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LIFETIMES OF ROTATIONAL STATES IN ^{164}Yb AND ^{162}Yb

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LIFETIMES OF ROTATIONAL STATES IN ^{164}Yb AND ^{162}Yb

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Времена жизни вращательных состояний изотопов ^{164}Yb, ^{162}Yb

Измерены времена жизни нескольких переходов в ротационных полосах основного состояния изотопов ^{164}Yb, ^{162}Yb. Использовалась реакция (^{40}Ar, $4n$), был применен метод допплеровского смещения на ядрах отдачи. Полученные значения B(E2) сравниваются с предсказаниями модели жесткого ротатора. Определены квадрупольные моменты Q_0 и параметры деформации β.

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Lifetimes of Rotational States in ^{164}Yb and ^{162}Yb

The lifetimes of several transitions in the ground-state rotational bands (g.s.r.b.) of ^{164}Yb and ^{162}Yb have been measured. The (^{40}Ar, $4n$) reaction has been used and the recoil-distance Doppler-shift method employed. The deduced B(E2) values are compared with those of the rigid-rotor model. Quadrupole moments Q_0 and deformations β are determined.

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I. Introduction

The study of electromagnetic transitions between nuclear states gives information on the structure of these states. In particular, the lifetimes of rotational states define the absolute transition matrix elements, and thus provide a possibility of checking nuclear model wave functions. The combination of the recoil-distance Doppler-shift method /1/, plunger technique using Ge counters /2,3/ and heavy ions has been used to study such lifetimes in heavy deformed nuclei. A compound-nucleus formation reaction with neutron evaporation (HI,xn) /4,5/, or a Coulomb excitation /6,7,8/ has been employed. As is known /6,7/, the Coulomb excitation gives a better accuracy in observing corrections to the rigid-rotor model. On the other hand, phase transitions for high spin values (the so-called back-bending effect) have been recently observed /5,9,10/ in the (HI, xn) reactions. This makes them interesting again in connection with the population of very high spin levels and for the eventual study of their lifetimes to answer some questions about their structure and the nature of the phase transitions.

We have described the apparatus for measuring the lifetimes of nuclei produced in (HI, xn) reactions /11/ in the range 10^{-12} to 10^{-9} s. using the recoil-distance Doppler-shift method, and our technique to deduce lifetimes, as well as some preliminary results on ^{164}Yb /12/. Here we apply this technique to measure the lifetimes of g.s.r.b. transitions in ^{164}Yb and ^{162}Yb. Further the $B(E2)$ values are deduced and their ratios compared with those of the rigid-rotor model. The absolute $B(E2)$ values give the intrinsic electric quadrupole moments Q_0 and the quadrupole deformation parameters β.

2. Experimental

The experiments have been performed in an external collimated heavy-ion beam at the U-300 cyclotron in Dubna. The reactions $^{128,126}_{52}Te(^{40}_{18}Ar, 4n)^{164,162}_{70}Yb$ have been used. The targets of 0.9-1.0 mg/cm^2 evaporated metallic ^{128}Te and ^{126}Te on an 0.7 μm Al backing stretched on a Bi lattice have been employed. The Doppler-shift target chamber has been described earlier /11/. The main feature is that the recoiling compound nuclei are stopped in a Bi-covered plunger. The distance between the plunger and the target, D, is varied from 0 to 10^4 μm and measured with a precision of ± 5 μm. The gamma rays are measured at 0° with respect to the ion beam with a $Ge(Li)$ spectrometer (the active volume and resolution are 1 cm^3 and 1.2 keV at 122 keV of ^{57}Co, respectively).

Two gamma peaks appear for each transition, an unshifted one at the correct energy $E_u = E$, from the nuclei stopped in the plunger, and a Doppler shifted one at an energy $E_s = E + \Delta E$, $\Delta E = \frac{v}{c} \cdot E$ (where v is the recoiling nucleus velocity, v/c being larger than 2% in our experiments), from the nuclei emitting gamma rays during their flight (Fig.1). The relative intensity R of the unshifted peak I_u to the total intensity $I_u + I_s$

$$R = \frac{I_u}{I_u + I_s} \qquad (1)$$

can be plotted as a function of a distance D or the time-of-flight $t = \frac{D}{v}$ (I_s being the intensity of the Doppler-shifted peak) (see Figs.2 and 3). The time $t_{1/2}$ for $R = 1/2$ gives a rough estimate of the nuclear transition half-life (the time from reaction to transition).

3. Data Handling

Before plotting the experimental values of $R(1)$, several corrections have been considered according to the formulas given in /12/, due to:

1) Distribution in the velocities of the recoiling nuclei because of distribution in ion-beam velocities, in recoiling angles, and because of finite target thickness (the sign of the correction to R is +).

2) Distribution in the target-plunger distances: because of non-parallel target-plunger surfaces (-).

3) Finite range of the recoiling nuclei in the plunger $(+)$.

4) Attenuation in the anisotropy of the gamma-ray angular distribution due to the large magnetic field of highly ionized atomic shells, acting on the nuclei that move in the vacuum $(+)$.

5) Relativistic changes in counter solid angle due to the motion of the nuclei emitting gamma rays during flight $(+)$.

6) Variation of counter efficiency between shifted and unshifted peaks (-).

7) Changes in counter solid angle due to the change of the distance between the counter and the nuclei emitting gamma rays during flight (-).

For our conditions corrections 1) and 2) are much below 1% and can be neglected; 3) is below 1% for 2 → 0 and 4 → 2, but a few percent and more than 20% for 6 → 4 and 8 → 6 (small D); 4) is fractions of percent up to a few percent; 5) and 6) are 1-3% but opposite signs and compensate to an accuracy better than 1%; 7) is below 1% for all transitions except for 2 → 0 (large D), for which it is up to 10%.

To extract the lifetimes from Figs. 2 and 3, it has been assumed that in compound-nucleus reactions with such heavy projectiles as ^{40}Ar , the g.s.r.b. is fed at the level with the highest observable spin /13,14/ . This has been checked experimentally in our cases by finding the relative intensities of the transitions (gamma intensities corrected for internal conversion), which have proved to be the same up to the transition $8^+ \rightarrow 6^+$ within the experimental errors. Then if we treat the g.s.r.b. transitions as a chain of transitions between the successive levels $i = 0,1,2,...$ with mean lifetimes τ_i , we obtain for the transition $j \rightarrow j+1$

$$R_j = \sum_{i=0}^{j} \mu_{ji} e^{-t/\tau_i} , \qquad (2)$$

where

$$\mu_{ji} = \prod_{\substack{\ell=0 \\ (\ell \neq i)}}^{j} \frac{\tau_i}{\tau_i - \tau_\ell} . \qquad (3)$$

Formulae (2) and (3) have been used to fit the experimental points of Figs. 2 and 3 by solid lines, deducing at the same time the mean lifetimes of the levels τ_i. Details can be found in ref. /12/.

4. Results

The results are presented in Tables I and 2 for ^{164}Yb and ^{162}Yb, respectively. To specify the notations we give several well known formulae /15/ that we have applied. The half-lives $T_{1/2}$ are connected with the mean lifetimes τ according to $T_{1/2} = (\ln 2)\tau \approx 0.693\,\tau$. The $B(E2)$ experimental values are deduced according to

$$\frac{B(E2)}{e^2 b^2} = \frac{0.0563\ ps\ MeV^5}{(1+a_T)T_{1/2}\ E^5} \tag{4}$$

and are obtained in $e^2\ barn^2$ if $T_{1/2}$ are in ps and the transition energy E in MeV. The $B(E2)$ rigid-rotor values are calculated from

$$B(E2; I+2 \to I) = \frac{5}{16\pi}\,\frac{3}{2}\,\frac{(I+1)(I+2)}{(2I+3)(2I+5)}\,e^2 Q_0^2\,, \tag{5}$$

where Q_0 (barn) is the intrinsic electric quadrupole moment.

Normalizing $B(E2;\ 2 \to 0)$ to experiment, the experimental value of Q_0 can be deduced from (5). Further the quadrupole deformation parameter β can be deduced from

$$\frac{\sqrt{5\pi}}{3Z R_0^2}\,Q_0 = \beta\,(1 + 0.16\beta\,), \tag{6}$$

$$\beta = \frac{1}{0.32}\left|\sqrt{1 + 0.64\,\frac{\sqrt{5\pi}}{3Z R_0^2}\,Q_0} - 1\right|,$$

$(R_0 = 1.2 \cdot A^{1/3} fm)$. Thus one obtains Table 3 with the Q_0 and β experimental values.

5. Discussion

Tables I and 2 show that the reduced transition probabilities $B(E2)$ measured agree with the rigid-rotor ones within the experimental errors. The same has been found for $^{160,158,156}Er$ in ref. /4/ . Perhaps there is some trend toward the lower values with increasing spin relative to the rigid-rotor ones as in the case of ^{160}Er./4/

The values of the quadrupole moment Q_0 and the deformation β for the $^{164,162}Yb$ nuclei (see Table 3) are less than those for the $^{176-168}Yb$ nuclei which are near the line of β-stability ($Q_0 = 7.7 - 7.4\,b$ and $\beta = 0.31 - 0.30$ for the $^{176-168}Yb$ nuclei). The comparison with the data of Table 3 shows that Q_0 and β decrease with decreasing mass number A . This corresponds to the decreasing moment of inertia $\mathcal{J}$ and decreasing E_{4^+}/E_{2^+} (increasing deviation from the rigid-rotor energy ratio) with decreasing A . It should be also noted that the time from the reaction to the decay of the 8^+ level increases with decreasing A .

In Table 3 we give for comparison the same quantities for $^{160,158,156}Er$ deduced from the data of ref. /4/ . One can see here the same trend (for the $^{170-162}Er$ nuclei nearer to the stability line: $Q_0 = 7.4 - 7.1\,b$ and $\beta = 0.32 - 0.30$).

All the trends discussed above are in agreement with the picture of the nuclei with Z midway between 50 and 82 going from the deformed to the transitional region when N decreases to 8-6 particles above the closed shell $N = 82$ /16/. For Yb nuclei this transition starts already with $A = 162$, $N = 92$, i.e., 10 particles above 82.

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TABLE 1.

HALF-LIVES $T_{1/2}$ AND B(E2; I + 2 → I) VALUES FOR THE G.S.R.B. LEVELS OF ^{164}Yb.

Transition	Energy E (keV)	$T_{1/2}$ (p s)	α_T [a)]	B(E2; I+2 → I) (e^2 $barn^2$) experiment	rigid rotor
2 → 0	123.5	882±88	1.42	0.92±0.09	(0.92)[b)]
4 → 2	262.8	29.9±3.0	0.110	1.35±0.14	1.32
6 → 4	375.0	5.2±0.7	0.039	1.40±0.19	1.45
8 → 6[c)]	462.8	2.0±0.5	0.022	1.30± 0.33	1.52
react. → 6[d)]		5.2±1.5			

TABLE 2.

HALF-LIVES $T_{1/2}$ AND B(E2 ; I+2 → I) VALUES FOR THE G.S.R.B. LEVELS OF ^{162}Yb.

Transition	Energy E (keV)	$T_{1/2}$ (p s)	α_T [a)]	B(E2; I+2 → I) (e^2 $barn^2$) experiment	rigid rotor
2 → 0	166.5	401± 59	0.50	0.73±0.11	(0.73)[b)]
4 → 2	320.3	14.1±2.1	0.061	1.12±0.17	1.05
6 → 4	436.2	3.2±0.6	0.026	1.09±0.20	1.15
8 → 6[c)]	521.4	1.4±0.5	0.016	1.03±0.37	1.21
react. → 6[d)]		12.2± 3.2			

a) The total internal conversion coefficient α_T is interpolated from the K-L- and M-shell values of ref. /17/.

b) Normalized to experiment.

c) The 8 → 6 lifetimes cannot be well separated from τ^o, therefore, these are only rough estimates.

d) τ^o -time from the reaction to the decay of the highest level 8^+ for ^{164,162}Yb (or to the population of the 6^+ level), 10^+ for ^{160}Er, 8^+ for ^{158}Er and 6^+ for ^{156}Er.

TABLE 3.

MOMENTS OF INERTIA $\mathcal{J} = \frac{3}{E_{2^+}} = \frac{3}{E_{2^+\to 0^+}}$, $E_{4^+}/E_{2^+} = (E_{4^+\to 2^+} + E_{2^+\to 0^+})/E_{2^+\to 0^+}$ RATIOS (3.33 FOR RIGID ROTORS AND 2 FOR HARMONIC VIBRATORS), INTRINSIC ELECTRIC QUADRUPOLE MOMENTS Q_o, QUADRUPOLE DEFORMATION PARAMETERS β, AND τ^o-TIMES[d)]

Nucleus	$\mathcal{J}$ (MeV^{-1})	E_{4^+}/E_{2^+}	Q_o (barn)	β	τ^o (p s)
$^{164}_{70}Yb_{94}$ e)	24.3	3.13	6.8±0.35	0.285±0.015	5.2±1.5
$^{162}_{70}Yb_{92}$ e)	18.0	2.92	6.1±0.45	0.255±0.02	12.2±3.2
$^{160}_{68}Er_{92}$ f)	23.8	3.10	6.5±0.15	0.28±0.01	4.2±2
$^{158}_{68}Er_{90}$ f)	15.6	2.74	5.3±0.15	0.235±0.01	7.6±2
$^{156}_{68}Er_{88}$ f)	8.7	2.32	4.1±0.1	0.185±0.005	11± 2

e) From this work.

f) Deduced from the $E_{4^+,2^+}$ and B(E2) data of ref. /4/.

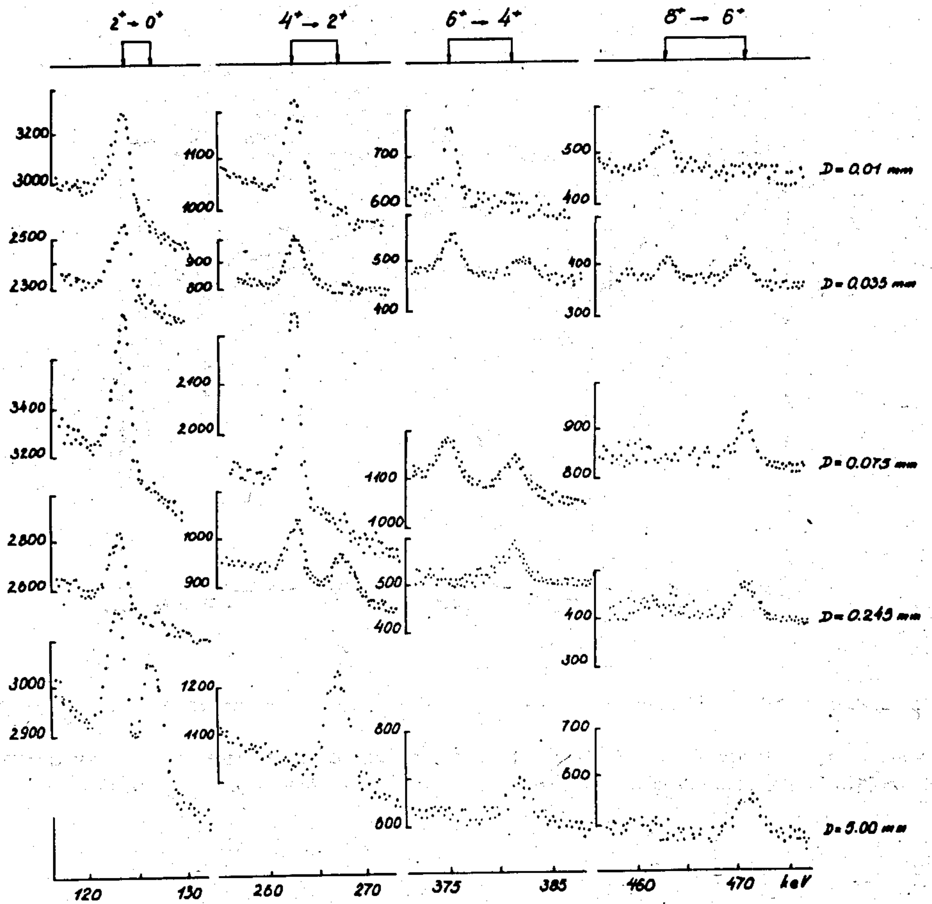

Fig.1. Gamma spectra of the transitions between g.s.r.b. levels in ^{164}Yb for different target-plunger distances D, resp. time-of-flight $t = \frac{D}{v}$.

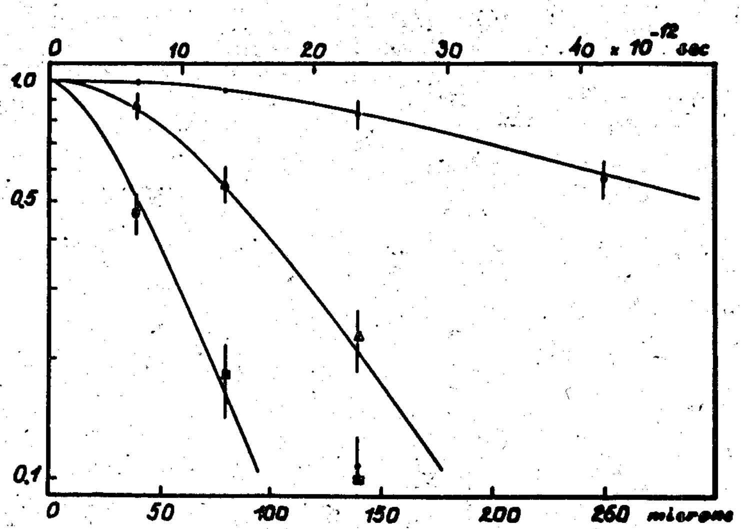

Fig.2. Decay curves of relative intensity R versus time-of-flight $t = \frac{D}{v}$ for the g.s.r.b. transitions in ^{164}Yb . Points give the experimental results, solid lines - the calculated ones according to (2) bestfit curves ($v = 6.15 \times 10^{6}$ m/s).

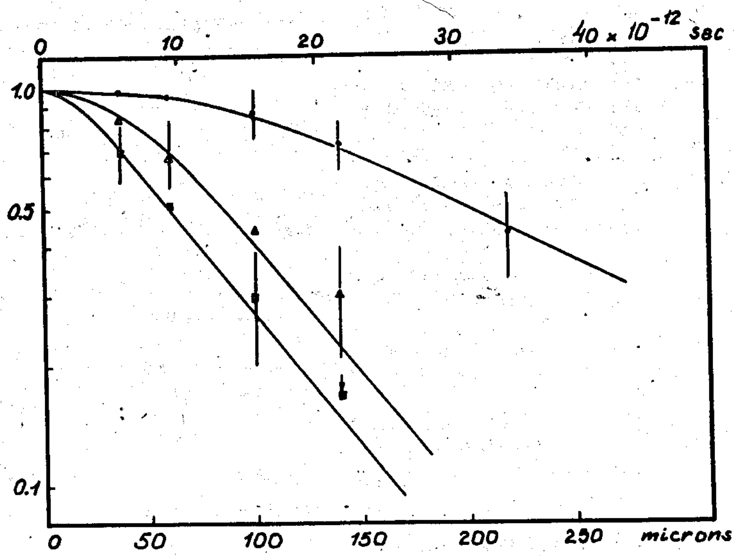

Fig.3. Decay curves of relative intensity R versus time-of-flight $t = \frac{D}{v}$ for the g.s.r.b. transitions in ^{162}Yb. Points give the experimental results, solid lines-the calculated ones according to (2) best-fit curves ($v = 6.42 \times 10^6$ m/s).