EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Proposal to the ISOLDE and Neutron Time-of-Flight Committee

Statistical properties of warm nuclei: Investigating the low-energy enhancement in the gamma strength function of neutron-rich nuclei

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Abstract

We propose to start a program to study the gamma-ray strength function of neutron rich nuclei in inverse kinematics with radioactive beams at HIE-ISOLDE. An unexpected increase in the gamma strength function at low energy has been observed in several stable nuclei using the Oslo method. This year these results were confirmed with a different experimental technique and model independent analysis developed by iThemba/Livermore. If this enhancement of the gamma strength function is also present in neutron rich nuclei, it will strongly affect the neutron capture cross sections, which are important input in stellar models of synthesis of heavier elements in stars. We propose to start with an experiment using a ^{66}Ni beam of 5.5 MeV/u, where the data will be analyzed using both methods independently, and we are sure to get enough statistics, before moving to more neutron rich nuclei. When/if neutron rich Ti, Fe or Mo beams will be available at ISOLDE we will submit additional proposals.

Requested shifts: 24 shifts, run (21 shifts 66Ni, 3 shifts for setup)
Beamline: [MINIBALL + CD and LaBr3]

Introduction

In the ground state the atomic nucleus is ordered with paired nucleons in time reversed trajectories, similar to electrons in superconducting solids. For cold nuclei, i.e. nuclei at low excitation energy, single-particle and collective states are well defined and have more or less pure wave functions. In this case one can measure the excitation energy of individual states and the transition probability between them. As the nucleus is heated by increasing its excitation energy, the proton and/or neutron pairs will break apart and thereby open up more degrees of freedom for nuclear excitations. When all pairs are broken the system becomes chaotic and can be described approximately as a Fermi gas. The density of levels increases with excitation energy and at some point the levels start to overlap, so that it is not possible to distinguish individual levels anymore. When this occurs it becomes impossible to study transition probabilities between individual states. In this region of quasi-continuous levels it is more suitable to describe the nucleus by statistical properties such as the level density (per energy unit) and the γ strength function, which is the average transition probability between states of a given energy difference. The level densities and γ strength functions are fundamental properties of the atomic nucleus which govern the formation and decay of excited nuclei. They are furthermore crucial parameters to describe nuclear reactions occurring for example in stars or nuclear reactors. In Oslo an experimental method [1] to measure both level densities and γ-strength functions has been developed (see method A, below).

Recently [2], we measured an unexpected increase in the γ-strength function for several Fe isotopes. We found that the probability to decay with low energy γ-rays was more than ten times larger than current theories predict, (see Fig. 1). Similar observations have later been reported by the Oslo group in, e.g., Mo [3] and Sc [4] isotopes. Similar observations are seen in preliminary data for ^{59,60}Ni. As with all new discoveries, the enhancement of low energy γ emission is controversial. It forces us to drastically change our view of how the nucleus emits γ-rays in the continuum. Furthermore, there are no theories today which can reproduce/explain these experimental results.

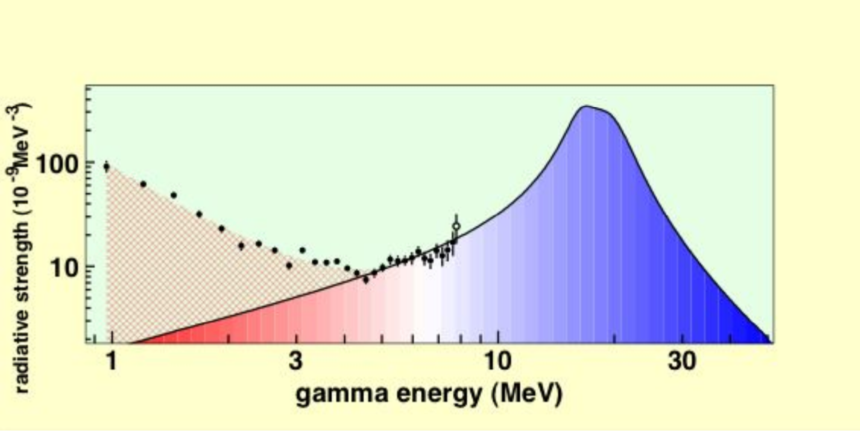

Figure 1: Experimental γ-strength function for ^{57}Fe (data points with error bars) compared to the tail of the giant electric dipole resonance. An increase of more than ten times is found at low γ-energies

This year these results were confirmed with a different experimental technique and model independent analysis developed by iThemba/Livermore (see method B below). This experimental approach was used to study the shape of the RSF in ^{95}Mo populated in the (d,p) direct reaction. The results were published in Physical Review Letters [5]. The work clearly supports, for the first time and independently, the picture of an increase of the RSF at low-energies in ^{95}Mo (Fig.2) as previously reported by Guttormsen et al., [3].

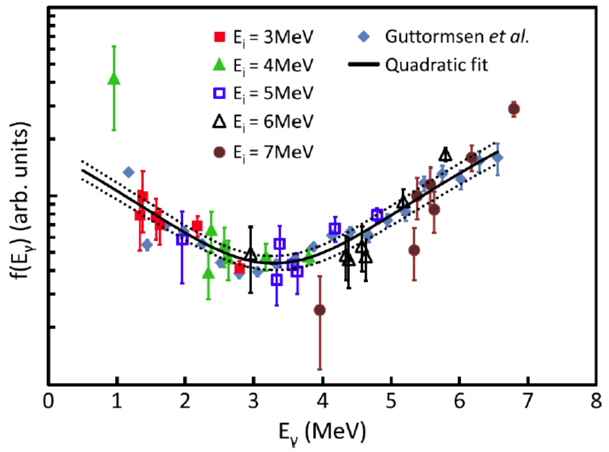

Figure 2: Comparison of the RSF from the work of Ref.[5](indicated by colored symbols) to results from Ref.[3]. The quadratic polynominal fit to the RSF of Ref.[3] is shown as a solid black line while fitted upper and lower error bars are shown as dotted black curves.

Level densities and γ strength functions are important input parameters in Hauser-Feshbach calculations of cross-sections, widely used in both nuclear astrophysics and reactor physics applications. These cross-sections are inputs into large network calculations of nucleosynthesis in stellar environments as are found during supernova explosions. With today's theories there is a discrepancy between the measured and calculated abundances of elements in our solar system. The enhanced probability to decay by low-energy γ rays, measured in Oslo for stable nuclei, will have a dramatic effect on neutron capture cross-sections if it also exists in neutron rich exotic nuclei [6], see Fig.3. Therefore it is important to measure if the low energy enhancement also exists in neutron-rich nuclei.

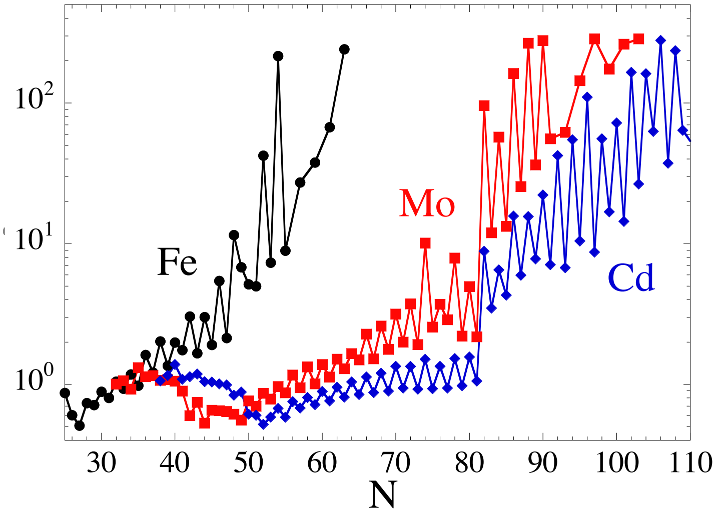

Figure 3. Calculated neutron capture cross sections including the low energy enhancement divided by the neutron capture cross section without; as a function of neutron number [6].

Method A (The Oslo method)

The nuclear physics group at the Oslo Cyclotron Laboratory has developed a unique technique to extract simultaneously the level density and γ-strength function from primary γ-ray spectra [1]. The experiments were carried out using the Oslo Cyclotron, which provides light-ion beams: protons, deuterons, ^{3}He and alpha particles. Typically a ^{3}He-beam of 38 MeV is used to study (^{3}He,α) and (^{3}He,^{3}He$'$) reactions on various target materials. Lately, we have also used the (p,p$'$), (p,d) and (p,t) reactions. The light ejectiles were detected in coincidence with γ rays from the excited residual nucleus on an event-by-event basis by the multi-detector system CACTUS, comprising 28 collimated 5”x5” NaI(Tl) detectors with a total efficiency of 15% for a 1.33MeV γ-ray. The charged particles are detected and identified by a efficient ΔE-E particle telescope called SiRi (Silicon Ring). SiRi is comprised of 8 trapezoid shaped telescopes arranged in a ring either at forward or backward angles covering a solid angle of 6% of 4π. Each trapezoid is segmented in 8 strips for the front detector with a common E detector. By plotting the energy deposited into the ΔE detector versus the E detector the different types of charged particles are uniquely identified. From the reaction kinematics it is trivial to extract the excitation energy of the residual nucleus from the energy and angle of the emitted particle. The spectrum of emitted γ rays can then be analyzed for a given excitation energy of the residual nucleus. The gamma spectra are corrected for the detector response function through an unfolding procedure. One of the main components of the Oslo method is an iterative subtraction technique to extract the primary γ rays from the cascade of γ rays originating from states at a given excitation energy. The method relies on the assumption that the γ-ray spectrum originating from a given state is independent of the mechanism with which it is populated, i.e. whether it is directly populated in the nuclear reaction or populated by a preceeding γ ray. The distribution of primary γ rays contains information on both the level density and the γ strength function, which are then extracted simultaneously in an iterative procedure.

Method B (Wiedeking)

A new model-independent experimental technique has been developed [5] to address questions regarding the existence and origin of the low-energy enhancement in the RSF. The method involves the use of coupled high resolution particle and γ-ray spectroscopy and its power lies in the ability to positively identify primary γ-ray decay from well-defined excitation energy regions to individual low-lying discrete states. A key aspect is the detection and extraction of correlated particle-γ-γ events. Proton energies from the silicon telescopes determine the entrance excitation energy into the residual nucleus produced in the reaction. Tagging on γ-ray transitions originating from low-lying discrete levels specifies the states which are being fed by the primary γ rays. When a discrete transition is detected in coincidence with a charged particle, additional requirements are applied to the second γ ray, so that the energy sum of the discrete and primary transition be equal to the excitation energy. Any particle-γ-γ event satisfying these conditions provides an unambiguous determination of the origin and destination of the observed primary transition. This approach is shown schematically in Fig.4.

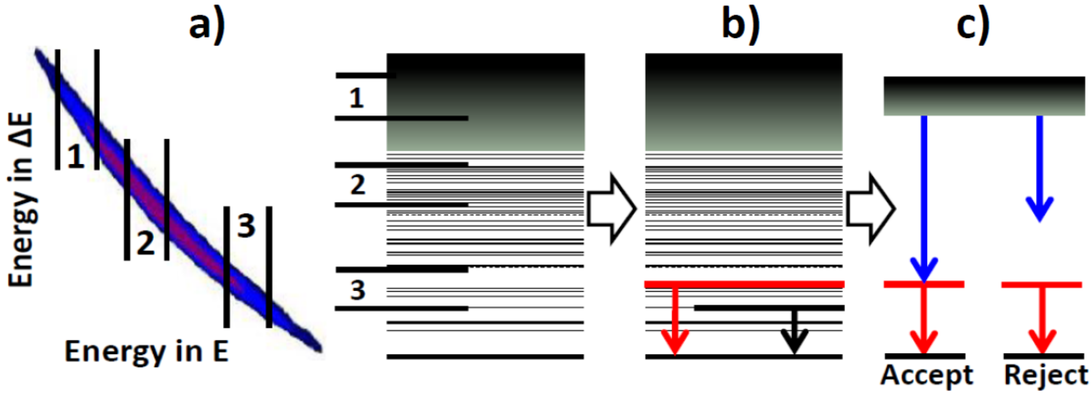

Figure 4: Procedure to extract primary gamma-ray transitions: (a) Tagging on proton energies determines the excitation energy of the nucleus populated in the reaction. High (low) proton energies yield low (high) excitation energies. (b) low-lying discrete levels are selected by tagging on gamma rays emitted from these states. (c) Applying the condition that the sum of discrete and primary gamma-ray energies must be equivalent to the excitation energy provides acceptable events of unambiguous origin and destination. Transitions not satisfying the requirements are rejected.

With the enhancement only observed in light and medium mass stable nuclei, it will be very interesting to use this new technique in studies on neutron-rich nuclei for which no RSF information is available. The experimental methodology for the proposed experiment will work in the same manner as described above. Results from this measurement will not only be used in conjunction with results from the Oslo method to determine the overall shape of the RSF but also to determine the RSF to individual discrete spin and parity states in neutron-rich systems.

Experimental setup

The Ni isotopes are produced with a standard UCx/graphite target irradiated with the proton beam from the PS Booster. We request a beam energy of 5.5 MeV/u for the ^{66}Ni beam. Assuming a proton current of 2 μA and an efficiency of HIE-ISOLDE of 5%, the expected beam intensities will be almost 1x10^7 at MINIBALL. As the life times of the Ni-isotopes that have been produced at ISOLDE are long compared to the breeding time the loss in efficiency will originate from the losses in the charge breeding set up. We require the slow extraction from the EBIS to reduce the instantaneous particle rate.

Beam purity (>95%) is important for the Oslo method analysis, while for the method of Wiedeking et al. it is not crucial, as one will gate on gamma lines in ^{66}Ni in the analysis. In IS469 excellent beam purity (better than 99%) was achieved for Ni isotopes, using a standard UCx target and RILIS for ionization.

To detect the charged particles we will use an annular strip CD detector (80 microns) as a Delta-E detector, followed by two QQQ2 E-detectors (1mm thick each). We need thick Si-detectors, since the most energetic protons will have more than 20 MeV. The Delta-E, E information is used for particle identification and reconstruction of the excitation energy of the ^{66}Ni nucleus from kinematics.

For both analytical methods it is important to determine the excitation energy of the ^{66}Ni nucleus as accurately as possible, as we wish to have less than 500keV excitation energy bins. The main contribution to the energy spread is due to the angular resolution of the first CD detector. The difference in angle of 2.5° (one strip) corresponds to ca. 225keV difference in excitation energy. The energy spread of the beam energy is less than 0.6% (FWHM), which corresponds to a difference in excitation energy of ca. 200keV. To minimize more uncertainty in the excitation energy from straggling/energy loss in the target, a very thin target of 0.1 mg/cm2 polyethylene will be used. The carbon in the target will not pose a problem, as we will gate on the protons in the analysis.

To increase the efficiency of detecting the higher energy gamma rays we propose to add 6 large volume LaBr3 detectors, removing some MINIBALL detectors. The group in Oslo is currently purchasing 2 (3,5 x 8 inch) $LaBr_3$(Ce) detectors and expects to have at least 6 by the time the experiment is scheduled. Also, the Saha Institute of Nuclear Physics, India has presented plans bring their $LaBr_3$ (Ce) array for a campaign at HIE-ISOLDE.

Summary of requested shifts:

We request a total of 24 shifts: 21 shifts of ^{66}Ni beam and 3 shifts for setting up.

References:

[1] A. Schiller et al., Nucl. Instrum. Methods Phys. Res. A 447, 494 (2000).

[2] A. Voinov et al., Phys. Rev. Lett 93, 142504 (2004);

[3] M. Guttormsen et al., Phys. Rev. C 71, 044307 (2005);

[4] A.C. Larsen et al., Phys. Rev. C 76, 044303 (2007).

[5] M. Wiedeking et al., Phys. Rev. Lett 108, 162503 (2012).

[6] A. C. Larsen and S. Goriely, Phys. Rev. C 82, 014318 (2010).

Appendix

DESCRIPTION OF THE PROPOSED EXPERIMENT

The experimental setup comprises: *(name the fixed-ISOLDE installations, as well as flexible elements of the experiment)*

Part of the Choose an item.	Availability	Design and manufacturing
MINIBALL + only CD	☒ Existing	☒ To be used without any modification
6 LaBr$_3$(Ce) detectors	☐ Existing	☐ To be used without any modification ☐ To be modified
	☒ New	☐ Standard equipment supplied by a manufacturer ☐ CERN/collaboration responsible for the design and/or manufacturing
	☐ Existing	☐ To be used without any modification ☐ To be modified
	☐ New	☐ Standard equipment supplied by a manufacturer ☐ CERN/collaboration responsible for the design and/or manufacturing
[insert lines if needed]		

HAZARDS GENERATED BY THE EXPERIMENT

(if using fixed installation) Hazards named in the document relevant for the fixed [MINIBALL] installation.

Additional hazards:

Hazards	*[Part 1 of the experiment/equipment]*	*[Part 2 of the experiment/equipment]*	*[Part 3 of the experiment/equipment]*
Thermodynamic and fluidic			
Pressure	[pressure][Bar], [volume][l]		
Vacuum			
Temperature	[temperature] [K]		
Heat transfer			
Thermal properties of materials			
Cryogenic fluid	[fluid], [pressure][Bar], [volume][l]		
Electrical and electromagnetic			
Electricity	[voltage] [V], [current][A]		
Static electricity			
Magnetic field	[magnetic field] [T]		
Batteries	☐		
Capacitors	☐		
Ionizing radiation			
Target material	[material]		
Beam particle type (e, p, ions, etc)	^{66}Ni		
Beam intensity	2×10^{8}		
Beam energy	5.5 MeV/u		
Cooling liquids	liquid N$_2$		

Gases	[gas]		
Calibration sources:	☐		
• Open source	☐		
• Sealed source	☐ Standard γ-ray source for MINIBALL[ISO standard]		
• Isotope			
• Activity			
Use of activated material:			
• Description	☐		
• Dose rate on contact and in 10 cm distance	[dose][mSV]		
• Isotope			
• Activity			
Non-ionizing radiation			
Laser			
UV light			
Microwaves (300MHz-30 GHz)			
Radiofrequency (1-300MHz)			
Chemical			
Toxic	[chemical agent], [quantity]		
Harmful	[chemical agent], [quantity]		
CMR (carcinogens, mutagens and substances toxic to reproduction)	[chemical agent], [quantity]		
Corrosive	[chemical agent], [quantity]		
Irritant	[chemical agent], [quantity]		
Flammable	[chemical agent], [quantity]		
Oxidizing	[chemical agent], [quantity]		
Explosiveness	[chemical agent], [quantity]		
Asphyxiant	[chemical agent], [quantity]		
Dangerous for the environment	[chemical agent], [quantity]		
Mechanical			
Physical impact or mechanical energy (moving parts)	[location]		
Mechanical properties (Sharp, rough, slippery)	[location]		
Vibration	[location]		
Vehicles and Means of Transport	[location]		
Noise			
Frequency	[frequency],[Hz]		
Intensity			
Physical			
Confined spaces	[location]		
High workplaces	[location]		
Access to high workplaces	[location]		
Obstructions in passageways	[location]		
Manual handling	[location]		
Poor ergonomics	[location]		

0.1 Hazard identification

3.2 Average electrical power requirements (excluding fixed ISOLDE-installation mentioned above): *(make a rough estimate of the total power consumption of the additional equipment used in the experiment)*

… kW