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LOW-LYING OCTUPOLE STRENGTH IN ^{112}Cd

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The low-lying octupole strength distribution in ^{112}Cd has been measured by means of inelastic proton scattering. A splitting of the strength has been observed and interpreted as due to the interaction between the quadrupole and octupole degrees of freedom. The splitting can be reproduced by the IBA-1 model if the coupling of f- and d-bosons is considered.

Owing to the coupling between the quadrupole and octupole degrees of freedom, the low-lying octupole strength in a nucleus is expected [1] to split into two or more levels with intensities dependent on the nature of the nucleus and on the strength of the coupling. In the literature other effects have been suggested to produce a similar splitting; for instance, the ^{208}Pb octupole splitting has been attributed [2] to the presence of a low frequency component in the single-particle octupole excitation.

In deformed nuclei the splitting due to the quadrupole–octupole coupling should produce [1] four 3^- states, each with a different K value ($K = 0, 1, 2$, and 3, K being the projection of the angular momentum on the symmetry axis of the nucleus). Each of these 3^- states will belong to a rotational band with a level sequence ordered by increasing value of spin. In vibrational nuclei the coupling should split the 3^- strength in only two 3^- levels; moreover the second 3^- level should belong to a quintuplet of negative parity states with angular momenta ranging from 1^- to 5^- and with a not well-defined order. An intermediate situation between the two geometrical limits described above is expected in transitional nuclei.

The interacting boson model (IBA), in version 1, which does not distinguish between the neutron and proton degrees of freedom, offers the possibility to investigate the splitting of the octupole strength in real nuclei far from the geometrical limits; the splitting is accounted for by considering the f-boson and its coupling with the s- and d-bosons. With this model the splitting of the octupole strength has been studied in Kr [3] and Sm [1] isotopes. In both analyses the parameters of the IBA-1 model responsible for the splitting were deduced from a simultaneous fit of excitation energies and strengths of only the first two 3^- levels of each nucleus considered in the isotopic series. In this letter we present the results of a similar search done in only one nucleus, ^{112}Cd, but with IBA-1 parameters deduced from the fit to many states produced by the coupling.

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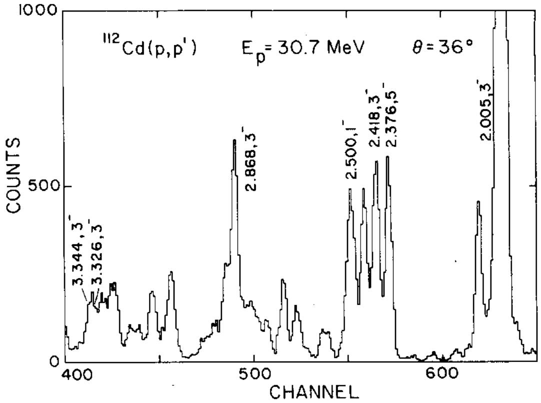

Fig. 1. The ^{112}Cd(p, p′) spectrum at $\theta_{\mathrm{Lab}} = 36°$; levels are labeled with excitation energies and J^{π} known or assigned through DWBA calculations.

The ^{112}Cd levels and transition strengths have been investigated through high resolution inelastic proton scattering. Many 3^- states up to the excitation energy of 3.5 MeV have been identified; four of them, approximately separated by 450 keV intervals, were found to share almost all the detected octupole strength. This splitting indicates a rotational character if it were not for the fact that the 3_2^- level is embedded in a bump 120 keV wide with a cluster of other states whose order and spin resemble the scheme for the octupole splitting in vibrational nuclei. A similar vibrational aspect for the other two strong 3^- levels could not be evidenced due to the increased level density, and perhaps, the decreased strength of the higher multiplets.

The experiment was performed with a 30.7 MeV analyzed proton beam from the KVI cyclotron. The experimental method was similar to that reported in refs. [4,5]. A typical momentum spectrum of scattered protons is shown in fig. 1 for a lab angle of 36° where the 3^- angular distribution has its maximum. All the levels relevant to this paper are marked in fig. 1 with the deduced excitation energy and assigned angular momentum. In table 1 all the observed 3^- levels are reported with the exhausted $L = 3$ energy weighted sum rule (EWSR). Similar results for the other multipolarities will be published elsewhere. Table 1 indicates that the 3^- strength is shared mainly among four levels with relative strengths 20, 2, 1.3, and 1, the last value obtained by summing up the strengths found in the two neighbouring levels at 3.326 and 3.344 MeV which are poorly separated.

The cluster of four levels around the 3_2^- state at 2.418 MeV (see fig. 1) has been identified to have the following order in increasing energy: 5^-, 3_2^-, 4^+, and 1^-. Due to the order, they appear to belong to the quintuplet predicted by the splitting in vibrational nuclei. The 4^+ level, third in the group, does not belong

Table 1
Transition rates and percentages of EWSR of octupole levels in ^{112}Cd deduced from a comparison of DWBA calculations and measured cross sections in the present (p, p′) experiment at E_p = 30.7 MeV.

E_x [a] (MeV)	ΔE_x [a] (keV)	β_3	$\Delta\beta_3$ [b]	$B(E3, 0^+ \to 3^-)$ [c] (e^2 fm^6)	EWSR (%)
2.005	1	0.0491	0.0049	20709	1.38
2.418	1	0.0148	0.0017	1890	0.152
2.572	2	0.0044	0.0021	<170	0.0145
2.644	3	0.0045	0.0011	172	0.0151
2.868	2	0.0122	0.0021	1288	0.123
2.962	4	0.0051	0.0013	219	0.0216
3.176	3	0.0050	0.0019	<212	0.0224
3.326	2	0.0073	0.0020	452	0.0501
3.344	1	0.0072	0.0015	439	0.0489

[a] Excitation energies and uncertainties determined from this work.

[b] Uncertainties in β_3 are determined from a χ^2-fit of the theoretical DWBA calculations to the experimental differential cross sections.

[c] The transition rates were obtained from the multipole moment of the real part of the optical potential (see ref. [6] for more detail).

to the multiplet. The assignment of 1^- to the spin of the fourth peak does not come from our analysis but was assumed from ref. [7]. The fourth peak is indeed a doublet that appeared well-separated only at a few angles. For this reason we used in the following analysis only the 1^- excitation energy but not its cross section. No indication for the unnatural parity states 2^- and 4^- of the quintuplet was found in the bump, or nearby it, perhaps because of the smallness of the two-step processes leading to their excitation.

The levels 5^-(2.376 MeV), 3_2^-(2.418 MeV), 1^-(2.500 MeV), 3^-(2.868 MeV), and 3^-(3.33 MeV) of ^{112}Cd were considered to be produced by the interaction of an f-boson with s- and d-bosons. The last two 3^- states are referred to hereafter as the 3_3^- and 3_4^- states, for convenience. In IBA-1 the relevant part of the hamiltonian for negative parity states is written as

$$H_{\mathrm{df}} = \mathrm{FELL} \times (L_{\mathrm{d}}\cdot L_{\mathrm{f}}) + \mathrm{FQQ} \times (Q_{\mathrm{d}}\cdot Q_{\mathrm{f}}) - 5 \times \mathrm{FEX} \times [(d^\dagger \tilde{f})^{(3)} \times (f^\dagger \tilde{d})^{(3)}]_0^{(0)}, \qquad (1)$$

where

$$L_{\mathrm{d}}\cdot L_{\mathrm{f}} = +2\sqrt{210}\,[(d^\dagger \tilde{d})^{(1)} \times (f^\dagger \tilde{f})^{(1)}]_0^{(0)},$$

$$Q_{\mathrm{d}}\cdot Q_{\mathrm{f}} = -2\sqrt{35}\,\{[(s^\dagger \tilde{d} + d^\dagger \tilde{s})^{(2)} - \tfrac{1}{2}\sqrt{7}\,(d^\dagger \tilde{d})^{(2)}] \times (f^\dagger \tilde{f})^{(2)}\}_0^{(0)}.$$

The parameters of the hamiltonian have been determined by fitting the excitation energies using the code PHINT [3]. The result of this search is reported in fig. 2 where the experimental scheme of levels included in the fit is compared with the prediction of the IBA-1 model. The parameter values (reported in the caption of fig. 2) result from a compromise to reproduce both the order of the observed levels of the quintuplet and the separation between the four 3^- levels. It is interesting to note that the unnatural parity states of the first quintuplet are predicted well outside the bump in which the other three members are clustered.

The experimental B(E3) transition rates between the examined states of the first quintuplet and the 0_1^+ and 2_1^+ states were deduced from a comparison of cross sections with coupled channel (CC) calculations. The 3_2^- and 5^- levels were coupled with the 0_{gs}^+, 2_1^+, and 3_1^- states. When only the direct one-step excitation from the gs is allowed for all the excited states (cross-dashed curves in fig. 3), the 5^- cross sections

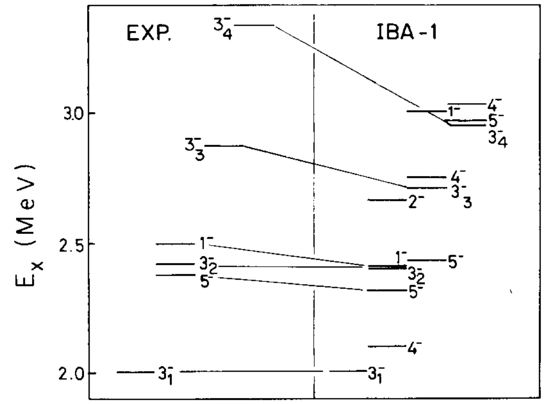

Fig. 2. Negative parity levels of ^{112}Cd between 2 and 3.4 MeV; experimental values are reported as well as ones calculated by the IBA-1 model including the coupling between f- and d-bosons (FELL = −0.014, FQQ = 0.016, FEX = −0.215).

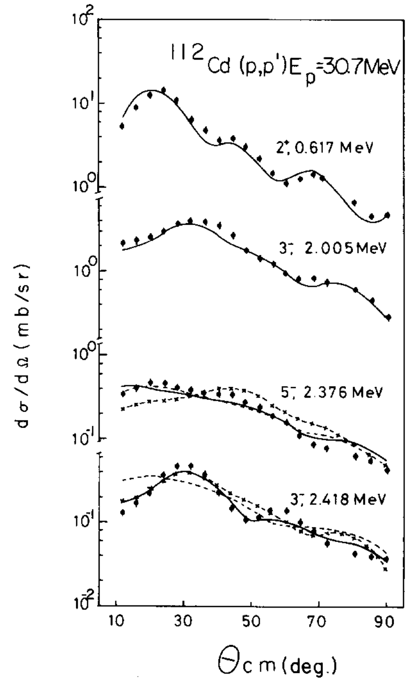

Fig. 3. Differential cross sections (dots) for inelastic proton scattering from the quoted levels of ^{112}Cd. The curves are results of CC calculations with a complete coupling scheme (full ones), and with considering only one-step (cross-dashed) or two-step (dashed curves) contributions. Optical model parameters were taken from table 5 of ref. [8] except for V_0 = 50.59, W_V = 2.236, and W_S = 7.934 MeV.

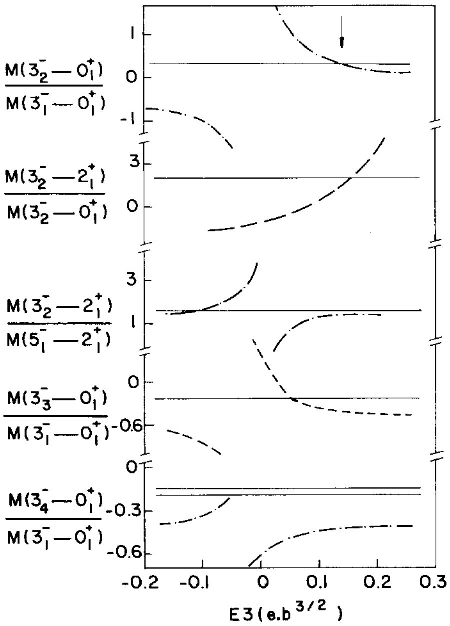

Fig. 4. Ratios between transition octupole moments for the excitations of the levels quoted. The full lines are experimental results deduced from octupole deformation parameters which in turn were determined from CC calculations (see fig. 3); the dashed and dash-dotted lines are the IBA-1 model results versus the parameter E3 of eq. (2). The arrow indicates the E3 value where IBA-1 and experimental results match.

are not reproduced; while, if only two-step processes through the 2_1^+ and 3_1^- are considered for the excitation of the 5^- and 3_2^- levels (dashed curves), the 3_2^- cross section shape is missed. The inclusion of both one- and two-step processes (full curves) is necessary for reproduction of all cross sections. For the 3^- states observed at higher excitation energies the B(E3) transition rates to the 0_1^+ (gs) were determined by comparing the experimental cross sections to distorted wave Born approximation (DWBA) calculations. The relative ratios between the various obtained octupole strengths are reported in fig. 4.

The octupole transition strength evaluated with the code FBEM [9] and due to the f- and d-boson coupling in IBA-1, is expressed as

$$M(\mathrm{E3}) = \{[\mathrm{E3SD} \times (s^\dagger \tilde{d} + d^\dagger \tilde{s})^{(2)} + (1/\sqrt{5})\mathrm{E3DD} \times (d^\dagger \tilde{d})^{(2)}]\,[(s^\dagger \tilde{f} + f^\dagger \tilde{s})^{(3)}]\}^{(3)} + \mathrm{E3} \times (s^\dagger \tilde{f} + f^\dagger \tilde{s})^{(3)} + \mathrm{E3DF} \times (d^\dagger \tilde{f} + f^\dagger \tilde{d})^{(3)}\,. \tag{2}$$

In a preliminary search we checked that to reproduce our experimental B(E3) values it was better to keep the parameters E3SD, E3DD, and E3DF to the default values of the code FBEM, i.e. 0, 0, and 1 $e\,\mathrm{b}^{3/2}$, respectively. The influence of the parameter E3 on the octupole strength is reported in fig. 4, where the transition multipole moments M [$B(\mathrm{E}\lambda) = M(\mathrm{E}\lambda)^2/(2J_i + 1)$] of the 3_2^-, 3_3^-, and 3_4^- to the gs, relative to that of the 3_1^- transition multipole moment and the ratios between transition octupole moments starting from the 2_1^+ and between those reaching the 3_2^- are also reported. The solid lines represent the experimental values obtained from the CC calculations; two full lines are indicated in fig. 4 for the $M(3_4^-)$ value. The smaller value corresponds to the strength found in only one of the two 3^- states around 3.33 MeV, the higher to their sum. The dashed lines in fig. 4 are relative to values calculated through eq. (2). At the arrow position in fig. 4 (E3 = 0.135 $e\,\mathrm{b}^{3/2}$), the calculations are able to reproduce all the considered experimental ratios with the exception of that related to the 3_4^- state.

The IBA-1 parameter values obtained in this analysis for ^{112}Cd are very similar to those found for Kr isotopes with the exception of the FELL value that was essentially zero in ref. [3]. As its value is also linked to the relative order of the quintuplet states, the difference can be attributed to the different quantities fitted here and in ref. [3]. There the degree of splitting was found to be inversely related to the quadrupole deformation parameter; thus, due to the value of β_2 ($\beta_2 = 0.20$; see ref. [8]) which is similar to the value of β_2 for the heavier Kr isotopes, the octupole splitting in ^{112}Cd should be considered weak as it was found in ref. [3] to be the case for the heavier Kr isotopes.

Summarizing it has been shown that the splitting of the ^{112}Cd octupole strength shows rotational as well as vibrational characters. Since the IBA-1 model, by coupling f- and d-bosons, reproduces both facets, the splitting can be attributed to the interaction between octupole and quadrupole degrees of freedom. This interaction in ^{112}Cd is rather weak.

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