# Collective structure in $^{70}$As

G. García Bermúdez,[1] J. Döring,[2,*] G. D. Johns,[2,†] R. A. Kaye,[2] M. A. Riley,[2] S. L. Tabor,[2] C. J. Gross,[3,4] M. J. Brinkman,[3] and H. Q. Jin[3]

[1]*Departamento de Física, Comisión Nacional de Energía Atómica, 1429 Buenos Aires, Argentina*

[2]*Department of Physics, Florida State University, Tallahassee, Florida 32306*

[3]*Physics Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831*

[4]*ORISE, Oak Ridge Associated Universities, Oak Ridge, Tennessee 37831*

(Received 22 April 1997)

High-spin states in $^{70}$As were populated using the $^{58}$Ni ($^{16}$O, $3pn$) reaction at 70 MeV energy. Lifetime measurements of the $11^{(+)}\rightarrow 9^{(+)}$ 980.7 keV and $(13^{+})\rightarrow 11^{(+)}$ 1342.7 keV transitions using the Doppler-shift attenuation method determined that both are enhanced $E2$ transitions. This measurement indicates the onset of deformation with increasing spin in $^{70}$As, as has been seen in neighboring nuclei. [S0556-2813(97)04310-0]

PACS number(s): 21.10.Re, 21.10.Tg, 23.20.−g, 27.50.+e

One of the most important characteristics of the mass 70–80 region is the sudden change in nuclear structure properties with the change of a small number of particles. In particular the observation of different deformations in the same nucleus leads to the introduction of the concept of shape coexistence phenomena.

It is well known that in this mass region soft nuclei, which present several collective bands with a rich variety of nuclear deformations such as prolate, oblate, and triaxial shapes, can be found. For instance, $^{82}$Sr presents a spherical ground state and evolves with increasing angular momentum into several bands with different deformations, all coexisting in the same nucleus [1,2].

The first example of this shape coexistence phenomenon was found in the study of high-spin states in $^{182}$Hg [3]. A subsequent work concerning the nuclear structure of $^{72}$Se [4] demonstrated these effects in the mass 70–80 region.

The purpose of this investigation is to study the doubly-odd nucleus $^{70}$As. This nucleus lies in the vicinity of the soft doubly-even $^{72}$Se and $^{68}$Ge nuclei. As a result the nuclear structure of $^{70}$As is expected to share some of the properties seen in both neighboring nuclei. Let us now outline the information available on the decay schemes of these nuclei.

The nucleus $^{68}$Ge displays bands of oblate and prolate deformation as well as a group of three $8^{+}$ states at around 5 MeV of excitation energy which aroused the interest of several groups and was extensively studied both experimentally and theoretically [5,6]. In contrast to the complicated structure exhibited by $^{68}$Ge, the decay scheme of $^{72}$Se is dominated by a single band [6]. Both nuclei present a nuclear structure in which shape coexistence effects are clearly observed.

The decay scheme of $^{70}$As was established [7,8] up to a tentative angular momentum of $(13^{+})$. Figure 1 shows a partial decay scheme [8] of the positive-parity levels of $^{70}$As and a very schematic view of its decay to the ground state. The low angular momentum states up to $8^{+}$ were analyzed in Ref. [8] and interpreted as a coupling of the unpaired proton and neutron moving in a spherical shell. Several levels of tentative positive-parity above 1676.2 keV were attributed to the excitations of both odd particles to the intruder $g_{9/2}$ subshell.

The observation of these positive-parity levels, usually grouped in a collective band, is a well known feature of this mass region and, in general, indicates the onset of deformation. For instance, a recent study of the neighboring doubly-odd nucleus $^{72}$As [9] found that the occupation of the $g_{9/2}$ subshell by the unpaired proton and neutron produced a band with a substantial deformation of $\beta_2\approx 0.26$ compared with a spherical ground state. A partial level scheme of $^{72}$As [9,10]

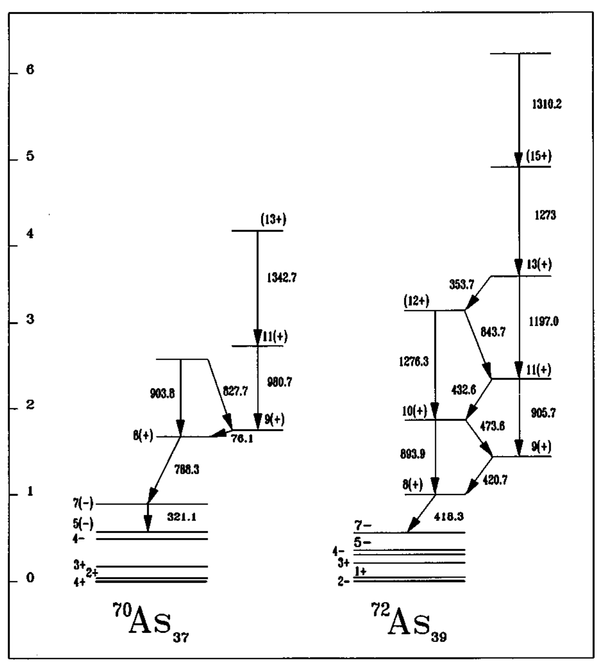


FIG. 1. Partial decay schemes of $^{70}$As and $^{72}$As adapted from Refs. [8] and [9,10], respectively. Only some of the lower energy levels and their connections with the positive-parity states are indicated.

*Present address: Department of Physics, University of Notre Dame, Notre Dame, IN 46556.

†Present address: Los Alamos National Laboratory, Los Alamos, NM 87545.

 

is included in Fig. 1 for comparison.

The aim of the present work is to determine this transitional region in which the nuclear structure evolves from a spherical to a deformed shape. To this end we have measured the lifetimes of $\gamma$ transitions deexciting levels of the positive-parity band.

The energies of the $\gamma$ rays of interest lie above 800 keV, and lifetimes of about one picosecond or lower are expected. Therefore the Doppler-shift attenuation method (DSAM) was used.

High-spin states in $^{70}$As were populated using the $^{58}$Ni ($^{16}$O, $3pn$) reaction at 70 MeV energy. The $^{16}$O beam was provided by the Florida State University (FSU) Tandem-LINAC accelerator facility. The target consisted of a self supporting 280 $\mu$g/cm$^2$ foil enriched to 99.7% in $^{58}$Ni. The backing material was $^{181}$Ta with a thickness of 50 mg/cm$^2$. Prompt $\gamma$-$\gamma$ coincidences were detected with the Pittsburgh-FSU combined detector array [11]. Ten Compton-suppressed Ge detectors were used during this experiment. Four of the detectors were placed at 90° relative to the beam line, two were at 35° and four at 145°. Each of the detectors was placed at a distance of 15 cm from the target. A total of approximately $10^8$ $\gamma$-$\gamma$ coincidences were measured.

The coincidence events were sorted into two different arrays. One of them collected all the $\gamma$-$\gamma$ coincidences detected in the 35° detectors and the other in either the 145° or 90° detectors. In turn, the other array stored the events in which one $\gamma$ ray was measured in the 145° detectors and the other in any of the others. From these two arrays it was possible to obtain the coincident $\gamma$-ray spectra in both the forward and backward directions.

This search established only two transitions affected by Doppler shifting. The non-observation of a Doppler shift for the 788.3 keV transition that deexcites the $I^{\pi}=8^{(+)}$ level (Fig. 1) indicates that below this level all the transitions were unshifted and therefore out of range for DSAM measurements.

The spectra were obtained by projecting out from the $\gamma$-$\gamma$ coincidence matrix the events in coincidence with the intense lower transitions such as the 788.3 keV and the 321.1 keV $\gamma$ rays. The spectra gated by these lines were summed to increase the statistical accuracy, and the results for the forward and backward detector angles are shown in Fig. 2.

The computer code FITS [12] was used to perform the analysis. This code calculates Doppler-shifted line shapes by taking into account several effects such as deceleration of the beam in the target, distribution of recoil velocities, detector resolution and geometry, direct feeding from known levels, and continuum side feeding. The stopping power was taken from Ziegler *et al.* [13] and the angular straggling was treated in Blaugrund's approximation [14].

The lifetime of the highest level was extracted without taking into account any side feeding and this result was used to fit the lifetime of the lower levels. In particular the $(13^+)\rightarrow 11^{(+)}$ transition of 1342.7 keV energy is the first observed $\gamma$ ray of the cascade and the result is considered as an effective lifetime necessary for the following analysis.

This $\gamma$ ray feeds the 2733.0 keV level which decays through the 980.7 keV transition. From the measurement of the intensity balance of the level, the contribution of the side feeding provides (43±9)% of the total intensity. The side-

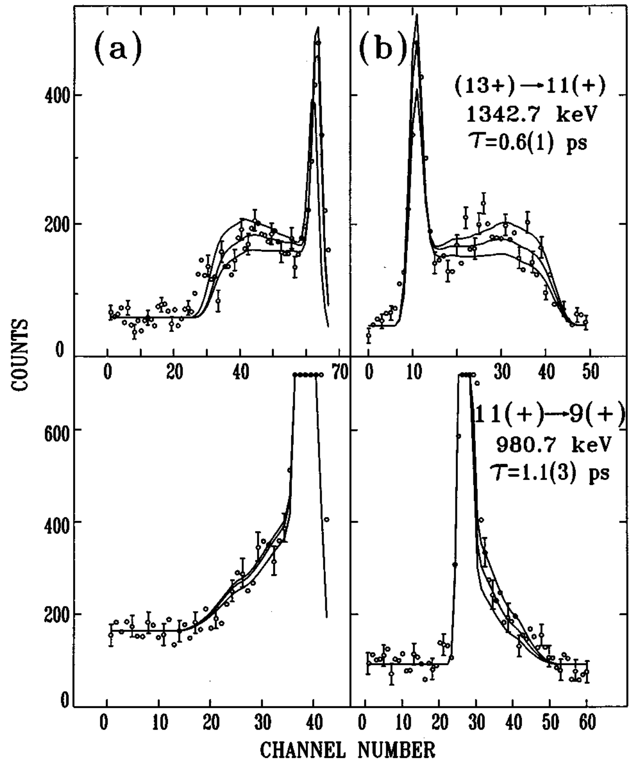


FIG. 2. Dopppler-shifted line shapes observed in the (a) backward and (b) forward detectors. The smooth curves represent the best-fit lifetimes and the uncertainty limits.

feeding time was assumed to be in the range between 0.05 up to 0.2 ps, which is typical for nuclei in this mass region populated by heavy-ion reactions and at this excitation energy and spin [15,16]. No other $\gamma$ ray deexciting lower energy levels exhibited a measurable Doppler shift in the spectra.

The theoretical line shape generated by the program was compared with the measured spectrum, and the lifetime was varied until the best fit was obtained. The side-feeding lifetime, which is fixed during a particular fitting calculation was varied to estimate its influence over the final result. The uncertainty in the lifetime was determined by comparing the accuracy of the best fit with the accuracy for lifetime fits near the measured best value. Figure 2 shows the best fit line shape simulations and also the fit obtained with the lifetime held fixed at the uncertainty estimates.

The experimental value for the 1342.7 keV transition of 0.6±0.1 ps is an effective lifetime or an upper limit for the 4075.7 keV level. The mean lifetime of the 980.7 keV transition was found to be 1.1±0.3 ps, which takes into account the lifetime of the 1342.7 keV feeding transition and a fixed 0.2 ps side-feeding lifetime. The final value of the 980.7 keV transition results from the average of the lifetimes obtained analyzing the spectra of both forward and backward detectors.

From these lifetimes, the reduced transition strengths can be calculated. The resulting $B(E2)$ values measured in single particle Weisskopf units (W.u.) are $48\pm^{20}_{10}$ and greater than 18 W.u. for the 980.7 and 1342.7 keV transitions, respectively (1 W.u.=17.8 $e^2$ fm$^4$). The transition quadrupole moments $|Q_t|=1.8(3)$ $e$ b and $|Q_t|\geq 1.1$ $e$ b were inferred

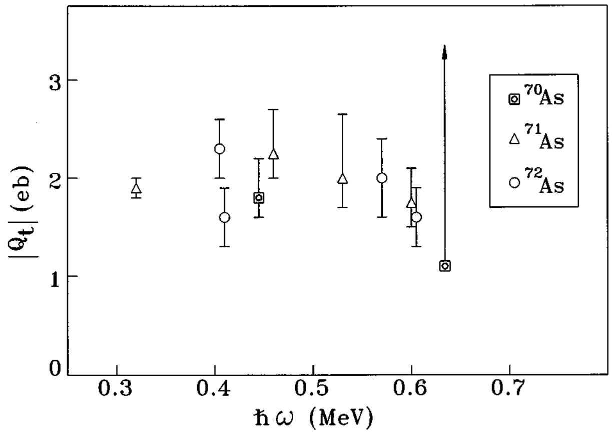


FIG. 3. The transition quadrupole moments, as a function of the angular frequency $\hbar\omega$, in $^{70}$As compared with the values measured in the positive-parity band in the neighboring nuclei $^{72}$As and $^{71}$As. The experimental point with an arrow indicates a lower limit

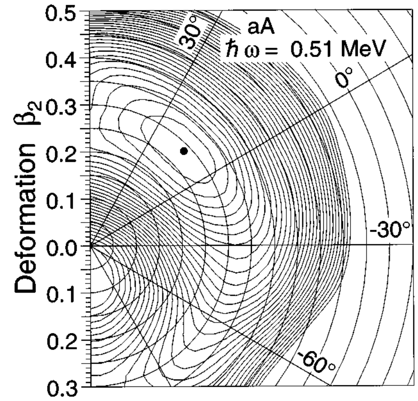


FIG. 4. Total Routhian surface in the $(\beta_2, \gamma)$ plane for the lowest positive-parity configuration in $^{70}$As at a rotational frequency of $\hbar\omega = 0.51$ MeV.

from the $B(E2)$ values according to the standard rotational formula [17]. For the intrinsic angular momentum $K$, a value of 4 was assumed.

This enhancement in the $B(E2)$ values, which implies a collective structure, also was observed in the $g_{9/2}$ positive-parity bands in neighboring nuclei. Figure 3 shows the transition quadrupole moments, as a function of the angular frequency $\hbar\omega$, in $^{70}$As compared with the values measured in the positive-parity bands in the neighboring nuclei $^{72}$As [9] and $^{71}$As [17]. As can be seen, the $|Q_t|$ moments fluctuate around a constant value and our measurement agrees rather well with these systematics.

The present measurement determined a strong enhancement in the $B(E2)$ values of the 980.7 and 1342.7 keV transitions depopulating levels of the positive-parity band that suggested the onset of deformation.

Thus the shape of the $^{70}$As can be interpreted as almost spherical near the ground state, as a recent $(p,n)$ reaction work suggested [18]. Then at higher spins, corresponding to the population of the $g_{9/2}$ subshell by the odd particles, the shape becomes deformed.

Total Routhian surfaces (TRS) were determined from Woods-Saxon Hartree-Fock-Bogolyubov (HFB) cranking calculations [19]. A TRS plot for $^{70}$As is shown in Fig. 4 for the positive-parity states which span the rotational frequencies close to the 980 keV transition. At low frequencies (not shown in the figure) the calculations predicted the shape of the nucleus to be very soft with respect to the triaxiality parameter $\gamma$ with a broad minimum near the oblate, noncollective axis at $\gamma \approx 60°$. At a frequency of 0.51 MeV, as shown in Fig. 4, a new nearly prolate, collective minimum ($\beta_2 \approx 0.3$ and $\gamma \approx 15°$) appears, which probably corresponds to the observed positive-parity band. It would imply a $Q_t$ value of 1.75 $e$ b in good agreement with the measured value.

In conclusion, the present lifetime measurements have demonstrated enhanced $E2$ transitions among the high-spin states of $^{70}$As, in agreement with Hartree-Fock-Bogolyubov calculations. This result parallels an earlier observation of the onset of deformation in the high-spin states of the neighboring isotope $^{72}$As.

This work was supported in part by the NSF-CONICET (Argentina) U.S.-Latin American Cooperative Science Program under Grant No. INT-9314496, in part by the National Science Foundation under Grant No. PHY-9210082, and in part by the U.S. Department of Energy under Contract No. DE-AC05-96OR22464.


[1] C. Baktash *et al.*, Phys. Lett. B **255**, 174 (1991).

[2] S. L. Tabor, J. Döring, J. W. Holcomb, G. D. Johns, T. D. Johnson, T. J. Petters, M. A. Riley, and P. C. Womble, Phys. Rev. C **49**, 730 (1994).

[3] D. Proetel, R. M. Diamond, P. Kienle, J. R. Leigh, K. H. Maier, and F. S. Stephens, Phys. Rev. Lett. **31**, 896 (1973).

[4] J. H. Hamilton, A. V. Ramayya, W. T. Pinkston, R. M. Ronningen, G. García Bermúdez, H. K. Carter, R. L. Robinson, H. J. Kim, and R. O. Sayer, Phys. Rev. Lett. **32**, 239 (1974).

[5] U. Hermkens, F. Becker, J. Eberth, S. Freund, T. Mylaeus, S. Skoda, W. Teichert, and A.v.d. Werth, Z. Phys. A **343**, 371 (1992).

[6] L. Chaturvedi *et al.*, Phys. Rev. C **43**, 2541 (1991).

[7] A. Filevich, M. Behar, G. García Bermúdez, M. A. J. Mariscotti, E. Der Mateosian, and P. Thieberger, Nucl. Phys. **A309**, 285 (1978).

[8] T. Bădică, V. Cojocaru, D. Pantelică, I. Popescu, and N. Scîntei, Nucl. Phys. **A535**, 425 (1991).

[9] J. Döring, S. L. Tabor, J. W. Holcomb, T. D. Johnson, M. A. Riley, and P. C. Womble, Phys. Rev. C **49**, 2419 (1994).

[10] D. Pantelica *et al.*, J. Phys. G **22**, 1013 (1996).

[11] S. L. Tabor *et al.*, Nucl. Instrum. Methods Phys. Res. B **79**, 821 (1993).

[12] E. F. Moore, P. D. Cottle, C. J. Gross, D. M. Headly, U. J. Hüttmeier, S. L. Tabor, and W. Nazarewicz, Phys. Rev. C **38**, 696 (1988).

[13] J. F. Ziegler and W. K. Chu, At. Data Nucl. Data Tables **13**, 463 (1974).
[14] A. E. Blaugrund, Nucl. Phys. **88**, 501 (1966).
[15] F. Cristancho and K. P. Lieb, Nucl. Phys. **A486**, 353 (1988).
[16] J. W. Holcomb, J. Döring, T. Glasmacher, G. D. Johns, T. D. Johnson, M. A. Riley, P. C. Womble, and S. L. Tabor, Phys. Rev. C **48**, 1020 (1993).
[17] R. S. Zighelboim, S. G. Buccino, F. E. Durham, J. Döring, P. D. Cottle, J. W. Holcomb, T. D. Johnson, S. L. Tabor, and P. C. Womble, Phys. Rev. C **50**, 716 (1994).
[18] Zs. Podolyák, T. Fényes, and J. Timár, Nucl. Phys. **A584**, 60 (1995).
[19] W. Nazarewicz, J. Dudek, R. Bengtsson, T. Bengtsson, and I. Ragnarsson, Nucl. Phys. **A435**, 397 (1985).