U.S. stockpile stewardship mission, and advancing our understanding of basic nuclear physics and cosmogenic nucleosynthesis. Developments in radioactive beam facilities, detector systems, and indirect techniques have enabled us to experimentally-constrain previously inaccessible cross sections. In addition, these advancements have improved predictive reaction theory for unstable nuclei, which assists to bridge some gaps. The A=95 mass region will be addressed in this talk, presenting the first experimentally-determined neutron-induced reaction rates on exotic strontium isotopes from this multi-institutional collaboration. We performed a radioactive beam experiment at CARIBU at Argonne National Laboratory and used the β-Oslo method to constrain the ^{93,94,95}Sr(n,γ)^{94,95,96}Sr cross sections. By leveraging Rb

beams to populate highly excited states in ^{94,95,96}Sr and using a total absorption spectrometer (TAS) known as the Summing NaI(Tl) (SuN) to measure the total energy emitted by the γ rays, we experimentally determined the nuclear level density (NLD) and γ-ray strength function (γSF). These extracted statistical nuclear properties are key ingredients in Hauser-Feshbach calculations of neutron-capture reaction rates. The NLD, γSF, and cross sections for these short-lived neutron-rich Sr isotopes will be presented. The analysis toolkit developed for this new measurement serves as a pivotal foundation for future measurements of heavy-mass fission products far from stability.

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Impact of level densities and γ-strength functions on r-process simulations

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Studies attempting to quantify the sensitivity of the r-process abundances to nuclear input have to cope with the fact that the theoretical models they rely on, rarely come with confidence intervals.
This problem has been dealt with by either estimating these intervals and propagating them statistically to the final abundances using reaction networks within simplified astrophysical models, or by running more realistic astrophysical simulations using different nuclear-physics models consistently for all the involved nuclei.
Both of these approaches have their strengths and weaknesses.
In this work, we run r-process calculations for five trajectories using 49 different neutron-capture rate models.
The results shed light on the importance of taking into account shell effects and pairing correlations in the network calculations.

Extraction of level densities from (n,x) reaction measurements on 68Zn using the evaporation technique

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During stellar evolution, nuclear reactions predominantly occur at energies significantly lower than the Coulomb barrier, highlighting the role of neutron-induced reactions in the synthesis of chemical elements, especially those heavier than iron. By employing the evaporation technique, neutron-induced reactions can also be utilized to extract nuclear level densities (NLD) of unstable isotopes, which are essential for accurate reaction rate calculations. The main idea of the evaporation technique is that the differential cross section for the emission of a particle from a compound nucleus is proportional to the appropriate transmission coefficient and NLD. Therefore, the detailed shape of the particle spectrum is determined by the energy dependence of the level density. Improved experimental NLD can be obtained by comparing the experimental spectra with those calculated using the Hauser-Feshbach theory and adjusting the theory parameters to more accurately reproduce the experimental spectra.
To probe nuclear level densities in the Ni region, particularly relevant to the i-process in metal-poor stars, cross sections measurements for the $^{68}Zn(n,p)^{68}$Cu and $^{68}Zn(n,a)^{65}Ni$ reactions were carried out at the Weapon Neutron Research (WNR) facility of the Los Alamos Neutron Science Center (LANSCE). A "white" neutron beam ranging in energy between 0.1 and 100 MeV impinged on a highly enriched ^{68}Zn target located at the center of the Low Energy NZ (LENZ) detection system. The reaction products were detected using annular S1 DSSD telescopes upstream and downstream of the target. Utilizing the wide energy spectrum of the neutron beam, an appropriate incident neutron energy range (10-13 MeV) was selected for the level density analysis so that both the direct and non-primary mechanism components in the evaporation spectra are minimal.
Our study aims to deduce nuclear level densities for the neutron-rich isotopes of ^{68}Cu and ^{65}Ni via the evaporation technique using a white neutron beam for the first time. In the future, we plan to expand the technique to heavier nuclei that may be relevant to stellar environments characterized by i-process neutron densities.
In this talk, we present details on the experimental setup, analysis, and preliminary results for the extraction of the nuclear level density of ^{68}Cu and ^{65}Ni.

This work is supported by the U.S. Department of Energy, Office of Science, Nuclear Physics program under the award number DE-SC0022538

SFyNCS, a multi-detector to measure gamma rays cascade

Author: Mathilde Pottier[1]

Co-authors: Adeline Ebran [1]; Laurent Gaudefroy [1]; Olivier Roig [1]; Vincent Méot [1]

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An almost 4π multi-detector, called SFYNCS (γ Strength function for Neutron Cross Sections), was built and commissioned in 2023 at CEA/DAM-Bruyères-le-Châtel. The goal of this new detection system is to undertake experiments studying the radiative deexcitation of nuclei and to find out nuclear level densities (NLD) and γ strength functions (gSF). This consists in measuring with 60 NaI(Tl) crystals, γ-rays energies from γ-cascades of exited nucleus produced in a (d,p) reaction and identified using a highly segmented ΔE-E silicon detector telescope. A measured ($E_{\gamma-rays}$, $E_{excitation}$) matrix is extracted to apply the Oslo method [1] in addition to an A.I. method based on Markov chain algorithm. Both methods giving NDL and gSF will be compared including consideration on the Brink-Axel hypothesis. These two ingredients are crucial for reaction models, for the purpose of getting predictive radiative capture cross-sections on nuclei for astrophysical studies or nuclear energy applications.
We will present the preliminary results we have obtained on the reaction ^{176}Lu(d,pγ)^{177}Lu interesting of the ^{177}Lu nucleus desexcitation. This reaction (d,p) is related to the neutron capture reaction (n,γ), here ^{176}Lu(n,γ)^{177}Lu, well-known in astrophysics through the s-process of the nucleosynthesis. As this latter reaction was studied recently using the DANCE detector at LANL in Los Alamos, we will show comparaisons with these data and a new data evaluation using the gSF and NLD obtained here and from calculations with the QRPA (Quasi-particle Random Phase Approximation) formalism. Perspectives of SFyNCS experiments will be discussed as well as the following of the Markov chain algorithm.

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Observational Consequences of Angular Momentum in Fission

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The role of angular momentum in fission has been the subject of intense recent attention. Published data showed that, while the fission fragment spins may be generated by highly correlated processes, the final, measured, fragment spins appeared to be largely uncorrelated. This talk will summarize advances made with the fission simulation model FREYA to study the role of angular momentum in fission. FREYA can easily simulate a variety of scenarios for generating fragment spin and determine the observational consequences.
The work of R.V. was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344. The work of J.R. was performed under the auspices of the U.S. Department of Energy by Lawrence Berkeley National Laboratory under Contract DE-AC02-05CH11231.

Effect of the Coulomb force on fission fragment angular momenta

Author: Jorgen Randrup

Nuclear fission produces fragments endowed with typically half a dozen units of angular momentum each. After scission has occurred and the fragments recede, they are still interacting via the Coulomb force which exerts an undulating but steadily decreasing torque on deformed fragments. This may lead to an amplification of their rotations, in effect shifting the fragment spin distributions upwards by 1-2 units. Complete dynamcial calculations are carried out to illustrate the effect quantitatively, but its essential features can be understood by simple perturbative considerations.

Extracting isomeric yield ratios of fission fragments

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In nuclear fission, a heavy nucleus splits and the fission fragments emerge spinning 2. The isomeric yield ratio (IYR) i.e. the population frequency of an isomer, is know to be sensitive to the angular momentum of the fragment. Measuring the IYR can therefore give information about about the initial sate of the fission fragments. This work uses a technique to reach short lived isomeric states where the IYR has not been measured before 1. We study the IYR of the 52ns isomer in 130Sn, extracted for the fissoning system 238U(n,f) at two different energies, as well as the 511ns isomer in 135Te extracted for the fissoning systems 232Th(n,f) and 238U(n,f) at two different energies. From looking at how the different fissoning systems affect the IYR, we get more knowledge about what impact the angular momentum generation. The fission code GEF is used in combination with the nuclear decay code TALYS to find the fragment angular momentum from the IYR.

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Study of the neutron-gamma competition in the deexcitation of fission fragments

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Nuclear fission is a very intricate and complex process that, despite being discovered more than 85 years ago, still lacks a full complete description. In fact, the question about the distribution of the deformation and excitation energy of the fissioning nucleus between the newly-born primary fission fragments right after scission is still discussed. The consensus states that around 80% of the energy released by fission converts into kinetic energy of the primary fission fragments while the remaining 20% are distributed between the primary fragments in terms of excitation energy. This distribution hasn't been properly measured up to now. The angular momentum of the primary fission fragments before any neutron emission hasn't been measured before either. In order to answer this question, one needs to probe the structure of these high excitation energy nuclei through the measurement and reconstruction of their prompt deexcitation channels, in other words: the prompt neutron and prompt gamma emission.
Performing these measurements and characterizing both the neutron and gamma prompt emissions and the competition between the two during the deexcitation of the primary fission fragments, fragment by fragment, is the core of my work. The experimental set up of my PhD experiment allows the measurement of both neutrons and gamma rays along with fragment selection and kinetics reconstruction thanks to a twin Frisch-Grid ionization chamber.
The capability to measure neutrons and gamma emissions concurrently, combined with the ability to select the decaying fragments, provides a complete insight on the primary fragment's structure. Further more, assessing the correlation between the prompt neutron and prompt gamma emissions will either confirm or refute the rather fragile consensus where when at high excitation energy: neutrons first and gammas after.

This line of research is crucial for advancing our understanding of nuclear fission, which has numerous applications and implications across various scientific fields, including nuclear energy, reactor physics and fundamental nuclear physics. This work holds promise in shedding light on the elusive aspects of fission and contributing to the development of a more complete understanding of this fundamental nuclear process.

Underground Nuclear Astrophysics: pushing direct cross section measurements toward the Gamow window

Author: Gianluca Imbriani

Nuclear fusion reactions are at the heart of nuclear astrophysics as they control the energy production in stars and determine the synthesis of the elements in our Universe. Most cross sections are too small to be directly measured in a laboratory at the stellar energies. They are extrapolated by means
of phenomenological nuclear models anchored to available high energy data. Cosmic rays, environmental radioactivity and beam-induced background reactions on target impurities, all represent a major limitation to the measurement of thermonuclear cross sections at stellar energies.

The LUNA collaboration (https://luna.lngs.infn.it) was the first to propose a new approach to nuclear astrophysics, by exploiting the extremely low background inside the Laboratori Nazionali del Gran Sasso (LNGS), which is part of the Italian Istituto Nazionale di Fisica Nucleare. In over 30 years of activity, LUNA has achieved extremely important results with major implications not only in nuclear astrophysics but also in cosmology and particle physics, using the LUNA 400 kV machine, a Singletron accelerator which has been operational since 2001.
The LNGS-INFN is currently expanding the accelerator laboratory having installed a 3.5 MV Singletron machine designed and built by High Voltage Engineering Europe (HVEE) . The 3.5 MV machine can deliver intense proton, helium, and carbon beams with well-defined energy resolution and stability.
A first experimental proposal for the use the new 3.5 MV machine, presented by the LUNA-Collaboration, focuses on measurements of the reactions:
• 14N(p,g)15O, which influences stellar evolution and nucleosynthesis, and specifically the "metallicity" of the solar core;
• 12C + 12C, which affects the final fate of intermediate-mass and massive stars and the associated nucleosythesis;
• 22Ne(a,n)25Mg, which provide the source of neutrons in stellar interiors.
During my talk I will report about some recent results and the future program of LUNA.

The direct determination of the cross section of the 12C + 12C reaction at astrophysical energies

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Carbon burning is the third stage of stellar evolution determining the final destiny of massive stars and of low-mass stars in close binary systems. Only stars with a mass larger than a critical value M^{*}_{up} 10M, can ignite C in non-degenerate conditions and proceed to the next advanced burning stages up to the formation of a gravitationally unstable iron core. Various final destinies are possible, among which a direct collapse into a black hole or the formation of a neutron star followed by the violent ejection of the external layers (type II SN). Less massive stars $M < M_{up}$ 7M, never attain the conditions for C ignition and will evolve into CO White Dwarfs. The values of M^{*}_{up} and M_{up} are linked to the $^{12}C + ^{12}C$ reaction rate: the little knowledge we have of it at astrophysical energies is the greater contribution to the uncertainty of these masses. Stellar C burning proceeds mainly through the $^{12}C(^{12}C,$ $)^{20}Ne$ and $^{12}C(^{12}C, p)^{23}Na$ channels. The cross-sections can be measured either detecting the emitted charged particles or the γ-rays produced by the decay of the excited states of 20Ne and 23Na.

$^{12}C + ^{12}C$ fusion reactions were investigated in a wide energy range, down to 2.1 MeV, still above the astrophysical energies. A direct measurement is necessary for both stellar evolution models and the correct analysis of indirect data. The aim of my PhD project is the direct determination of the cross section of the
$^{12}C + ^{12}C$ reaction at astrophysical energies through γ spectroscopy at LNGS. Here a devoted setup is being developed to reach an extremely low background condition. The project will make use of the new MV accelerator available at the Bellotti Ion Beam Facility at LNGS, in the context of the LUNA MV research project. This accelerator is capable of producing a high intensity carbon beam (150 μA for a beam of $^{12}C^{+}$ and 50 pμA for a beam of $^{12}C^{++}$) with great energy resolution and stability. The detection setup will be made of several NaI scintillators and an HpGe. NaI detectors will be placed in a compact arrangement around the HpGe, covering a ~3.5 solid angle: such a configuration guarantees a high detection efficiency, while preserving the excellent HpGe resolution (1.2 keV at 1.33 MeV). The NaI configuration will also function as an active veto for Compton, environmental radioactivity and beam-induced background events.
The detectors array will be placed in a 2cm thick copper shielding surrounded by a 25cm lead shielding which will further reduce the
environmental background of more than 2 orders of magnitude.

With this setup, we'll be able to measure the level density of ^{24}Mg through the de-excitation of ^{20}Ne and ^{23}Na nuclei. This will allow us to explore the possible cluster structures of the ^{24}Mg nucleus. In particular, we'll be able to examine the E_{cm} = 1.5 MeV - 4 MeV energy

window, where the cluster states could be found.

With my contribution I will present details of recent results in setup development and Geant4 simulations.

Correlated Gamma Neutron Energy measurements on Niobium

Author: Keenan Myers

Co-authors: Charles Henderson [1]; Elan Park-Bernstein [1]; Emma Rice [1]; Isabel Hernandez [1]; Jon Batchelder [2]; Joseph Gordon ; Joshua Brown [2]; Lee Bernstein [3]; Speero Tannous [1]; Thibault Laplace [2]; Tyler Johnson [1]; Tyler Nagel

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Measurements of neutron inelastic cross sections on niobium are needed for improvement of nuclear reaction modeling for stockpile stewardship, magnetic confinement fusion, and space exploration. The Gamma Energy Neutron Energy Spectrometer for Inelastic Scattering (GENESIS), located at the 88 Inch Cyclotron at Lawrence Berkeley National Lab, is the first facility that allows experiments which measure correlated high-resolution gamma and outgoing neutron energy spectra using a modular combination of organic scintillators and high-purity germanium detectors. An experiment was performed with a naturally mono-isotopic ^{93}Nb target with the GENESIS array. The 88-inch Cyclotron provided a pulsed neutron source via the thick target deuteron breakup mechanism using 25 MeV deuterons on a thick carbon target, The incident neutron energy for an event observed in the array is determined using time of flight.The pulse period of the beam leads to multiple energies being associated with each pulse due to frame overlap. Modeling will be performed where physical parameters including nuclear level density, photon strength and optical model parameters are adjusted until they optimally reproduce the gamma-ray and neutron spectra observed in the array addressing the ambiguity due to frame overlap. This presentation will present preliminary results and planned improvements of the GENESIS array.

High precision spectroscopy of fission shape isomers with Nu-Ball2 : Exploring the gamma back-decay

Author: Corentin HIVER

Co-authors: Giorgia PASQUALATO ; Jonathan WILSON

Fission shape isomers (SI) are poorly understood metastable states characterized by a second superdeformed potential energy minimum co-existing with normal deformed states in the low- spin regime 1. Although many such isomers have been observed in the actinide region, our understanding of the states in the second minimum remains very limited. For most SIs, the only available information is their half life, determined via their exclusive decay mode - delayed fission. However, an interesting possibility of competing branch of γ back-decay towards normally deformed states opens up as the number of protons decreases, as fission barrier becomes harder to penetrate. The nature of this back-decay, however, remains poorly understood, owing to the fact that at the time of their discovery (several decades ago) the techniques of γ ray spectroscopy were not sufficiently well-developed.
In this context, we performed in 2023 two high-precision γ-ray spectroscopy experiments to study 236mU and 232mTh using the Nu-Ball2/PARIS spectrometer. Nu-Ball is a hybrid spectrometer that combines 24 High Purity Germanium (HPGe) Clovers and 64 phoswiches (LaBr3/NaI) of the PARIS collaboration 2, covering more than 90% of the total solid angle. In addition, a Double-sided Stripped Silicon Detector (DSSD) 3 was used to measure the energy of the outgoing light charged particles. Each detector was managed by a state-of-the art fully digital FASTER electronics [4] that allowed for triggerless data acquisition at high data rates. The exceptional selectivity of such a setup comes from a combination of the high resolution of the HPGe detectors, high energy efficiency, charged particle selection, and calorimetry to determine prompt and delayed energy balances.
The full characterisation of these back-decay γ rays enables a unique and precise way to determine the parameters of fission barriers, which play an essential role in the theory of fission. Moreover, spectroscopy in the second well will allow for a better understanding of nuclear structure of these mysterious high-deformation states. Here, the first results of the nu-Ball2/PARIS fission shape isomer experiments will be presented.

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Taking advantage of nuclear isomers

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Nuclear isomers are metastable excited states with half-lives that can range over orders of magnitude from nanoseconds to billions of years. The states owe their long half-lives to a hindered transition to the ground state which arise due to a mismatch between starting and final states. Isomeric states impact multiple nuclear science applications including nucleosynthesis. The decay modes of isomeric states are varied leading to the potential emission of charged particles, photons, and (potentially) neutrons.

With recent advances in analysis techniques, it is possible to determine model-independent partial level densities in some short-lived nuclei. The application of these analysis techniques following beta decay can provide a partial level density over a limited spin range. If the parent nucleus has multiple isomeric beta decaying states with different spins, then a partial level density can be inferred within different spin windows. This provides a means to extract some of the first information on the spin distribution at high excitation energy in the resulting nucleus. Simulated results will be presented along with the prospects for application to experimental data and the experimental facilitates needed to isolate the required isomeric states.

Remeasuring of the γ-decay branching ratio of the Hoyle State

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The triple-alpha process is one of the most fundamental processes in stellar nucleosynthesis, and in particular, the stellar production of carbon. This process entails the fusion of three helium nuclei to form an intermediate state in ^{12}C. This intermediate state can decay back into its three constituent alpha particles or radiatively decay to form stable ^{12}C. At temperatures between 0.1 - 2 GK, the triple-alpha reaction is almost exclusively mediated by the Hoyle state in 12C. Understanding the properties of the Hoyle state is therefore important for the modeling of the subsequent stellar evolution.

The creation of stable carbon through this process happens mainly through two available decay branches, leaving the ^{12}C in its ground state. The radiative decay of the Hoyle state to form stable 12C proceeds mainly through gamma decay and pair production. The radiative width of the gamma-branch has been measured several times between the period 1961 to 1976 [1-7]. Most of the measurements performed up until 1976 have yielded results which are in decent agreement with one another. However, a recent measurement performed in 2019 by Kibédi *et al.* [8] resulted in a significantly larger radiative branching ratio (Γ_{rad}/Γ) compared to all previous measurements.

Given the astrophysical significance of the Hoyle state, resolving this conflict is crucial. Therefore, new measurements have been performed to reinvestigate the gamma-decay branching ratio of the Hoyle state. The experiments have been performed at the Oslo Cyclotron Laboratory through the ^{12}C(p, p'$\gamma\gamma$)-reaction. In these experiments, the SiRi particle telescope [9] was employed to detect proton ejectiles and the OSCAR LaBr3 array was used to detect the coincident gamma-ray decays. Preliminary results from this measurement will be presented, together with the analysis method and experimental details.

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Testing indirect experimental method for constraining the 193,194Ir(n,γ) cross sections

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As far as nucleosynthesis or element formation is concerned, almost all the nuclei heavier than iron have been made in part by the slow neutron capture and the rapid neutron capture processes (50% each), respectively known as the s- and r- processes [1].
The neutron capture reactions 192Ir(n,γ)193Ir and 193Ir(n,γ)194Ir are indirectly studied by analysing data obtained from the Oslo Cyclotron Laboratory (OCL). These data will allow for the study of 193,194 Ir iso- topes, from the 192Os(,tγ) and 192Os(,dγ) reactions, respectively. The 193Ir(n,γ)194Ir cross sections which our measurement will constrain will provide a comparison to existing (n,γ) measurement data [2].
In addition, the 192Ir(n,γ)193Ir reaction is a branching point in the s-process making it very interesting, but it is challenging to measure the (n,γ) cross section directly since 192 Ir is unstable. Therefore the OCL data may provide very valuable information on the 192Ir(n,γ)193Ir cross section by indirectly constraining it with the experimental nuclear level density (NLD) and γ-strength function (γSF).
An array of Sodium Iodine (NaI)Tl detectors, called CACTUS, detected γ-rays and the silicon particle telescope array, called SiRi, was used to detect charged particles in coincidence. The NLDs and γSFs are being extracted below the neutron separation energy, Sn, using the Oslo Method [3]. Furthermore, the NLDs and γSFs will be used as inputs in the open-source code called TALYS to calculate cross-sections of 193,194 Ir. I will provide preliminary results of the measured NLDs and γSFs from the 192Os(,dγ)194Ir reaction which will be used as inputs in the code TALYS to calculate cross-sections of 193,194Ir.

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Giant Monopole studies at iThemba LABS

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The Isoscalar Giant Monopole Resonance (ISGMR) is a collective nuclear excitation that was discovered nearly five decades ago. Our current comprehension of the ISGMR in stable nuclei relies heavily on experimental investigations conducted at the Texas A&M University (TAMU) Cyclotron Institute and the Research Center for Nuclear Physics (RCNP) over the past thirty years. These investigations involved small-angle (including 0°) inelastic -particle scattering measurements at energies of 240 MeV and 386 MeV, respectively. Non-negligible differences in the monopole strength distributions are observed for some nuclei, e.g. 24Mg, the even-even isotopes of Ca, Zr and Mo, as well as for 208Pb. These differences could impact the extracted centroid energy assigned to the ISGMR, as well as the description of K-splitting in light nuclei such as 24Mg. In light of the potential impact on our understanding of nuclear incompressibility, inelastic -particle scattering measurements were performed at 200 MeV at iThemba LABS to elucidate these differences. The agreement in the monopole strength distributions for particular data-sets imply that they should be prioritized for evaluating nuclear incompressibilities. At a minimum, it's crucial to recognize the structural differences in monopole strength distributions across all accessible data-sets before commenting on the value of, and potential trends in, the nuclear incompressibility.

On the path to gamma-beam experiments: Activities with the ELIGANT setups from ELI-NP

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The ELIGANT instruments are the dedicated tools being developed for studying high-energy collective nuclear excitations using the gamma beam at ELI-NP. The topics of interest in these studies range from fundamental nuclear structure properties of the Giant Dipole Resonance and the low-energy strength enhancement in the Pygmy Dipole Resonance region, as well as applications in p-process nucleosynthesis and propagation of Ultra-High Energy Cosmic Rays. The tools at our disposal consist of large-volume LaBr3:Ce and CeBr3 detectors for high-energy γ-rays, liquid scintillators and lithium glass scintillators for high- and low-energy neutron time-of-flight. In preparation for the gamma-ray beam, these instruments have been installed and commissioned with sources. They have also been used for preparatory experiments at the IFIN-HH Tandem accelerators, aiming to provide the ELI-NP physics program with a running start with complementary measurements. Most notably, several in-beam campaigns performed was in collaboration with the Department of Nuclear Physics, where the ELIGANT detectors were mounted in the ROSPHERE spectroscopic array at one of the 9MV beamlines, and a series of experiments were performed aiming for GDR and PDR properties via γ-ray studies. Here, we will give an overview of the ELIGANT group's present and future activities.

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Electric dipole response of sd-shell nuclei within the Large-Scale Shell Model approach

Author: Oscar Le Noan

Co-author: Kamila SIEJA

Photo-nuclear reaction rates provide key inputs to various applications of nuclear physics and consist fundamental probes of nuclear structure, from single particle to collective excitations, revealing nature of complicated nucleonic correlations. Among the excitations of nuclei
due to the external field, the E1 dipole response is of particular interest. In this talk, I will discuss recent systematic calculations of E1 dipole response of long-lived sd-shell nuclei within the large-scale shell model framework that are of special interest for the PANDORA collaboration. It will be shown that our theoretical framework permits to reproduce to a good accuracy the position of the GDR peak and the shape of the E1 distributions in the experimentally known cases. If time allows, the enhancement of the TRK sum rule and its connection to various terms of the nuclear Hamiltonian as well as the analysis of the pygmy-dipole modes in this region will be presented.

PGCM description of M1 transition strength in ^{24}Mg

Authors: Stavros Bofos[1]; Jaime Martínez-Larraz[2]; Mikael Frosini[3]; Benjamin Bally; Thomas Duguet[1]; Tomas R. Rodriguez[4]; Kamila SIEJA

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The theoretical description of γ-ray strength functions (γSF) is of special interest in the field of nuclear astrophysics, where some processes - like the radiative neutron capture - are dependent of this quantities, with the dipole modes playing a dominant role. The use of reliable theoretical models to predict γSF is a main aim, where the interacting shell model is known to provide precise results for the electromagnetic transitions. However, due to the computational complexity of the exact diagonalization of the model-space, it is restricted to certain regions of the nuclear chart. In a recent study 1, the quasiparticle random-phase approximation (QRPA) has been used to compute M1 strength functions in 25 nuclei from $A = 26$ to $A = 136$ using shell model calculations as a benchmark, employing identical Hamiltonians and valence spaces. It was concluded that the lack of correlations in the nuclear states and the truncation of the many-body space to two-quasiparticle excitations on top of the mean-field states could be important limitations in the description of dipole M1 strength, while it was suggested that methods like the projected generator coordinate method (PGCM) could produce an improvement caused by the enriched wave functions originated from the breaking and posterior restoration of the symmetries of the system, also giving the possibility to include varied collective degrees of freedom.

In this work, different approaches using the PGCM have been tested to reproduce the M1 transition strength between the different 1^+ excited states and the 0^+ ground state of ^{24}Mg, with the exact diagonalization of the Hamiltonian as a benchmark.

1 https://doi.org/10.48550/arXiv.2312.11040

Constraining the i Process Elemental Abundances through Indirect Neutron Capture Rate Measurements of ^{90}Sr and ^{140}Cs with SuN

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The slow (s) and rapid (r) neutron capture processes have long been considered to produce nearly the entirety of elements above Fe, but when comparing their yields with spectroscopic data, inconsistencies in abundance arise in the Z=40 region. These differences are expected to be attributable to the intermediate (i) neutron capture process.

Increases in the ^{90}Sr(n,γ)^{91}Sr and ^{140}Cs(n,γ)^{141}Cs capture cross sections have been shown to decrease simulated abundances of Zr and Ce respectively, with neither having previously experimentally measured reaction rates. Constraining the uncertainties on these reactions will provide information to explain the discrepancies between the observed and predicted elemental abundances of Zr and Ce in i-process environments such as CEMP-i stars.

The completed β-Oslo analysis of ^{91}Sr to reduce uncertainties in the ^{90}Sr(n,γ)^{91}Sr reaction will be presented, measured via the β-decay of ^{91}Rb into ^{91}Sr with the SuN total absorption spectrometer at the NSCL in 2018. By measuring both γ-ray and excitation energies, a coincidence matrix was produced to perform the Oslo analysis, providing experimental information on the Nuclear Level Density (NLD) and γ-ray Strength Functions (γSF), two critical components in limiting the uncertainty of the neutron capture cross section when it cannot be directly measured.

In addition, the first preliminary results of the β-Oslo analysis of ^{141}Cs will be discussed, investigating the neutron capture rate of ^{140}Cs, completed with SuN at ANL in 2021.

These constrained uncertainties will allow us to better characterize the contribution of ^{90}Sr and ^{140}Cs to the i process and progress in explaining observed abundances in suspected i-process stellar environments.

Study of the charged particle decays from 48Cr using CAKE

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The observation of γ-ray decays from the radioative isotope ^{44}Ti makes it one of the significant isotopes in the diagnosis of core-collapse supernovae (CCSNe) explosions [1]. The abundance of ^{44}Ti from CCSNe explosions has been shown to be strongly dependent on the $^{44}\text{Ti}(\alpha,p)^{47}\text{V}$ reaction rate, which destroys ^{44}Ti [2]. Direct measurements of the $^{44}\text{Ti}(\alpha,p)^{47}\text{V}$ reaction within the Gamow window ($E_{\text{c.m.}}$ = 2 - 6 MeV) have been challenging due to the low cross sections and insufficient radioactive ion beam intensities [3,4]. As a result, the reaction rate is still based on statistical models, which may not be reliable for α-induced reactions on N=Z nuclei due to the lower effective level density in the compound nucleus. To get the necessary experimental constraints of the $^{44}\text{Ti}(\alpha,p)^{47}\text{V}$ reaction such as the level density and branching ratios of the compound nucleus, ^{48}Cr, a high-resolution 0° $^{50}\text{Cr}(p,t)^{48}\text{Cr}$ coincidence measurement was performed using the K600 magnetic spectrometer and an array of five double-sided silicon detectors called CAKE. Preliminary results from the coincidence measurements will be presented.

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The Future of Nuclear Data in the USA

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[1] *UC Berkeley/Lawrence Berkeley National Lab*

The Nuclear Science Advisory Committee (NSAC) is charged with determining the priorities for government-funded nuclear science research in the United States. NSAC has been developed Long Range Plans (LRP) every 6-8 years since 1979 with the most recent one released in October of 2023. Top priorities were given to executing the research program started in the last decade, developing ton-scale neutrinoless double beta-decay measurements and building a new electron-ion collider. Unlike earlier years, the 2023 NSAC LRP also recognized the importance of Nuclear Data activities and endorsed its expansion. This followed a pair of reports written in response to a 2022 charge to NSAC to assess the recent accomplishments and status of the US Nuclear Data Program and explore opportunities to enhance and advance its custodianship of nuclear data.

In this talk I will present an overview of the NSAC's recommendations for nuclear data, focusing on topics presented at the Oslo workshop series since its inception in 2007 including nuclear level densities, photon strength functions, nuclear astrophysics, fission, nuclear energy systems and the production of radioisotopes for medical applications.