Enhanced low-energy γ-decay probability – Implications for r-process (n,γ) reaction rates

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Abstract

An unexpected enhancement in the average, reduced γ-decay strength at very low γ-transition energies has been observed in fp-shell nuclei as well as in the Mo region. Very recently, it has been discovered in ^{138}La, which is, so far, the heaviest nucleus to display this feature. In this work, we present an experimental and theoretical overview of the low-energy enhancement. In particular, experimental evidence for the dipole nature of the enhancement, and shell-model calculations indicating strong, low-energy $M1$ transitions are shown. Possible implications of this low-energy enhancement on astrophysical (n,γ) reaction rates of relevance for r-process nucleosynthesis are discussed.

1. Introduction

One of the remaining major challenges in nuclear astrophysics today is to properly describe the nucleosynthesis for elements heavier than iron [1]. The main nucleosynthesis processes creating heavy elements were identified by Burbidge, Burbidge, Fowler and Hoyle [2] and also independently by Cameron [3]. The slow neutron-capture (s-) process and the rapid neutron-capture (r-) process are known to produce almost 100% of the observed nuclides heavier than iron. The s-process is rather well understood from a nuclear-physics point of view, as it relies on a nuclear reaction network in the vicinity of the β-stability line where the relevant reaction rates are to a large extent experimentally accessible (see Ref. [4] and Refs. therein). The r-process, on the other hand, remains elusive due to two main factors: (i) the astrophysical site(s) is(are) not yet clearly identified; popular suggestions include

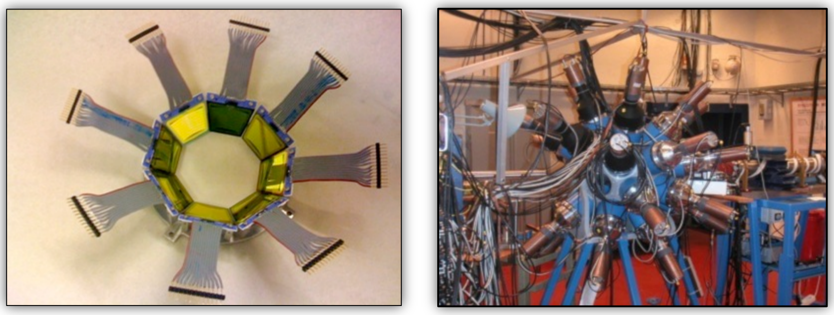

Fig. 1: (Color online) The Silicon Ring SiRi [16] and the γ-detector array CACTUS [15].

the neutrino-driven wind following a core-collapse supernova, and neutron-star mergers [5, 6]; (*ii*) the majority of the crucial nuclear-data input required for modeling r-process abundances are not experimentally constrained, and large theoretical uncertainties in the determination of *r*-process reaction rates are a substantial obstacle for a meaningful comparison with observed *r*-process abundances. In sophisticated and more realistic scenarios for the rapid neutron capture (*r*-) process, (n,γ) rates may play a pivotal role [5], especially for cold *r*-process scenarios where an $(n,\gamma)-(\gamma,n)$ equilibrium cannot be established. Hence, a good knowledge of nuclear γ-decay properties at high excitation energy (up to the neutron separation energy S_n) is crucial. The *nuclear level density* and the *γ-ray strength function* (γSF) are two of the main ingredients needed to calculate radiative neutron-capture cross sections and reaction rates.

Until recent years, the γSF was believed to decrease with decreasing transition energy, which is reflected in current recommendations and implementations of γSF models [7, 8, 9]. However, measurements of the γSF for highly excited iron isotopes (up to S_n) clearly demonstrate the opposite [10, 11]; for these nuclei, the γSF for γ energies less than 4 MeV exhibits an increase as the γ-ray energy decreases. In the following, the experiments revealing the low-energy enhancement will be discussed, as well as theoretical interpretations of the phenomenon, and its potential impact on radiative neutron-capture rates for very neutron-rich nuclei.

2. Experiments, level density and γSF data

The low-energy enhancement was first discovered in ^{56,57}Fe [10], where the Oslo method [12, 13, 14] was applied on particle-γ coincidence data from the (^{3}He,^{3}He$'\gamma$) and (^{3}He,$\alpha\gamma$) reactions. The MC-35 Scanditronix cyclotron delivers proton, deuteron, ^{3}He and α beams. The current experimental setup at the Oslo Cyclotron Laboratory (OCL) consists of the γ-ray detection array CACTUS [15], which is built up of 26 collimated NaI(Tl) detectors, and the Silicon Ring (SiRi), which is a segmented $\Delta E - E$ particle-telescope array [16] measuring the charged particles emitted in the nuclear reactions (see Fig. 1). The energy of the emitted particles, taking into account the reaction kinematics and the Q-value of the reaction, gives information on the excitation energy of the residual nucleus. A brief overview of the Oslo method is given below.

The Oslo method consists of four main steps:

1. Unfold the excitation-energy tagged NaI spectra to correct for the detector response [12];
2. Obtain the distribution of primary γ rays for each excitation-energy bin by an iterative subtraction method [13];

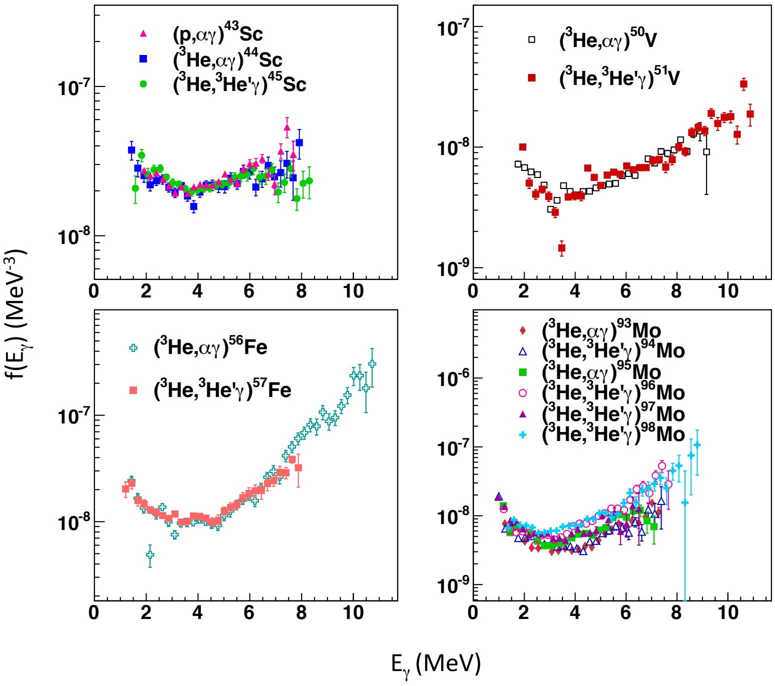

Fig. 2: (Color online) Data from OCL showing the γSF of Sc [20, 21] (upper left), Fe [10] (lower left), V [22], and Mo isotopes [23].

3. Extract the functional form of the level density $\rho(E)$ and the γSF $f(E_\gamma)$ from an iterative, simultaneous χ^2 fit of the landscape of primary γ rays [14];
4. Normalize the obtained level density and γSF to known, discrete levels, neutron-resonance parameters, and/or other auxiliary data [14, 17].

Note that for step 3, no particular, initial assumptions are needed for the shape of the level density and/or the γSF; in fact, a flat distribution is used for the first trial function. The final result does not depend on the choice of the initial trial function.

Regarding nuclear level densities, one of the perhaps most important results is that they increase linearly in a log plot (see e.g. Ref. [18] and references therein), which is interpreted as the nuclear temperature being constant and they are very well approximated by the constant-temperature expression [19]: $\rho(E) = 1/T \exp(E - E_0)/T$, where T is the nuclear temperature and E_0 is an energy shift. This implies that a first-order phase transition is taking place [18].

The low-energy enhancement has been observed in many light nuclei using the Oslo method, such as Sc [20, 21], V [22] and Mo isotopes [23] (Fig. 2). Very recently, the low-energy enhancement was found in ^{138}La [24], which is the heaviest nucleus exhibiting this feature as of today. For a full list of references and for open access to the data, see [25]. In Ref. [10], the low-energy enhancement was confirmed by examining intensities of two-step cascade spectra following neutron capture on ^{56}Fe, i.e. ^{56}Fe$(n,\gamma\gamma)^{57}$Fe. Recently, the low-energy enhancement was also confirmed for the ^{95}Mo case [26], using a new technique to extract the relative γSF from the quasicontinuum to individual low-lying levels.

As the standard Oslo method is restricted to measuring nuclei close to the valley of stability, a new method has been developed, the β-*Oslo method* [27], where level density and γSF are inferred from total absorption spectra following β decay of a neutron-rich nucleus. The first case where the method was used was the β decay of ^{76}Ga into ^{76}Ge, where the γ rays emitted from ^{76}Ge were measured with the segmented, total-absorption spectrometer SuN [28]. Now, the initial excitation energy of ^{76}Ge is given by the sum of all γ rays, while the individual segments provide the γ spectra for each excitation-energy bin. Having the excitation-energy vs. γ-ray energy matrix at hand, the Oslo method can be used to extract the level density and γSF. This technique is very promising for neutron-rich nuclei where the Q-value for β decay is close to the neutron separation energy in the daughter nucleus, and when there is no significant branch of β-delayed neutrons. New data on ^{70}Ni taken at NSCL/MSU in February 2015 represent the first case of a neutron-rich nucleus analyzed with the β-Oslo method [29].

For a long time, the low-energy enhancement was a complete puzzle, as it appeared to contradict all established models of the electric dipole strength, which was believed to be the dominant contributor to the γSF for γ-ray energies below the neutron separation energy. Speculations about its physical origin included abnormally strong rotational $E2$ transitions in the quasicontinuum, or even vibrational transitions, or simply that there were leftovers of strong $E2$ transitions from the ground-state rotational bands that were not subtracted correctly in the procedure to obtain the primary-γ distributions. Hence, gaining insight into the multipolarity of the low-energy enhancement was of utmost importance. Recent experimental work has indeed shown that the low-energy enhancement in ^{56}Fe is dominated by dipole transitions [11], as seen from angular distributions of the low-energy enhancement utilizing the angles of the NaI detectors in CACTUS. The remaining experimental challenge is to firmly establish the electromagnetic character of the low-energy enhancement, be it magnetic or electric or a mix of both, as theoretical approaches explaining this feature differ on this point. This will be discussed in the following section.

3. Theoretical descriptions of the low-energy enhancement

There has been significant progress in the theoretical understanding of the low-energy enhancement the two last years. From having no theoretical explanation, there are now three articles describing and (at least qualitatively) reproducing the experimental results. First, in Ref. [30], the authors make use of the thermal continuum quasiparticle random-phase approximation and explain the low-energy enhancement as due to $E1$ transitions from thermally excited single-quasiparticles. Moreover, the shell-model calculations presented in Refs. [31, 32] demonstrate $M1$ transitions with strong $B(M1)$ values for low transition energies, providing a steadily increasing and non-zero γSF as $E_\gamma \to 0$. The shell-model $B(M1)$ values from Ref. [32] are shown in Fig. 3; note that these are directly proportional to the $M1$ γSF and the level density at the intial excitation energy, see Eq. (1) in Ref. [32].

As the theoretical interpretations differ on the electromagnetic nature of the low-energy enhancement, it is imperative to determine experimentally whether it is magnetic or electric, or whether both contribute to the observed structure. In Ref. [10], an attempt was made to determine the electromagnetic character by calculating the $(n, \gamma\gamma)$ two-step cascade intensities within a statistical decay model, but with no success; it was found that the error bars were too large and, within the experimental uncertainties, both $E1$ and $M1$ (and even $E2$) transitions could be present.

In principle, on the theoretical side, it would be ideal to calculate both $E1$ and $M1$ transitions within the same framework and model. As of today, the shell-model calculations concern only $M1$ (and $E2$) transitions, while the QRPA approaches have been restricted to $E1$ transitions only. Hence, in the future, an experimental effort to nail down the electromagnetic character, in combination with a theoretical development to include all dipole transitions within the same framework, is highly desired to understand the mechanism behind the low-energy enhancement.

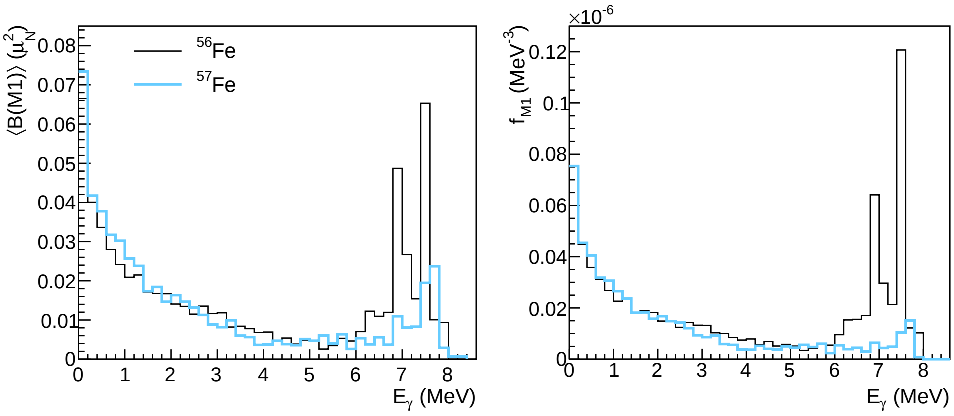

Fig. 3: Averaged $B(M1)$ values for transition-energy bins of 200 keV and excitation energies between $E \approx 6-8$ MeV and $\approx 5-8$ MeV for ^{56,57}Fe (left) and the corresponding γSFs (right); from the calculations of Ref. [32]. Note that these are from positive(negative)-parity levels for ^{56}Fe(^{57}Fe) only.

4. Impact on radiative neutron-capture reaction rates

As mentioned in Sec. 1., the nuclear level density and γSF are important input parameters for calculating astrophysical (n,γ) reaction rates. Moreover, the low-energy enhancement in the γSF may have a non-negligible effect on these rates, as shown in e.g. Refs. [33, 34]. Here, using the nuclear-reaction code TALYS [8], and assuming that the low-energy enhancement will persist also for very neutron-rich nuclei involved during the *r*-process neutron irradiation, an increase in the (n,γ) rates of a factor of $\sim 10-100$ is found for neutron-rich Fe, Ge, Mo and Cd isotopes.

Such a significant effect on the reaction rates brings further motivation to obtain a good understanding of the low-energy enhancement, since a direct measurement of any (n,γ) rate on unstable nuclei, and even less on nuclei of r-process relevance is currently not possible, and will probably remain out of reach for many years to come. Furthermore, a large-scale *r*-process network calculation typically involves ≈ 5000 nuclei and ≈ 50000 reaction rates. Thus, one has to rely on theoretical estimates of these rates, which in turn call for robust and sound theoretical approaches to obtain a reasonable predictive power [5]. Hence, testing these models against experimental data, both for stable and neutron-rich nuclei, is crucial. A close interaction between nuclear experiment and theory as well as astrophysics observations and theory will hopefully bring new insight on the many remaining mysteries of the heavy-element nucleosynthesis.

5. Summary

A low-energy enhancement has been discovered in the γSF of many nuclei. Theoretically, there are two approaches providing an explanation for the low-energy enhancement; however, they differ on the physical mechanism behind the structure and its electromagnetic character. An experimental determination of the electromagnetic character of the low-energy enhancement is necessary to resolve this discrepancy.

The low-energy enhancement, if present in very neutron-rich nuclei, may have a significant impact on astrophysical (n,γ) reaction rates relevant to the *r*-process. Reducing the uncertainties in the nuclear input data of large-scale *r*-process calculations is highly desirable, and as such, a deep understanding of the γSF would be of great importance both for a fundamental nuclear structure perspective as well as from a nuclear astrophysics point of view.

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