OBSERVATION OF LARGE ORBITAL SCISSORS STRENGTH IN ACTINIDES*

M. Guttormsen[a], L.A. Bernstein[b], A. Bürger[a], A. Görgen[a]
F. Gunsing[c], T.W. Hagen[a], A.C. Larsen[a], T. Renstrøm[a]
S. Siem[a], M. Wiedeking[d], J.N. Wilson[e]

[a]Department of Physics, University of Oslo, 0316 Oslo, Norway
[b]Lawrence Livermore National Laboratory
7000 East Avenue, Livermore, CA 94550-9234, USA
[c]CEA Saclay, DSM/Irfu/SPhN, 91191 Gif-sur-Yvette Cedex, France
[d]iThemba LABS, P.O. Box 722, 7129 Somerset West, South Africa
[e]Institut de Physique Nucleaire d'Orsay
Bat. 100, 15 rue G. Glemenceau, 91406 Orsay Cedex, France

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The $M1$-scissors resonance (SR) has been measured for the first time in the quasi-continuum of actinides. Particle-γ coincidences are recorded with deuteron and ^{3}He induced reactions on ^{232}Th. An unexpectedly strong integrated strength of $B_{M1} = 11$–$15\ \mu_n^2$ is measured in the $E_\gamma = 1.0$–3.5 MeV region. The increased γ-decay probability due to the scissors mode is important for cross-section calculations for future fuel cycles of fast nuclear reactors and may also have impact on stellar nucleosynthesis.

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1. Introduction

The γ decay of excited atomic nuclei is to a large extent governed by collective transitions. In particular, the enhanced $E2$ γ decay of rotational bands is well known. The softest collective $M1$ mode, the scissors resonance (SR), appears when the deformed proton and neutron clouds oscillate against each other like the blades of a scissors. Such an isovector collective motion was first predicted by Lo Iudice and Palumbo [1].

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In the quasi-continuum region it is not feasible to measure the reduced $B(XL)$ values between specific states, simply because the levels are so close in energy. Instead, one uses the concept of radiative strength function (RSF) to measure the average electromagnetic properties of γ transitions.

The RSF is crucial input for calculating neutron-induced reaction cross sections for neutron energies starting from the low keV range. Such data are particular relevant for the calculations on future and existing nuclear power reactors [2], and in stellar nucleosynthesis [3, 4]. The low energy part of the RSF is only poorly known, and the presence of additional resonance modes may strongly influence these cross sections.

The SR built on the ground state has been extensively studied in (γ,γ') and (e,e') reactions [5]. For deformed rare-earth nuclei one finds experimentally integrated strengths of $B_{M1} = 3$–$4\ \mu_N^2$. However, the SR may also be built on all states according to the Brink hypothesis [6], and measurements of the γ-decay in the quasi-continuum show significant higher SR strength. Here, the two-step cascade method and the Oslo method give integrated strengths of 6–7 μ_N^2 [7, 8].

2. Experiment and method

The experiments were conducted at the Oslo Cyclotron Laboratory (OCL) with a 12-MeV deuteron and a 24-MeV ^{3}He beam bombarding a self-supporting target of ^{232}Th with thickness of 0.968 mg/cm^2. Particle-γ coincidences were measured with the SiRi particle telescope[9] and the CACTUS γ-detector systems. The SiRi detectors were placed in the backward direction, covering eight angles from $\theta = 126$ to 140° relative to the beam axis. The CACTUS array consists of 28 collimated $5'' \times 5''$ NaI(Tl) detectors with a total efficiency of 15.2% at $E_\gamma = 1.33$ MeV.

The Oslo method was used to extract simultaneously the nuclear level density and the RSF from particle-γ coincidences [10, 11]. The present experiment allowed us to apply the method to the ^{231,232,233}Th and ^{232,233}Pa nuclei.

3. Results and conclusions

The richest data set came from the $^{232}\mathrm{Th}(d,p\gamma)^{233}\mathrm{Th}$ reaction. The p–γ coincidence matrix could even be separated into two independent data sets in order to test the assumptions behind the Oslo method [12]. Figure 1 shows the SR for the two initial excitation regions $E = 3.2$–3.9 MeV and $E = 4.0$–4.8 MeV. The lower panel also displays the result using the full data set. The SR is seen to be split into two resonances, however, the physical reason for this is not clear. There are predictions [13] that γ deformation of the nuclear shape could be responsible for the splitting, but the

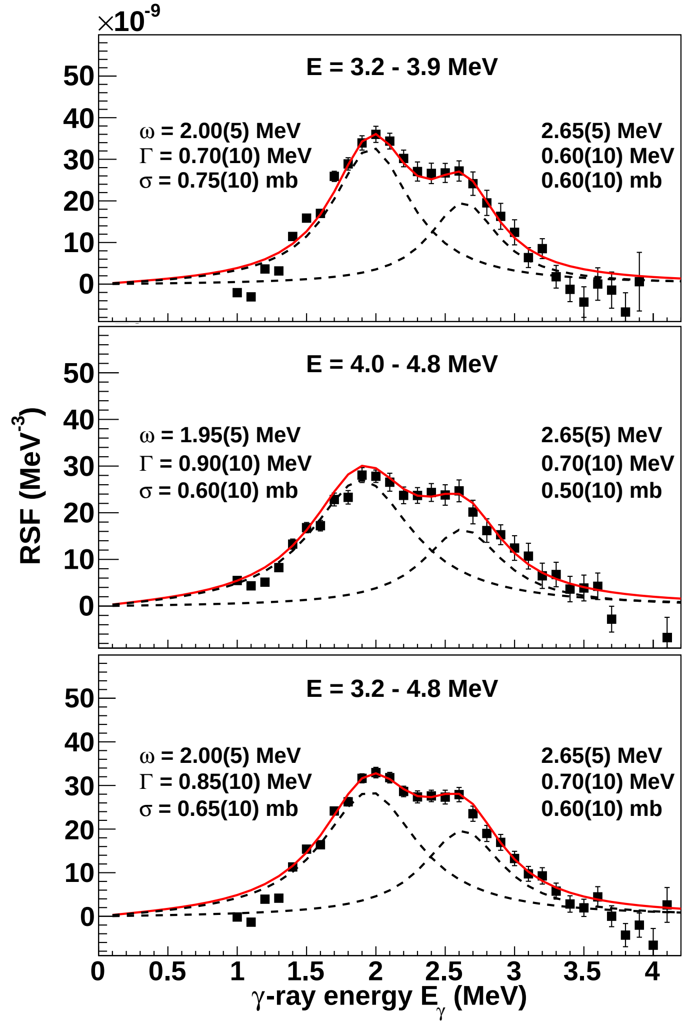

Fig. 1. The SR for various excitation-energy regions of ^{233}Th. The strengths are obtained by subtracting the underlying tail of the GEDR and GMDR. The resonance centroid (ω), width ($\mathit{\Gamma}$) and strength (σ) are given for the lower and higher resonance components. For more details see Ref. [12].

model predicts a relative strength of the two components that is contrary to our results. We have chosen the sum-rule approach [5] to obtain the total theoretical strengths of the SR

$$B_{M1} = \omega_{M1} S_{-1} = \omega_{M1} \frac{3}{16\pi} \mathit{\Theta}_{\mathrm{IV}} (g_p - g_n)^2 \mu_N^2 \,, \tag{1}$$

where we use bare gyromagnetic factors. In the quasi-continuum region, we assume that the isovector moment of inertia approaches the rigid one, and thus assume

$$\Theta_{\rm IV} \sim \Theta_{\rm rigid} = \tfrac{2}{5} m_N r_0^2 A^{5/3}(1 + 0.31\delta) \tag{2}$$

with $r_0 = 1.15$ fm and δ being the nuclear quadrupole deformation. The resonance parameters of the SR for the five nuclei measured in this work are presented in Table I. The experimental ω_{M1} and B_{M1} values given are centroid and strength for the entire SR strength distribution. The agreement with the predicted sum-rule strength is gratifying, however, the splitting of the SR remains to be theoretically described.

TABLE I

Scissors mode parameters.

Nuclide	δ	ω_{M1} [MeV]	B_{M1} μ_N^2	$\omega_{M1} S_{-1}$ μ_N^2
^{231}Th	0.183	2.49(20)	11.2(30)	17.4
^{232}Th	0.192	2.23(20)	13.8(40)	15.8
^{233}Th	0.200	2.24(10)	15.3(20)	16.0
^{232}Pa	0.192	2.14(20)	14.7(40)	15.1
^{233}Pa	0.192	2.29(20)	12.7(30)	16.3

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