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Schwengner, R.;

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Low-energy magnetic dipole strength in cadmium isotopes

R. Schwengner

Helmholtz-Zentrum Dresden-Rossendorf, 01328 Dresden, Germany

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Magnetic dipole strength functions have been deduced from averages of large numbers of M1 transition strengths calculated within the shell model for the nuclides ¹⁰⁵Cd, ¹⁰⁶Cd ¹¹¹Cd, and ¹¹²Cd. Enhancements of the M1 strengths toward low transition energy have been found for all nuclides considered. These properties are compared with those of experimental photon strength functions obtained from ³He-induced reactions, which seem to indicate a disappearance of the low-energy enhancement in the heavier isotopes.

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I. INTRODUCTION

The investigation of properties of γ -ray strength functions has been the subject of numerous experimental and theoretical works in the past years. By describing average transition strengths in a certain range of high excitation energy and high level density, γ -ray strength functions are a main input to calculations of reaction rates within statistical reaction models. These calculations are used, for example, to obtain information about neutroncapture cross sections of unstable nuclides. A number of new phenomena has been found on top of the low-energy tail of the isovector giant dipole resonance (GDR), such as the pygmy dipole resonance (PDR) between about 6 and 10 MeV consisting of electric dipole (E1) excitations [1-3], the scissors mode in deformed nuclides around 3 MeV based on magnetic dipole (M1) excitations [4], and the low-energy enhancement or so-called upbend, an increase of dipole strength with decreasing γ -ray energy below about 2 MeV. It was shown that the PDR affects neutron-capture rates determining the path of the astrophysical s-process of the nucleosynthesis [5, 6], while the pronounced enhancement of the dipole strength at low γ -ray energy may have a potentially large impact on neutron-capture reaction rates of very neutron-rich nuclides occurring in the r-process [7].

The low-energy enhancement has been observed in a number of nuclides in various mass regions, mainly using light-ion induced reactions in connection with the socalled Oslo method to extract level densities and γ -ray strength functions. These studies started with 56,57 Fe [8] and continued to heavier nuclides, for example Ge isotopes [9], Y isotopes [10], Mo isotopes [11], Cd isotopes [12], and Sm isotopes [13, 14]. The Oslo method was also applied in connection with β decay of $^{76}\mathrm{Ga}$ [15]. A dominant dipole character of the low-energy strength was demonstrated in Ref. [16] and an indication for an M1 character was discussed for the case of ⁶⁰Ni [17]. An exceptional case is represented by the Cd isotopes. The light isotope ¹⁰⁵Cd shows the upbend below about 1.5 MeV, whereas the strength functions of the neighbor 106 Cd and of the heavier isotopes 111 Cd and 112 Cd do not show an upbend [12]. Possible reasons for this behavior, speculated in Ref. [12], may be the uncovering of a mass region exhibiting the onset of the low-energy enhancement.

To understand the mechanism producing the enhanced strength at low-energy, various model calculations have been performed. Shell-model calculations revealed that a large number of M1 transitions between excited states produces an exponential increase of the γ -ray strength function that peaks at $E_{\gamma} \approx 0$ and describes the lowenergy enhancement of dipole strength observed in Mo isotopes around the neutron shell closure at N = 50 [18]. Large B(M1) transition strengths appear for transitions linking states with configurations dominated by both protons and neutrons in high-j orbits, the spins of which recouple. The low-energy enhancement of M1 strength was confirmed in shell-model calculations for 56,57 Fe [19] and 44,46 Ti [20]. In the latter work, also the E1 strength function was calculated, which does not show an upbend comparable to that of the M1 strength. A correlation between the low-energy M1 strength and the scissors mode was found in shell-model calculations for the series of isotopes from 60 Fe to 68 Fe [21]. The low-energy M1 strength decreases and the scissors strength develops when going into the open shell. The simultaneous appearance of the two modes is in accordance with experimental findings in Sm isotopes [13, 14]. Later on, M1 strength functions have been calculated for isotopic series in several mass regions from Z = 8 to 32 [22, 23] and Z = 52 to 58 [24]. These shell-model studies confirmed that the low-energy enhancement of M1 strength appears in almost all nuclides studied and is strongest in nuclides near shell closures. The only cases without a low-energy enhancement are the N = Z nuclides ⁴⁸Cr [25] and ¹⁰⁸Xe [24].

With respect to those results, the trends of the strength functions observed in the Cd isotopes remain an open issue for the understanding of the occurrence of the lowenergy enhancement as a general feature. As an approach to this problem, the present work presents predictions of shell-model calulations for the M1 strength functions of the Cd isotopes and confronts these with the experimental findings.

II. SHELL-MODEL CALCULATIONS

The shell-model calculations for the cadmium isotopes were carried out in the jj45pn model space with the jj45pna Hamiltonian [26, 27] using the code NuShellX@MSU [28]. The Hamiltonian was not specifically adjusted to the isotopes considered The model space included the proton orhere. bits $(1f_{5/2}, 2p_{3/2}, 2p_{1/2}, 1g_{9/2})$ and the neutron orbits $(1g_{7/2}, 2d_{5/2}, 2d_{3/2}, 2s_{1/2}, 1h_{11/2})$. To make the calculations feasible, the configuration spaces were truncated. Two protons were allowed to be excited from the (fp)orbitals to the $1g_{9/2}$ orbital. In ¹⁰⁵Cd and ¹⁰⁶Cd, at least three neutrons occupied the $1g_{7/2}$ and at least two the $2d_{5/2}$ orbital. One neutron could be lifted to each of the $(2d_{3/2}, 2s_{1/2})$ orbitals and up to two to the $1h_{11/2}$ orbital. In ¹¹¹Cd and ¹¹²Cd, at least six neutrons occupied the $1g_{7/2}$ and at least four the $2d_{5/2}$ orbital. Up to two neutrons could be lifted to each of the $(2d_{3/2}, 2s_{1/2}, 1h_{11/2})$ orbitals. Reduced electric quadrupole transition strengths B(E2) were calculated applying effective charges of $e_{\pi} = 1.6e$ and $e_{\nu} = 1.0e$ as used in recent calculations of B(E2) values between low-lying states in ¹⁰⁶Cd [29].

The 2^+_1 state in ¹⁰⁶Cd was calculated at $E(2^+_1)_{\text{calc}}$ = 0.480 MeV, compared to an experimental value of $E(2_1^+)_{exp} = 0.633$ MeV. The calculated strength of the ground-state transition, $B(E2, 2_1^+ \rightarrow 0_1^+)_{calc} = 718$ e^{2} fm⁴, is compatible with the experimental value of $B(E2, 2_1^+ \rightarrow 0_1^+)_{exp} = 769(9) \ e^2 \text{fm}^4$. The corresponding values for ¹¹²Cd are $E(2_1^+)_{calc} = 0.468$ MeV, $E(2_1^+)_{exp} = 0.618$ MeV, $B(E2, 2_1^+ \to 0_1^+)_{calc} = 905 \ e^2 \text{fm}^4$, and $B(E2, 2_1^+ \to 0_1^+)_{exp} = 972(6) \ e^2 \text{fm}^4$. In the heavier isotopes, more than two neutrons may be lifted to the $1h_{11/2}$ orbital. To enable this in the calculations, stronger limitations have to be applied to the other neutron orbitals. With at least five neutrons in the $2d_{5/2}$ orbital, at most one in each of the $(2d_{3/2}, 2s_{1/2})$ orbitals and still up to two in the $1h_{11/2}$ orbital, one obtains a reduction of the $B(E2,2^+_1 \rightarrow 0^+_1)_{\rm calc}$ value to 692 $e^2 {\rm fm}^4$ in $^{112}{\rm Cd}.$ At the same time, the low-energy M1 upbend gets steeper and the peak near $E_{\gamma} = 0$ increases by a factor of about two. Such an increase is a typical effect appearing when making the configuration space small. Allowing up to three neutrons in the $1h_{11/2}$ orbital along with the other limitations just mentioned, one obtains similar values, $B(E2, 2_1^+ \rightarrow 0_1^+)_{\text{calc}} = 634 \ e^2 \text{fm}^4$ and a slightly higher peak of the upbend near $E_{\gamma} = 0$, while the mean neutron numbers in the $1h_{11/2}$ orbital do not considerably exceed the number of two in most states. The calculations described in the following refer to the limitations given first in this section.

The calculations were performed for the lowest 40 states of each spin from 0 to 10 and each parity. Reduced magnetic dipole transition strengths B(M1) were calculated applying effective g factors of $g_s^{\text{eff}} = 0.7g_s^{\text{free}}$ for all transitions from initial to final states with energies $E_i > E_f$ and spins $J_i = J_f, J_f \pm 1$. This resulted



FIG. 1: M1 strength function for ¹⁰⁵Cd deduced from the present shell-model calculations (black solid line), E1 strength function based on the GLO model (green dashed line), the sum of the M1 and E1 strength functions (red solid line), and experimental data from ³He-induced reactions (blue circles).

in about 24000 M1 transitions. M1 strength functions were deduced according to

$$f_{M1}(E_{\gamma}, E_i, J_i, \pi) = 16\pi/9 \ (\hbar c)^{-3} \ \overline{B}(M1, E_i \to E_f, J_i, \pi) \ \rho(E_i, J_i, \pi), \quad (1)$$

with $E_{\gamma} = E_i - E_f$, where the $\overline{B}(M1, E_i \to E_f, J_i, \pi)$ are averages in considered (E_i, E_f) bins for given J_i, π , and $\rho(E_i, J_i, \pi)$ are level densities derived from the present calculations. The strength functions $f_{M1}(E_{\gamma})$ were obtained by averaging step-by-step over E_i, J_i , and π .

III. RESULTS

For a comparison with the experimental dipole strength functions f_1 determined in Ref. [12], an E1 part had to be added to the present calculated M1 strength functions. As the data in Ref. [12] were compared with the generalized Lorentzian (GLO) model [30, 31], this was also used here with identical parameters for the E1strength. The M1 and E1 strength functions as well as their sums are graphed for the considered isotopes in Figs. 1, 2, 3, and 4.

The M1 strength functions in all four isotopes show an enhancement toward $E_{\gamma} = 0$ below about 1 MeV. Toward high energy, the upbend is followed by a saddle and a bump between about 2 and 4 MeV. This bump corresponds to the one seen in open-shell Fe [21] and Sm isotopes [13, 14] and is considered as a scissorslike resonance. Prominent peaks in the high-energy part of the M1 strength function arise from strong transitions from the highest calculated levels to the ground or first excited states. These dominate the average strength because of



FIG. 2: As Fig. 1, but for 106 Cd.



FIG. 3: As Fig. 1, but for 111 Cd.



FIG. 4: As Fig. 1, but for 112 Cd.



FIG. 5: As Fig. 1, but for 100 Cd. There are no experimental data available for this nuclide.

the small number of transitions in the highest energy bins and hence overestimate the M1 strength function at the upper end of the calculated spectrum. All total (E1 + M1) strength functions f_1 also exhibit the lowenergy enhancement. In 105 Cd, the calculated f_1 lies below the experimental one. Besides, the enhancement starts below about 0.7 MeV, whereas the experimental one reaches to about 1.5 MeV. In 106 Cd, calculated and experimental f_1 behave similarly between about 2 and 4 MeV. There are no experimental data below about 2 MeV and hence no information about a possible upbend. In the heavier isotope ¹¹¹Cd, a good agreement of calculated and experimental f_1 is seen between about 1.5 and 4 MeV. Also in this isotope the upbend in the calculated f_1 starts where the experimental data stop. In 112 Cd, a beginning upbend may be indicated by the three experimental values below 2 MeV, but the value at the lowest energy is considerably smaller in contrast to the calculated f_1 that starts to increase at about this energy.

To reveal the development of the low-energy M1strength with nucleon numbers approaching shell closures, the M1 strength function was also calculated for the N = 52 isotope ¹⁰⁰Cd. The results are shown in Fig. 5. The f_{M1} reaches about twice the magnitude at $E_{\gamma} \approx 0$ compared with the heavier isotopes. It shows a steady decrease toward high energies, while the bump between 2 and 4 MeV seen in the heavier isotopes disappears. The increase of the low-energy strength and the disappearance of the scissorslike resonance when approaching shell closures is consistent with the properties found for the series of Fe isotopes [21].

IV. CONCLUSIONS

M1 strength functions deduced from shell-model calculations for the isotopes ¹⁰⁰Cd, ¹⁰⁵Cd, ¹⁰⁶Cd, ¹¹¹Cd, and ¹¹²Cd do not confirm a disappearance of the low-energy

enhancement of dipole strength in the heavier isotopes, which was suspected on the basis of experimental data. The low-energy enhancement of M1 strength is present in all isotopes. However, it gets weaker when going into the open neutron shell, while a bump develops in the region of the scissors resonance. This behavior resembles the properties of M1 strength found in other mass regions. Except for ¹⁰⁵Cd, the calculated low-energy upbend is below the lowest energies, for which experimental data are available. Therefore, a definite conclusion about the appearance of the upbend is not possible on the basis of the existing data. A more comprehensive study of the behavior of the strength functions at very low energy

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in ¹¹¹Cd and ¹¹²Cd on the basis of new high-resolution experiments may clarify the situation.

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