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SPIN DETERMINATION OF NUCLEAR SUPERDEFORMED BAND IN ^{142}Eu

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Spin determination of nuclear superdeformed band in ^{142}Eu

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Abstract

The superdeformed band in ^{142}Eu is investigated. The spin value of the lowest level observed (fed by 482.3 keV) is assigned to be $I_0 = 14$ from the ab fitting of the transition energies, one unit higher than the lower limit ($I_0 = 13$) and much lower than the upper limit ($I_0 = 19$) estimated from the Harris-type fitting. The analysis of the kinematic and dynamic moments of inertia provides a support to our spin assignment. The analyses of transition energies and nuclear moments of inertia exhibit a clearcut indication of a structure change near $I \approx 40$ ($\hbar\omega \approx 600$keV).

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Since the discovery of the superdeformed (SD) band in ^{132}Ce [1], followed soon after by an SD band in ^{152}Dy [2], more than fifty SD bands have been well established in the $A \sim 130$, 150, and 190 regions [3]. Now, extensive efforts are being made to search for new SD regions. Recently, the SD band in odd-odd nucleus ^{142}Eu, intermediate to the $A \sim 130$ and $A \sim 150$ regions, was observed [4]. This band has a remarkably constant energy spacing ($\sim 58-64$ keV) between adjacent transitions, and a nucler dynamic moment $\mathcal{J}^{(2)} \sim 69 - 63\hbar^2\mathrm{MeV}^{-1}$, which corresponds closely to that of the SD band in odd-odd nucleus ^{150}Tb after an $A^{5/3}$ normalization.

Obviously, the spin determination is one of the most important things for understanding the physics inherent in SD band. Unfortunately, in no case so far have the spins in an SD band been determined by direct experiment because the link between the SD band and the lower deformation states has not been established reliably. In Ref. [5] a method based on the Harris parametrization of $\mathcal{J}^{(2)}$ was proposed to determine the spins of SD bands. However, the spins determined by this method are of a rather large uncertainty because $\mathcal{J}^{(2)}$'s are extracted from the transition energy differences with an uncertainty of about 5%. Moreover, strictly speaking, this procedure gives only the spin minus the aligned spin ($I - i$) rather than I. For example, the spin of the lowest SD level fed by 482.3 keV in ^{142}Eu was estimated to be $I_0 = 13$ (for its lower limit) to $I_0 = 19$ (upper limit) [4].

Recently, an effective approach to determine the spins of SD bands directly from the observed transition energies themselves was proposed [6,7]. It was found that the observed SD rotational spectra can be reproduced extremely well by the closed two-parameter expression [8],

$$E(I) = a\left[\sqrt{1 + bI(I+1)} - 1\right] \tag{1}$$

which is valid for a nucleus with stable quadrupole deformation and small axial asymmetry. The spin values of the SD bands observed in $A \sim 190$ region have been determined reasonably in this way [7]. Following this line the spin determination of the SD band in ^{142}Eu is presented in this report.

The SD band in ^{142}Eu was observed with twenty stretched $E2$ transitions [4]. The transition energies may be least squares fit to

$$E_\gamma(I) \equiv E_\gamma(I \to I-2) = a\left[\sqrt{1+bI(I+1)} - \sqrt{1+b(I-2)(I-1)}\right] \qquad (2)$$

but, unlike the SD bands in the $A \sim 190$ region, the fitting with all the observed transitions is unexpectedly poor. The deviations of the calculated transition energies from the observed results are about (even more than) 4keV, which are markedly larger than the experimental errors. Detailed analysis shows that, according to eq. (2), the γ-transition energy, $E_\gamma(I)$, and also its increment, $\Delta E_\gamma(I) \equiv E_\gamma(I+2) - E_\gamma(I)$, vary monotonically with I. But $\Delta E_\gamma(I)$ values observed in ^{142}Eu decrease with I at lower spin values, and increase for the higher transitions (Fig. 1). This is usually considered as an indication of bandcrossing. Hence, for determining the exit spin I_0, only the transitions below the bandcrossing are taken into account in the fitting. Moreover, the lowest transition (482.3keV) is also excluded from the fitting because of a possible larger error in measurement due to the sudden dropping of transition intensity [9]. Indeed, a perfect V-shaped root mean square (rms) deviation

$$\sigma = \left[\frac{1}{n}\sum_{i=1}^{n}\left|\frac{E_\gamma^{cal}(I_i) - E_\gamma^{exp}(I_i)}{E_\gamma^{exp}(I_i)}\right|^2\right]^{\frac{1}{2}} \qquad (3)$$

can be obtained in the fitting with transitions 2 – 13 (Fig. 2), which reveals an minimum at $I_0 = 14$ with rms deviation $\sigma = 7.6 \times 10^{-4}$. Therefore, the spin

of the lowest SD level in ^{142}Eu is assigned unambiguously as $I_0 = 14$ (i.e. the 482.3keV transition is $16 \to 14$), which is higher than the lower limit ($I_0 = 13$) estimated from the Harris-type fitting [4] but much lower than the upper limit ($I_0 = 19$). In our calculation the calculated energies for the lowest twelve transitions ($40 \to 38 \to 36 \to \cdots \to 18 \to 16$) are in good agreement with the observed values by deviations < 0.8keV (see Table I). For the higher transitions, the calculated energies deviate from the observed ones farther and farther, which may be attributed to a bandcrossing. In fact, as pointed out in Ref. [4], just at $I \sim 40$ the SD band is fed to $\sim 50\%$ of the maximum intensity, which is conventionally regarded as an indication of where the SD yrast line crosses the normal yrast line.

The spin assignment given above is also confirmed from the calculated $\Delta E_\gamma(I) - I$ plot which is also shown in Fig. 1. It can be seen that a best aggreement between the calculated and observed ΔE_γ values (of course, only for the lower transitions 2 – 13) can be obtained for $I_0 = 14$.

Furthermore, the kinematic moment of inertia $\mathcal{J}^{(1)}$ and dynamic moment of inertia $\mathcal{J}^{(2)}$ also can be evaluated from eq. (1), namely,

$$\mathcal{J}^{(1)} = \mathcal{J}_0\left[1 - \frac{(\hbar\omega)^2}{a^2 b}\right]^{-1/2}, \qquad \mathcal{J}^{(2)} = \mathcal{J}_0\left[1 - \frac{(\hbar\omega)^2}{a^2 b}\right]^{-3/2}, \qquad (4)$$

where $\mathcal{J}_0 = \hbar^2/ab$ is the bandhead moment of inertia. It is obvious that for different spin assignments, the magitudes and behaviors of $\mathcal{J}^{(1)}$ and $\mathcal{J}^{(2)}$ may be quite different. In Fig. 3 the moments of inertia for ^{142}Eu are shown by full lines (for $\mathcal{J}^{(2)}$) and dashed lines (for $\mathcal{J}^{(1)}$) for $I_0 = 13 - 16$. It is seen that for $I_0 = 13 - 15$ both $\mathcal{J}^{(1)}$ and $\mathcal{J}^{(2)}$ increase with rotational frequency and $\mathcal{J}^{(2)} > \mathcal{J}^{(1)}$, but when $I_0 \geq 16$ both $\mathcal{J}^{(1)}$ and $\mathcal{J}^{(2)}$ decrease and $\mathcal{J}^{(1)} > \mathcal{J}^{(2)}$. Nevertheless, $\mathcal{J}^{(1)}$ and $\mathcal{J}^{(2)}$ can be extracted

directly from the observed transition energies,

$$\mathcal{J}^{(1)}(I-1) = \frac{(2I-1)\hbar^2}{E_\gamma(I)}, \qquad \mathcal{J}^{(2)}(I) = \frac{4\hbar^2}{\Delta E_\gamma(I)}, \tag{5}$$

and the rotational frequency is estimated by

$$\omega(I-1) = \frac{E_\gamma(I)}{2\hbar}. \tag{6}$$

The $\mathcal{J}^{(2)}$ values are independent of the I values assumed, but the $\mathcal{J}^{(1)}$ values are dependent strongly on the I values. The $\mathcal{J}^{(1)}$ and $\mathcal{J}^{(2)}$ values extracted in this way are also shown by circles in Fig. 3. It is very interesting to note that the best agreement between the values given in these two procedures is obtained for $I_0 = 14$, at least in the range of 250keV $\leq \hbar\omega \leq$ 600keV, which again provides a support to our spin assignment. When $\hbar\omega >$ 600keV, $\mathcal{J}^{(1)}$ and $\mathcal{J}^{(2)}$ manifest themselves a structural change due to the bandcrossing.

An additional support to the spin determination made above can be provided as follows. According to eq. (4), the quantity

$$R \equiv \sqrt{\frac{\left[\mathcal{J}^{(1)}\right]^3}{\mathcal{J}^{(2)}}} = \mathcal{J}_0 \tag{7}$$

is independent of ω within a band. The experimental R-values may be extracted via eq. (5). Extensive analyses [10] on the experimental data show that the relation (7) remains valid for the normally deformed nuclei in rare-earth and actinide regions, as well as the SD bands available in the $A \sim 190$ and 150 regions. For ^{142}Eu, the R-values are shown in Fig. 4 for $I_0 = 13 - 16$. Indeed, an almost horizontal $R - I$ plot below the bandcrossing is obtained for $I_0 = 14$ (with $\mathcal{J}_0 = 63.5\hbar^2\text{MeV}^{-1}$). On the contrary, the R values vary with I by an appreciable amplitude for $I_0 \neq 14$.

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TABLE I. The spin assignment of ^{142}Eu. For the definition of the rms deviation, σ, see Caption of Fig. 1. Only the lowest transitions 2 - 13 are involved in the least squares fitting.

Observed[a]	Calculated $E_\gamma(I \to I-2)$ values (keV)					
$E_\gamma(I \to I-2)$	$I_0 = 13$[b]		$I_0 = 14$[c]		$I_0 = 15$[d]	
(keV)	I	E_γ	I	E_γ	I	E_γ
1624.0	53	1560.0	54	1591.8	55	1624.1
1561.0	51	1512.1	52	1538.4	53	1564.7
1501.2	49	1463.1	50	1484.3	51	1505.3
1441.6	47	1413.0	48	1429.6	49	1445.8
1382.0	45	1361.8	46	1374.3	47	1386.4
1323.2	43	1309.5	44	1318.4	45	1326.9
1264.1	41	1256.2	42	1262.0	43	1267.4
1205.3	39	1201.8	40	1205.0	41	1207.9
1147.5	37	1146.4	38	1147.4	39	1148.4
1089.0	35	1089.9	36	1089.4	37	1088.8
1030.0	33	1032.5	34	1030.8	35	1029.2
971.5	31	974.2	32	971.8	33	969.7
912.3	29	914.9	30	912.4	31	910.1
852.9	27	854.7	28	852.5	29	850.4
793.0	25	793.7	26	792.2	27	790.8
732.2	23	732.0	24	731.5	25	731.2
670.8	21	669.4	22	670.5	23	671.5
608.7	19	606.2	20	609.2	21	611.9
546.5	17	542.4	18	547.5	19	552.2
482.3	15	478.0	16	485.6	17	492.5
	13	413.1	14	423.5	15	432.8
	11	347.7	12	361.1	13	373.2
	9	282.0	10	298.6	11	313.5
σ		0.0031		0.0008		0.0038

[a]Reference 4.

[b]$a = 1.80157 \times 10^5$keV, $b = 9.23758 \times 10^{-5}$.

[c]$a = 3.75904 \times 10^5$keV, $b = 4.18813 \times 10^{-5}$.

[d]$a = 1.17715 \times 10^7$keV, $b = 0.12681 \times 10^{-5}$.

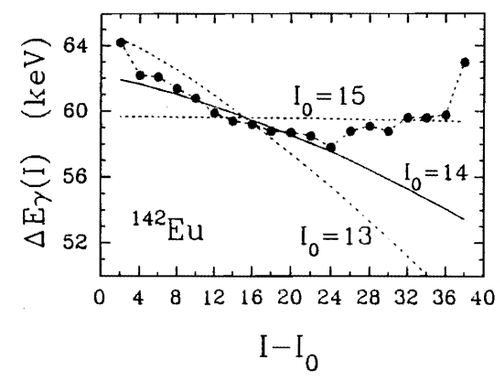

Fig. 1. The transition energy difference $\Delta E_\gamma(I)$ in the SD band of ^{142}Eu. The filled circles denote the experimental values, while the full (dashed) line(s) for the calculated values when the spin of the lowest SD level (fed by 482.3 keV) is assigned to be $I_0 = 14$ (13 and 15). A good agreement is obtained for the lower transitions 2 - 13 when $I_0 = 14$.

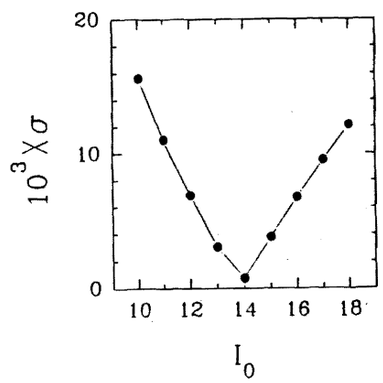

Fig. 2. The rms deviations for various spin assignments of ^{142}Eu. The least-squares fitting was made with lowere transitions 2 - 13. An minimal deviation is reached when $I_0 = 14$. However, if the prescribed spin values are shifted from the correct ones, the deviations between the calculated and measured transition energies are definitely larger than the uncertainties on the transition energies.

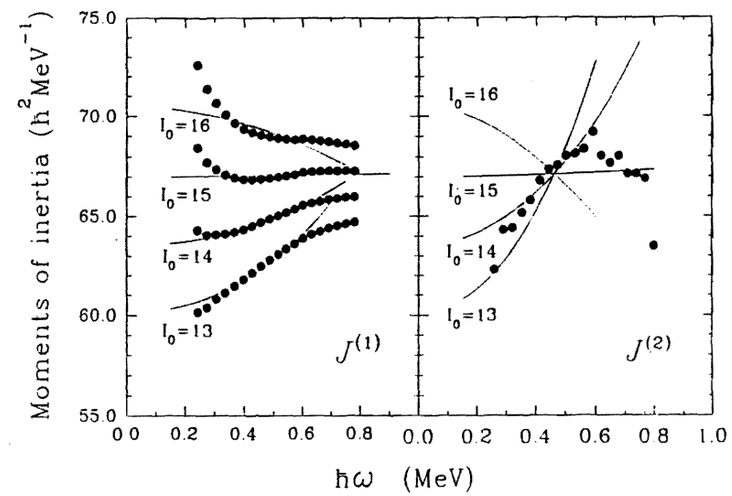

Fig. 3. (a) The kinematic moments of inertia for the SD band in ^{142}Eu. The circles stand for the $\mathcal{J}^{(1)}$ values extracted by eq. (5), while the lines denote those calculated by eq. (4) (fitting with transitions 2 - 14).

(b) The same as (a) but for the dynamic moments of inertia. The $\mathcal{J}^{(2)}$ values extracted by eq. (5) (circles in the figure) are independent of the spin assignment.

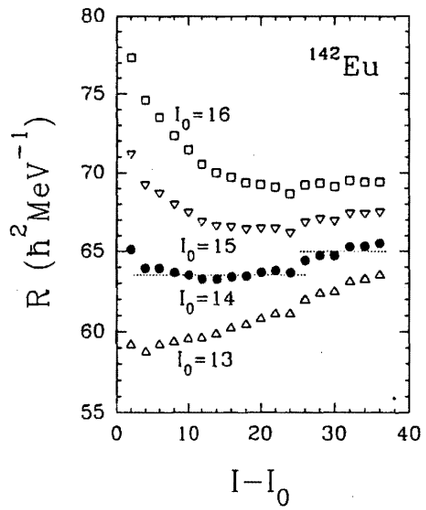

Fig. 4. The ratio $R \equiv \sqrt{[\mathcal{J}^{(1)}]^3/\mathcal{J}^{(2)}}$ extracted from the observed transition energies for various spin assignments. A fair constant ratio R is obtained below the bandcrossing for $I_0 = 14$.