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The half-lives of several transitions in the ground-state collective bands of ^{160}Er, ^{158}Er, and ^{156}Er, produced by (^{40}Ar, 4n) reactions have been measured by a recoil-distance Doppler-shift method. These lifetimes are compared with those of several models. The mean time interval between the reaction and the population of the ground band was also determined.

The measurement of transition moments is an important method of testing nuclear models. In particular, the E2 moments of the $2 \rightarrow 0$ transitions in the ground-state collective bands of even-even nuclei have yielded much information on the nature of these bands. In the present work we have measured the $2 \rightarrow 0$ and several higher ground-band E2 moments (lifetimes) in each of three even-even Er nuclei, using a recoil-distance method. These nuclei were produced in the reactions ^{120,122,124}Sn(Ar, 4n)^{156,158,160}Er.

The recoil-distance Doppler-shift method[1] is well suited to measure half-lives in the range 10^{-9} to 10^{-12} sec.[2-5] Basically the method consists of stopping part of the excited nuclei recoiling from a thin target with a movable plunger placed closely behind the target. The fraction of the nuclei that live long enough to reach the plunger before emitting their radiation

will yield a normal gamma-ray line, whereas the rest will decay in flight and yield a Doppler-shifted line. By varying the distance of the plunger from the target, the fraction of unshifted transitions can be changed, and one can obtain the half-life of the transition if the velocity of the recoiling nucleus is also known.

The (Ar,4n) reaction produces a tightly collimated beam of product nuclei recoiling along the beam direction. Using a Ge(Li) detector at 0° to the beam direction, we were able to resolve completely the shifted and unshifted lines for all transitions over ~100 keV. The average recoil velocity could be obtained directly from the fractional energy difference of the shifted and unshifted lines, after a correction was made for the finite solid angle of the detector (the effective angle is different from 0° for large solid angles). The lead-covered plunger was attached to a precision micrometer with which its position could be adjusted to ±0.002 mm. The targets were 1 mg/cm^2 thick metallic foils of separated tin isotopes which were supported over seven closely-spaced holes, 1.5 mm in diameter, in a tantalum disk. The foils were examined under a microscope and found to be flat within about 0.01 mm.

Some typical spectra for ^{160}Er are shown in Fig. 1. We have integrated the areas under the shifted and unshifted peaks, and calculated the fraction of each line that is unshifted at each distance. The analysis of these data is rather complex as account must be taken of the preceding rotational transitions, and also of the 10-20 unobserved transitions that precede entry into the ground band. The (Ar,4n) reactions are advantageous in that almost all the feeding of the ground band occurs at high spin values. Thus the formation

and decay of a given level are marked by the ground-band transitions which populate and depopulate that level. In the analysis we have used a computer program which considers three consecutive transitions at a time, e.g., $8 \rightarrow 6 \rightarrow 4 \rightarrow 2$. The program makes a least-square fit to the first set of data ($8 \rightarrow 6$ above) varying the target location and a sequence of three arbitrary transitions to mock up whatever cascade precedes this first observed transition. Simultaneous least-square fits to the following two sets of data ($6 \rightarrow 4$ and $4 \rightarrow 2$ above) are made with their two lifetimes as the only additional variables. A modified program was also used in which two components of different intensity and half-life were allowed to feed the highest state for which data were being considered. Addition of a second (slower) component turned out to be of significance in the case of ^{158}Er, but of little importance for ^{156,160}Er.

A number of corrections had to be considered.[6] An important one was that due to attenuation of the angular distribution of the gamma radiation by the large hyperfine field (~40 Mgauss) acting at the nucleus when the highly stripped target ion recoils into vacuum.[7,8] This caused a maximum correction of 6% for half-lives of the order of 3×10^{-11} seconds. Small corrections for differences in absorption, efficiency, and effective solid angle between the shifted and unshifted lines were also made.

There are several sources of error. Although we do not know the absolute distance between the target and plunger to better than ±0.02 mm, this does not contribute any error to the lifetime determinations of the individual rotational transitions, as each of these is measured relative to the preceding transition. The target and plunger are neither flat nor parallel to each other within ±0.02 mm, which gives rise to instrumental limiting slopes corresponding to a mean life of $\sim3\times10^{-12}$ sec. However, the rotational transitions

are determined appreciably better than this by considering not the slope of a transition, but its separation from that of the preceding transition. In addition, there are possible errors in deducing the average velocity of the recoiling nuclei from the difference in energy of the Doppler-shifted and unshifted peaks. Seven determinations of this difference show a maximum range of ±2% from the average value, and this error cancels out completely in the ratio of two half-lives measured in the same experiment. It should be noted that the $2 \rightarrow 0$ transitions in $^{158,160}Er$ were determined in separate experiments using a longer recoil chamber and somewhat thinner targets. The most significant error for the fast transitions is in the peak area integrations. The spectra are not particularly clean, and a small extraneous peak could cause a systematic error in the integration of a particular line. The uncertainty introduced by the integrations is estimated to be $\pm 0.47 \times 10^{-12}$ sec for $^{160,158}Er$ and $\pm 0.66 \times 10^{-12}$ sec for ^{156}Er which has somewhat poorer spectra. An error of ±5% has been set for the best transitions to account for other systematic errors and for the fact that a number of corrections (mentioned above) ranging up to a few percent in magnitude had to be made to the raw data.

Figure 2 shows a comparison of the experimental points and the computer-calculated curves for ^{160}Er. The lowest points of the fastest transitions tend systematically to be high, which probably indicates small amounts of somewhat slower feeding. The half-life values obtained are shown in Table I together with the energies of the transitions and the ratio of v/c for the recoils. Also listed are the experimental B(E2) values, and these are compared with three sets of theoretical B(E2) values.

Several qualitative conclusions can be drawn from the B(E2) values in Table I. Within our limits of error, all these values are nearly consistent

with the rigid-rotor limit; however, those for ^{160}Er probably fall below this limit for high spin values and may even show an absolute decrease for the highest spin values, whereas those for the other two nuclei probably go above this limit. In fact, the B(E2) values for ^{156}Er are fit about as well by the vibrator limit, as might be expected from the energy-level spacings in this nucleus. Since the more vibrational nuclei start with smaller B(E2; 2 → 0) values than the rotors, but increase more rapidly with increasing spin, there is a tendency for the B(E2) values to become the same at higher spins. Thus for the three nuclei studied here the spread between the B(E2; 2 → 0) values is a factor of 2.5, but between the B(E2; 6 → 4) values it is only a factor of 1.3. This type of behavior has already been noted for the transition energies of even-even nuclei at high spin,[9] and suggests that the difference between the rotational- and vibrational-type nuclei near the ground state may be disappearing with increasing angular momentum.

It is also of interest to compare the B(E2) values with the predictions of the centrifugal stretching model.[10] The last column in Table I makes this comparison using the calculations of Davydov and Ovcharenko.[11] The values of μ are taken from fits to the energy levels. The experimental B(E2) values do not increase as much as predicted by this model for ^{160}Er. Thus, in this nucleus centrifugal stretching is not the only change taking place with increasing angular momentum. This conclusion has previously been reached in other similar cases based on 1) the mixing of the ground- and β-bands,[12,13] 2) the Mössbauer isomer-shift work,[14-18] 3) the μ-mesic X-ray studies,[19] and 4) theoretical calculations.[20,21] It is generally supposed that the other important change occurring with increasing angular momentum is a reduction of the pairing correlations due to the

Coriolis force. It is not clear how this reduction would affect the B(E2) values. For ^{158}Er, however, the B(E2) values from the centrifugal stretching model fit very well and it will be of interest to see if such nuclei between rotors and vibrators do indeed stretch. For ^{156}Er, the centrifugal stretching and vibrator models give very nearly the same prediction, and in this case our data cannot really distinguish these values from those of the rigid rotor.

The decay curves, such as those in Fig. 2, also indicate the mean time interval between the reaction (d=0) and the population of the ground band (1/e point on the curves for the fastest rotational transitions). These mean feeding times are $(6\pm3)\times10^{-12}$, $(1.1\pm0.3)\times10^{-11}$, and $(1.6\pm0.3)\times10^{-11}$ sec, respectively, for ^{160}Er, ^{158}Er, and ^{156}Er. Considering that 10-20 transitions must be emitted in this time interval, these feeding times seem rather short, especially for the rotor, ^{160}Er. This subject is discussed more fully in another publication.[22] The trend between ^{160}Er and ^{156}Er is rather striking, and it will be of interest to see if this reflects a general difference between rotors and vibrators, or is just something peculiar to these three cases.

This type of half-life measurement has been shown to give sufficient accuracy to distinguish among alternative models for the collective band of even-even nuclei. It can also obviously be used to measure many other lifetimes in the range 10^{-9} - 10^{-12} sec, where, in general, high precision will be less critical. We have made measurements on the reaction, ^{152}Sm(^{20}Ne,4n)^{168}Hf, and these studies appear to be feasible on reactions of this type, although the problem of side feeding has not been fully evaluated in this case. It seems clear that this method can produce much systematic information on lifetimes and feeding times following (HI,xn) reactions.

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FIGURE CAPTIONS

Fig. 1 Spectra from $^{124}Sn(^{40}Ar,4n)^{160}Er$ taken with the plunger set at the indicated distances from the target. The positions of the unshifted (shifted) lines are given at the top (bottom) of the figure.

Fig. 2 The fraction of each transition which is unshifted in energy vs. the separation distance of the target and plunger. The symbols represent experimental points for the ground-band transitions in ^{160}Er. The solid lines are the computer-calculated curves, and the dashed line for the $8 \rightarrow 6$ transition shows the effect of using the program which allows two components to feed the ground-state band.

FOOTNOTES AND REFERENCES

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Table I.

Nucleus	Transition	Energy (keV)	Recoil v/c(%)	$T_{1/2}$ (psec)	$\alpha_T \times 10^2$ $(\alpha_K + 1.3\alpha_L)$	$B(E2;I \to I-2)$ $(e^2 \times 10^{-48} cm^4)$	$B(E2)_{rot}$ [a]	$B(E2)_{vib}$ [a]	$B(E2)_{c.s.}$ [a]
^{160}Er	$2 \to 0$	126.2	1.96	919±46	1.30	.83±.04	(.83)	(.83)	(.83)[b]
	$4 \to 2$	264.3	1.80	34.5±1.7	.089	1.16±.06	1.19	1.66	1.25
	$6 \to 4$	376.3	1.80	5.39±.47	.037	1.34±.12	1.31	2.49	1.48
	$8 \to 6$	464.6	1.80	2.16±.47	.020	1.18±.27	1.37	3.32	1.70
	$10 \to 8$	532.1	1.80	1.24±.47	.014	1.05±.40	1.40	4.15	1.91
^{158}Er	$2 \to 0$	192.7	1.96	300±15	.283	.55±.03	(.55)	(.55)	(.55)[c]
	$4 \to 2$	335.7	1.87	14.4±.72	.050	.87±.04	.79	1.10	.87
	$6 \to 4$	443.8	1.87	2.80±.47	.026	1.14±.19	.87	1.65	1.11
	$8 \to 6$	523.8	1.87	1.21±.47	.015	1.16±.45	.91	2.20	1.35
^{156}Er	$2 \to 0$	344.4	2.20	33.2±1.7	.047	.33±.02	(.33)	(.33)	(.33)[d]
	$4 \to 2$	452.9	2.20	5.42±.66	.022	.53±.06	.47	.66	.61
	$6 \to 4$	543.2	2.20	1.14±.66	.013	1.03±.60	.52	.99	.91

a) These values have been normalized to the experimental $2 \to 0$ values.

b) These values have been calculated for $\mu = 0.3$ and $\gamma = 10°$.

c) These values have been calculated for $\mu = 0.4$ and $\gamma = 10°$.

d) These values have been calculated for $\mu = 0.8$ and $\gamma = 10°$.

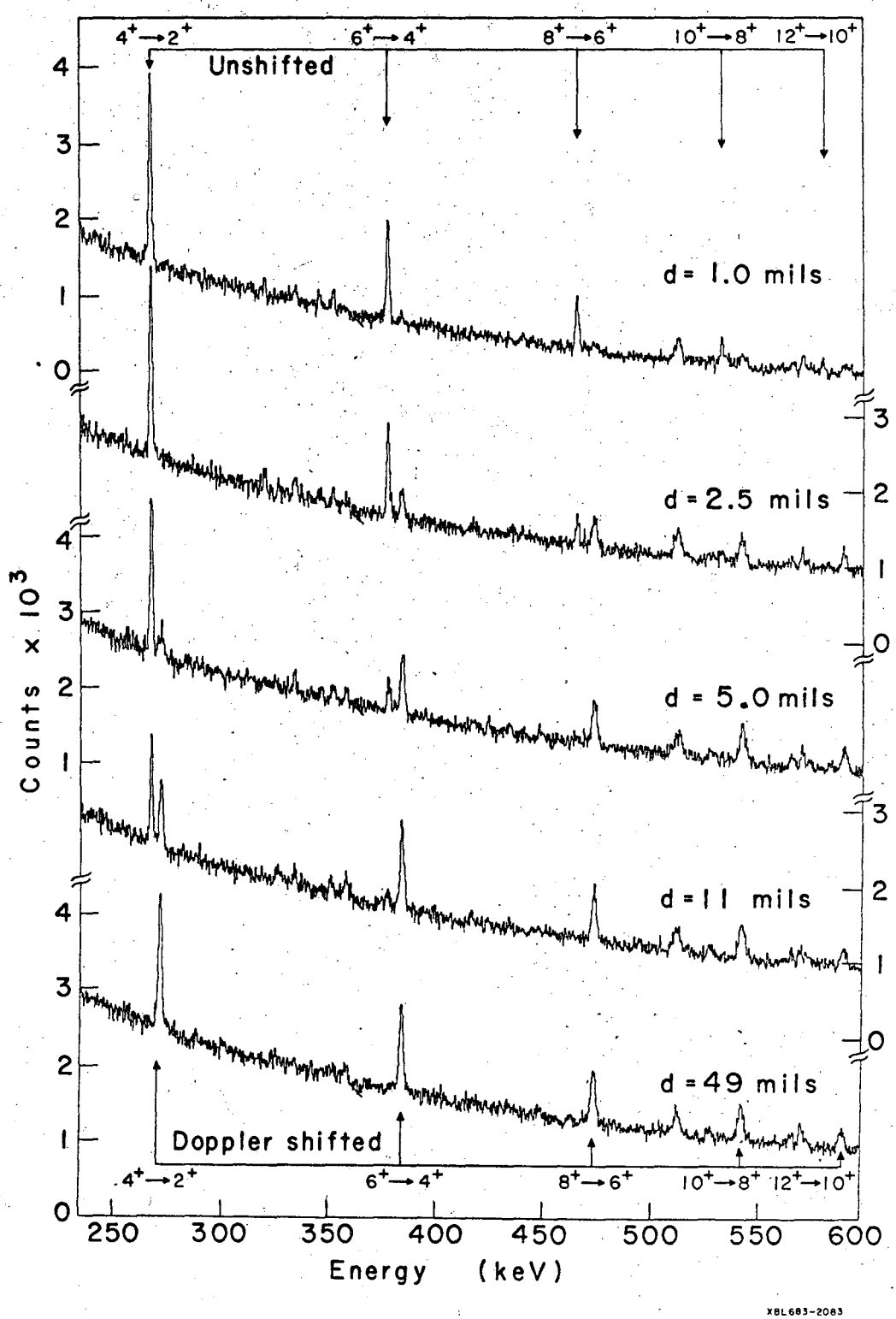
4+→2+
6+→4+
8+→6+
10+→8+
12+→10+
Unshifted
d = 1.0 mils
d = 2.5 mils
d = 5.0 mils
d = 11 mils
d = 49 mils
Doppler shifted
Counts x 10^3
Energy (keV)
250
300
350
400
450
500
550
600
XBL683-2083

Fig. 1

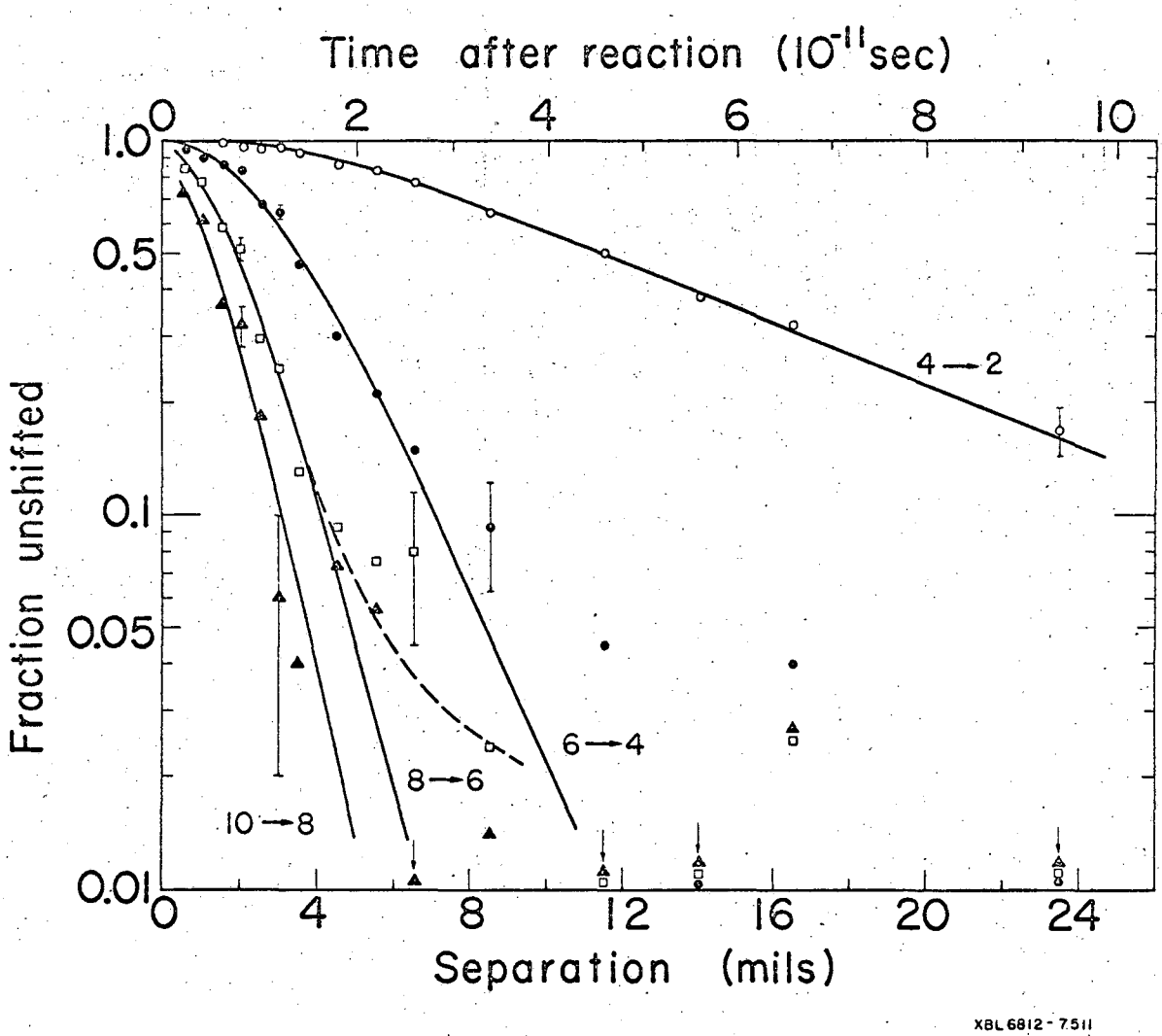
Time after reaction (10^{-11}sec)
0
2
4
6
8
10
1.0
0.5
0.1
0.05
0.01
Fraction unshifted
4→2
6→4
8→6
10→8
0
4
8
12
16
20
24
Separation (mils)
XBL6812-7511

Fig. 2

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