UPBEND AND M1 SCISSORS MODE IN NEUTRON-RICH NUCLEI — CONSEQUENCES FOR r-PROCESS (n,γ) REACTION RATES*

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An enhanced probability for low-energy γ-emission (*upbend*, $E_\gamma < 3$ MeV) at high excitation energies has been observed for several light and medium-mass nuclei close to the valley of stability. Also the M1 *scissors mode* seen in deformed nuclei increases the γ-decay probability for low-energy γ-rays ($E_\gamma \approx 2$–3 MeV). These phenomena, if present in neutron-rich nuclei, have the potential to increase radiative neutron-capture rates relevant for the r-process. The experimental and theoretical status of the upbend is discussed, and preliminary calculations of (n,γ) reaction rates for neutron-rich, mid-mass nuclei including the scissors mode are shown.

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1. Introduction

Resonance-like structures in the γ-ray strength function (γSF), which is a measure of the average, electromagnetic decay properties of the nucleus, may reveal the underlying nuclear structure and shed light on decay modes at high excitation energy. The unexpected enhanced decay strength at low γ-ray energies (the *upbend*, $E_\gamma < 3$ MeV) found in fp-shell [1, 2] and $A \sim 90$–100 nuclei [3, 4] represents a recent finding in that respect. If this upbend is present also in neutron-rich nuclei, their (n, γ) reaction rates could be significantly enhanced [5]. Similarly, the presence of the M1 *scissors mode* in deformed nuclei (Refs. [6, 7] and references therein) may enhance the γSF for low γ-ray energies and correspondingly the astrophysical (n, γ) rates. In the following, the present knowledge of the upbend is presented, and for the scissors mode preliminary reaction-rate calculations for neutron-rich nuclei in the region $A \sim 60$–180 are shown.

2. The low-energy upbend

The low-energy upbend was first discovered in ^{56,57}Fe [1] and $^{93-98}$Mo [3] using the Oslo method [8], and was later confirmed in ^{95}Mo [4] using a completely different and virtually model-independent technique. Very recently, the multipolarity of the upbend was measured in ^{56}Fe to be of dipole nature [9]. However, current theoretical descriptions on the upbend differ on the electromagnetic character: the work of Litvinova and Belov [10] for ^{94,96,98}Mo within the thermal-continuum quasiparticle random phase approximation predicts an electric character, while shell-model calculations for $^{94-96}$Mo and ^{90}Zr by Schwengner *et al.* [11] give a strong enhancement for low γ-energy M1 transitions due to a re-coupling of high-j proton and neutron orbits. Recent large-basis shell-model calculations on ^{56,57}Fe by Brown *et al.* [12] show again a large increase in the M1 strength for low γ-ray energies, further supporting the M1 nature of the upbend. The dominant mechanism is found to be $0\hbar\omega$ transitions within the f-shell. It remains to be seen experimentally whether the upbend is of E1 or M1 type, or a mix of the two. Such a determination would be very important for our understanding of this phenomenon, and for predicting its behavior in very neutron-rich nuclei, currently out of reach experimentally.

A new and very promising technique has been developed at NSCL/MSU by Spyrou *et al.* [13] to measure level density and γ-ray strength in neutron-rich nuclei by β-decay tagged γ-ray spectra (β-Oslo method). The first results for γ spectra of ^{76}Ge following β-decay of ^{76}Ga provided a significant constraint on the ^{75}Ge$(n, \gamma)^{76}$Ge reaction rate [13], not directly accessible due to the radioactive nature of ^{75}Ge. More experiments are scheduled at NSCL/MSU to further test and develop the technique. In parallel, radioactive-beam experiment proposals applying the Oslo method in inverse kinematics are approved/in preparation at HIE-ISOLDE and NSCL/MSU.

3. The scissors mode

The scissors mode is found in stable nuclei with a sizable deformation, such as rare-earth nuclei [14] and in the actinide region [15]. So far, however, it has not been studied in neutron-rich nuclei, although mass models (such as Ref. [16]) predict rather large ground-state deformations. From sum rules [15] for the scissors mode, the centroid and strength is estimated for a wide range of neutron-rich nuclei in the $A \sim 60$–180 region [19], as illustrated for ^{110}Ru in Fig. 1 (a).

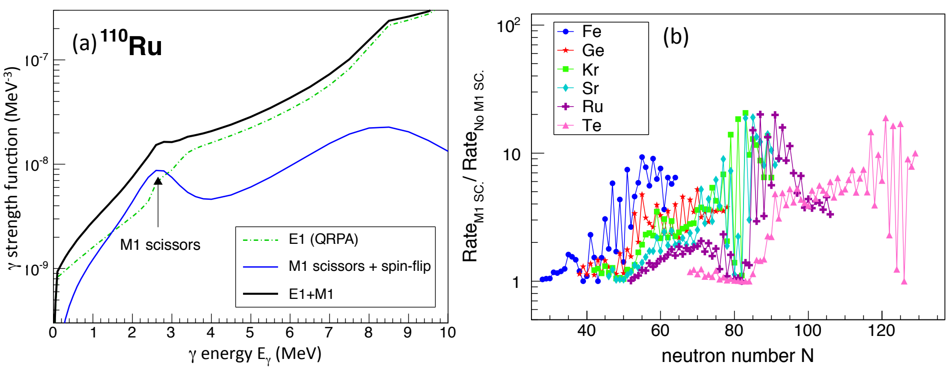

Fig. 1. (a) Theoretical predictions of the dipole γSF for ^{110}Ru, with E1 strength from Ref. [17], and M1 strength composed of the scissors mode and the spin-flip resonance from systematics [18]; (b) Ratios of astrophysical (n, γ) reaction rates at $T = 1.0$ GK with/without the M1 scissors mode for Fe (dots blue), Ge (stars red), Kr (squares green), Sr (diamonds cyan), Ru (crosses purple) and Te (triangles pink) neutron-rich isotopes [19] using the reaction code TALYS-1.4 [20]. Note that these calculations are preliminary.

Using the TALYS-1.4 reaction code [20], radiative neutron-capture rates are calculated with and without the scissors mode in the γSF. The resulting reaction-rate ratios for neutron-rich Fe, Ge, Kr, Sr, Ru, and Te isotopes are shown in Fig. 1 (b). It is evident that including the scissors mode induces a rather strong enhancement in the (n, γ) rates of the order of ~ 10–20 for the most extreme (and neutron-rich) cases. Hence, the effect of the scissors mode resembles the one for the upbend for neutron-rich nuclei [5]. It is clear that the low-energy part of the γSFs of neutron-rich nuclei needs to be experimentally investigated in order to verify (or disprove) the existence of the upbend and the scissors mode. This is of paramount importance for our understanding of the γ-decay properties of neutron-rich nuclei, as well as the possibility of enhanced astrophysical (n, γ) rates. The latter might have a significant influence on the r-process abundances depending on the astrophysical site and the actual conditions for this process [21].

4. Summary and outlook

The upbend and the scissors mode found in the γSF are very intriguing, because they may shed new light on nuclear-structure phenomena. A determination of the electromagnetic character of the upbend is crucial in order to understand the underlying mechanism. If the upbend and/or scissors mode are present in neutron-rich nuclei, they may significantly increase the corresponding astrophysical neutron-capture rates. Upcoming experiments at HIE-ISOLDE and NSCL/MSU will address this question.

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