Lifetime Measurements to Test the Coexistence of Spherical and Deformed Shapes in ^{72}Se

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Mean lives of the 4^+ to (12^+) yrast states in ^{72}Se populated in the reaction ^{58}Ni(^{16}O, $2p$) were extracted from a line-shape analysis of the Doppler-broadened lines. The results strongly support the interpretation of the crossing of states built on near-spherical and deformed shapes in the yrast cascade. A least-squares fit of a collective Hamiltonian to the experimental data yielded a potential energy surface with spherical and strongly deformed prolate minima.

In a recent Letter[1] we reported evidence for coexistence of near-spherical and deformed shapes in ^{72}Se. The high-spin states observed up to (12^+) populated in the reaction ^{58}Ni(^{16}O, $2p$) were interpreted as members of a rotational band built on a deformed shape with a 0^+ band head at 937 keV. The energy pattern *alone* of the low-energy 0^+ and yrast-cascade states, however, also may be interpreted in a vibrational model with large anharmonicity. Lifetimes of the yrast states combined with that of the 0^+ state can provide more definitive evidence to distinguish various theoretical approaches. Such measurements are complicated by the lifetimes of the cascade and side feeders. As we show here, these problems can be eliminated and the lifetime of all but the uppermost state obtained by carrying out γ-γ coincidence studies and gating on the transitions that feed *into* the states of interest. Thus, we have carried out, for the first time to our knowledge in a complex decay, lifetime measurements of the yrast states from spin 4^+ to spin (12^+) in ^{72}Se where all feeder problems were eliminated by γ-γ coincidence work. These data strongly support our interpretations of the levels in ^{72}Se.

Recent theoretical work has suggested[2] that no second minimum exists in ^{72}Se to argue against our earlier interpretation.[1] To further test our interpretation, we have used the Gneuss-Greiner approach[3,4] of varying the potential energy to see what type potential-energy surface can reproduce the experimental levels and their properties. Indeed the best fit is for a surface with at least two minima, one corresponding to a spherical nucleus and one to a strongly deformed nucleus. New 4^+ and 6^+ states in the spherical shape are predicted and good candidates for these states are reported here.

Two 48-h in-beam γ-γ coincidence experiments in ^{72}Se produced in the reaction ^{58}Ni(^{16}O, $2p$) at 46 MeV were carried out with two Ge(Li) detectors at 0° and 90° at the Oak Ridge National Laboratory tandem Van de Graaff Laboratory. The γ-γ coincidence data are essential because by gating on a *higher* yrast-cascade transition, one can eliminate the problem of longer-lived side feeders to each state except the (12^+) state. The coincidence technique employed here is a powerful new approach in lifetime measurements in complex decays. The mean lives were obtained from a line-shape analysis of the Doppler-broadened peaks. As will be seen, singles plunger data can easily have sizable errors which are not present in coincidence work. All the coincidence data were analyzed quantitatively to see if other peaks accidentally fall in the unshifted or shifted yrast-cascade peaks.

The line shapes of the (12^+)-(10^+), (10^+)-8^+, 8^+-6^+, 6^+-4^+, and 4^+-2^+ transitions were analyzed with the computer program DOPCO[5] which calculates the line shape for a given stopping power and lifetime and includes the lifetimes of each of the cascade feeders. The stopping powers were calculated with the computer program STOPPO.[5] The stopping powers according to Northcliffe and Schilling[6] were used since they gave somewhat better fits.

Various combinations of singles, individual coincidence spectra, and summed spectra from several yrast gates were analyzed. An example is shown in Fig. 1. For the 4^+, 6^+, and 8^+ states, spectra from gates set on transitions out of the 8^+ and higher-spin yrast states were analyzed. These coincidence gates eliminate all side feed-

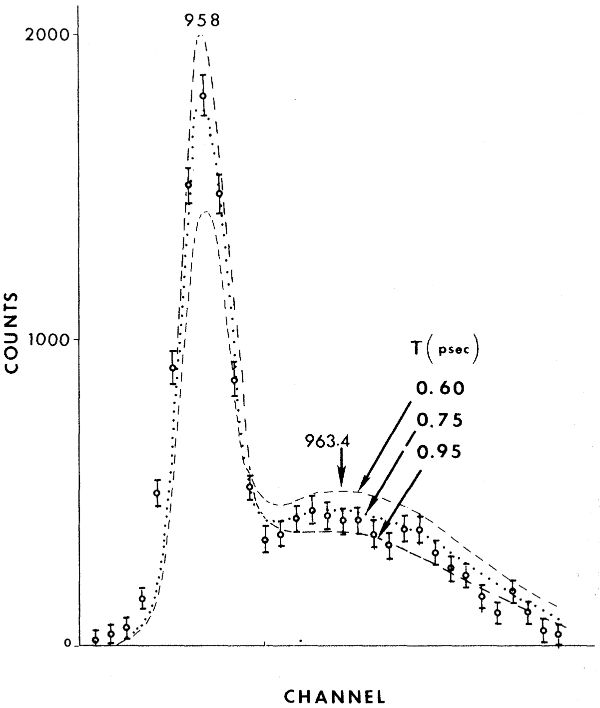

FIG. 1. Fits of the Doppler-broadened 958-keV, $8^+ \rightarrow 6^+$ transitions as seen in coincidence. Theoretical curves for three different mean lives are shown.

ers to the 4^+ and 6^+ states. While no individual γ rays other than those in the yrast cascade were observed to populate the 8^+ and higher states, each is fed about 50% by the yrast cascade and 50% by unidentified γ rays (presumably a large number of weak transitions). For the 8^+ state, the lifetime obtained from fits to the spectra from gates on the higher yrast states was the same as that found from an analysis of the singles data, to indicate that lifetimes associated with the unidentified γ rays are very short. The mean life of the highest state, (12^+), was determined first and then of each successively lower one.

The results of our analysis are included in Table I along with the results of other studies[8,9] which used the plunger technique for the 8^+ and lower states and line-shape analysis above that. The 6^+ mean life of Lemberg *et al.*[8] is short because of their longer lifetime from the 8^+ feeder state. With our more accurate 8^+ lifetime, their 6^+ lifetime is 2.0 ± 0.5 psec,[10] in agreement with our 6^+ value. Their (10^+) lifetime is believed to be incorrect because they used only singles data and did not properly distinguish the 1078 keV and its shifted peak from other lines. Thus, it is important to note that our data show one should expect that coincidence data will be necessary to extract lifetimes in complex decays in beam.

The deformation parameters, β, are also given in Table I. The lifetimes and changes in β between the spin-2 and the spin-6 and above states clearly support the interpretation of the higher-spin states as members of a strongly deformed rotational band in ^{72}Se. At the very least, the short lifetimes and large decay strengths of these yrast states indicate strong collective effects.

In order to get an impression of the type of collective potential-energy surface producing the low-energy spectrum of ^{72}Se, a least-squares fit of a collective Hamiltonian, as previously described,[3,4] was made to the experimental results for the levels[1] and our $B(E2)$ values. The data

TABLE I. Mean life results for ^{72}Se and rms deformations calculated from them. The $B(E2)$ values are compared to single-particle estimates. The deformations $|\beta|$ were calculated according to work of Alder *et al.* (Ref. 7).

Level (keV)	J^π	This work (psec)	Lemberg *et al.*[a] (psec)	Weighted average (psec)	$\|\beta\|$	$B(E2)/B(E2)_{sp}$
862.2	2^+	5.7 ± 1.2[b]	5.1 ± 0.6	5.2 ± 0.5	0.20(1)	19
1637.1	4^+	$4.5^{+1.5}_{-1.0}$	4.5 ± 0.4	4.5 ± 0.4	0.23(1)	37
2467.4	6^+	2.6 ± 0.07	0.9 ± 0.3[c]	2.2 ± 0.4[c]	0.27(2)	54
3425.5	8^+	$0.75^{+0.10}_{-0.08}$	1.6 ± 0.5	$0.75^{+0.10}_{-0.08}$	0.32(2)	76
4505.0	(10^+)	0.35 ± 0.07	<0.1	0.35 ± 0.07[d]	0.34(3)	92
5710.6	(12^+)	0.25 ± 0.04	<0.1	0.25 ± 0.04[d]	0.30(2)	74

[a]Ref. 8.

[b]Ref. 9.

[c]The 0.9 ± 0.3 psec mean life is based on their long mean life for the feeding from the 8^+ state. For our more accurate 8^+-state mean life, their mean life for the 6^+ state is 2.0 ± 0.5 psec (Ref. 10). This latter result is used in the weighted average.

[d]The results of Lemberg *et al.* (Ref. 8) are excluded for reasons discussed in the text.

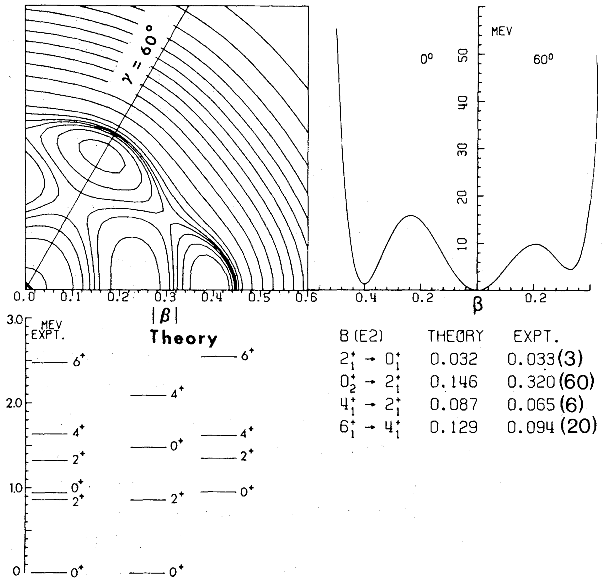

FIG. 2. Energy levels and $B(E2)$ values for ^{72}Se calculated from least-squares fits to the experimental data are shown in the lower half. In the upper left are contour lines of the potential-energy surface in a β and γ plot where $a_0 = \beta\cos\gamma$ and $a_2 = (\beta/\sqrt{2})\sin\gamma$. For a given γ value one sees how the potential changes with β which has the same linear scale along any line with constant γ. In the upper right are shown cuts through the surface at $\gamma = 0°$ and $\gamma = 60°$ plotted as a function of β. The units of the $B(E2)$ values are $10^{-48}e^2\ \mathrm{cm}^4$.

used and the resulting theoretical values are shown in Fig. 2 together with the potential-energy surface. The fit used six parameters in the potential energy and one for an anharmonic kinetic term. The latter proved to be necessary to give both the correct moment of inertia for the rotational band and the level spacing of the vibrational levels.

The potential-energy surface has three minima, with all of the experimental levels being located in the spherical and prolate minima only. The third minimum on the oblate axis has little influence on these states and its existence or nonexistence cannot be inferred from presently known experimental data. It should be borne in mind that these are least-squares-fit results, so that those parts of the potential-energy surface which have no bearing on the experimental quantities are just a by-product of the fit in the important areas and need not be meaningful physically. This is simply an expression of the fact that the experimental data are not sufficient to determine the surface in its entirety. The main intention of the present fit is to show that the coexistence of a spherical and a deformed minimum is able to explain the data. The low-spin states of the rotational band built on the $0^{+\prime}$ state are distorted considerably by the interaction with the spherical 2^+ state. This makes the application of the $I(I+1)$ rule and of the spherical-vibrator or simple-rotator model for the explanation of the low-energy spectrum highly doubtful. Additional support for the potential-energy surface comes from the prediction of 4_2^+ and 6_2^+ states in the near-spherical minimum at 2095 and 3254 keV, respectively. These states could be mixed with more deformed ones. States are seen at 2406 and 3214 keV with the predicted branching ratios to the lower 4^+ and 2^+ states.

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