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Evidence for the first $9/2^+$ state in ^{75}Br and maximum deformation at $N \sim 42$*

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Evidence for the first $9/2^+$ state in ^{75}Br at 694 keV has been obtained through the ^{75}As (55 MeV α,$4n$) reaction. This result shows a sharp change in the systematics of the $9/2^+$ states in the Br isotopes and implies that the maximum of prolate deformation is reached for $N \sim 42$. The previously postulated correlation between $9/2^+$ and 2^+ states in the neighboring even-even nuclei is confirmed by the present experiment.

[NUCLEAR REACTION ^{75}As($\alpha, 4n\gamma$), E=30 to 55 MeV; measured $\sigma(E, E_\gamma, \theta)$, γ-γ coin. ^{75}Br deduced levels, $J, \pi, T_{1/2}$. Ge(Li) detector.]

I. INTRODUCTION

The behavior of the first excited $\frac{9}{2}^+$ states of the odd-A nuclei in the $28 \leq Z$, $N \leq 50$ region has prompted a number of studies. In the special case of the odd-Z nuclei, the excitation energy of these states decreases abruptly as N varies from $N=50$ to $N=42$, instead of being constant as should be expected from the shell model.

Murray *et al.*[1] have noted that similar behavior is exhibited by the excitation energy of the 2^+ states in neighboring doubly even nuclei. In this case, however, a distinct minimum is reached for $N \simeq 42, 44$ showing an increase of energy for smaller neutron number. This behavior implies a change in deformation which reaches a maximum for such neutron numbers. Murray *et al.*[1] speculated on the existence of a correlation between the trend shown by the first excited $\frac{9}{2}^+$ and 2^+ states in these nuclei. As pointed out by these authors, a hint that such a correlation might take place for $N<42$ is given by the $\frac{9}{2}^+$ state of the $N=40$ ^{73}As isotope which lies at about 120 keV above that in ^{75}As. More recent data on ^{71}As further support this hypothesis.

In the ^{81,79,77}Br isotopes, the $\frac{9}{2}^+$ states are found at 541, 210, and 108 keV above the $\frac{3}{2}^-$ ground states, respectively. On the basis of the trend inferred from these data it has been suspected[2] that in the lighter ^{73,75}Br isotopes the $\frac{9}{2}^+$ state might even become the ground state. However, if the behavior of the $\frac{9}{2}^+$ state stems from the deformed structure exhibited by the 2^+ states, then the $\frac{9}{2}^+$ states of the lighter isotopes should be expected to appear some few hundred keV above the ground state.

Previous radioactive studies directed to find the position of the $\frac{9}{2}^+$ state in ^{73}Br[1] and ^{75}Br[2] have given negative results. However, Murray *et al.*[1] concluded from their work that in ^{73}Br the $\frac{9}{2}^+$ state should be at higher excitation energy than the corresponding level in ^{77}Br.

In this paper we present a new level scheme for ^{75}Br and we wish to report on evidence for the existence of the first $\frac{9}{2}^+$ state at 694.6 keV. This result implies a sharp change in the systematics and confirms the assumption of a correlation with the behavior of 2^+ states in the even-even cores.

II. EXPERIMENTAL METHOD

A. Experimental setup

A 55 MeV α-particle beam was obtained from the Buenos Aires synchrocyclotron. This beam was subsequently degraded so that energies between 30 and 55 MeV in steps of 5 MeV were attained. The target was natural As in the form of As_2O_3 (99.8%), bound to a thin Mylar foil. The target area was about 0.5 cm^2 and the thickness was 20 mg/cm^2. The γ radiation was detected with a coaxial Ge(Li) detector of 7% efficiency and 2.3 keV energy resolution. In order to see the low energy spectrum with better resolution, a small x-ray Ge(Li) detector with 300 eV resolution for a 5 keV transition was used.

The analysis of the γ-ray spectra was performed with the aid of the computer program SAMPO.[3] Standard radioactive sources of ^{152}Eu and ^{133}Ba were used for energy and efficiency calibration. All the γ-ray energies are estimated to be accurate to about 0.3 keV. The overall error of our efficiency calibration can be estimated as ±5%.

B. Experimental results

The ^{75}Br isotope was investigated through the ^{75}As($\alpha, 4n$) reaction. The singles γ-ray spectrum taken at $E_\alpha = 55$ MeV is shown in Fig. 1. There are several lines which belong to other reactions like ($\alpha, 3n$), ($\alpha, 2np$), and ($\alpha, 3np$).

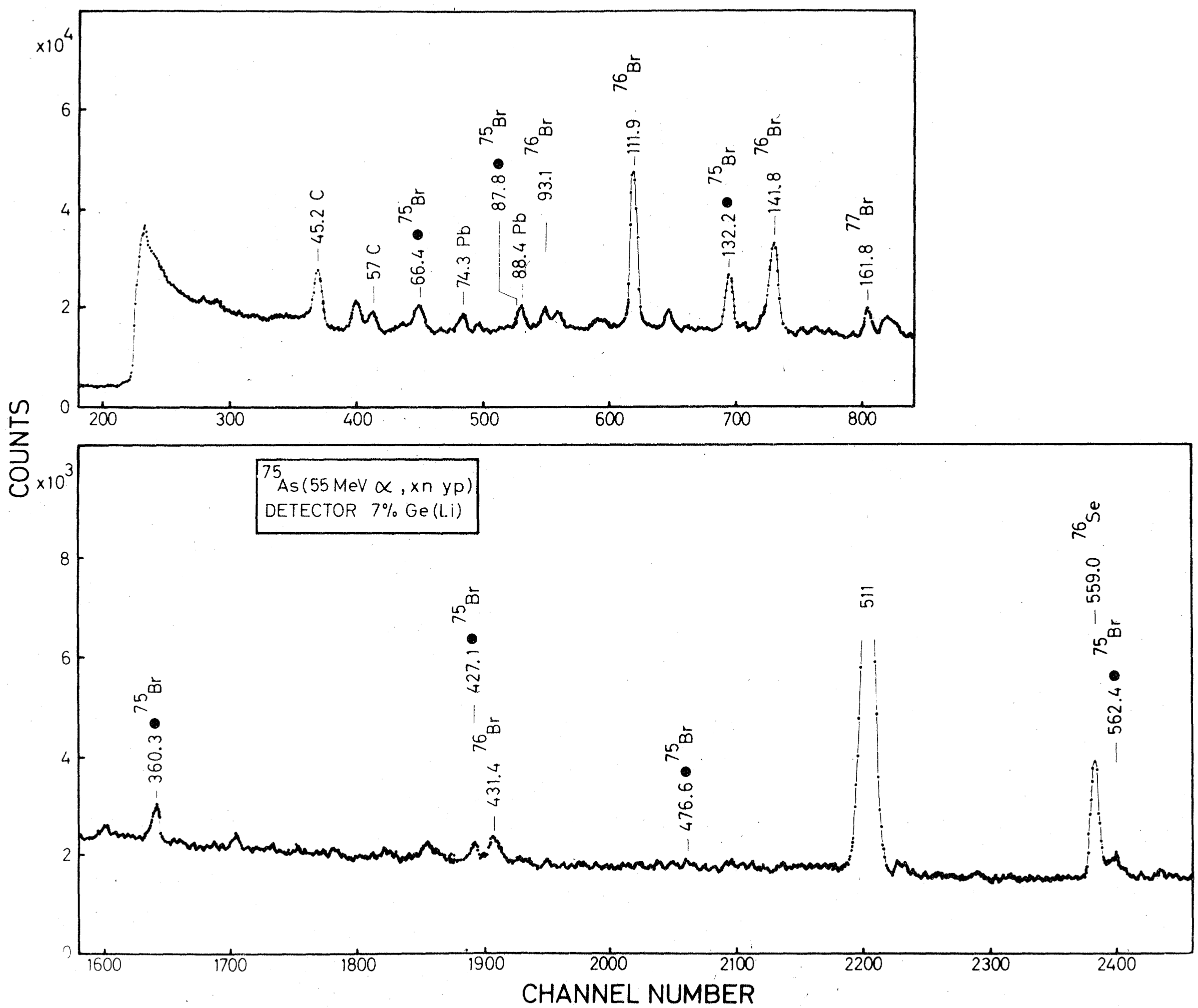

FIG. 1. Low energy part of the singles γ-ray spectrum from the ^{75}As$(\alpha, xny p)$ reaction at 55 MeV.

C. Isotopic assignment

The isotopic assignment of the γ rays was done on the following basis:

(a) Relative excitation functions. The α beam was varied between 30 and 55 MeV in steps of 5 MeV. In Fig. 2 the excitation functions for representative γ rays from the (α, np), $(\alpha, 2n)$, $(\alpha, 3n)$, $(\alpha, 2np)$, $(\alpha, 3np)$, and $(\alpha, 4n)$ reactions are shown. As can be seen, reactions involving two, three, and four particles can be easily distinguished from each other.

(b) The γ rays which are produced by the competitive $(\alpha, 3np)$ reaction are well known from the $(\alpha, 2n)$ reaction work of Protop *et al.*[4]

(c) The 87.8 and 132.2 keV transitions are known from the previous radioactive work.[2] Similar relative excitation functions and coincidences with the above mentioned γ rays make it possible to assign other γ rays to the ^{75}Br isotope.

From the above arguments lines at 66.4, 87.8, 132.2, 360.3, 427.1, and 562.4 keV were assigned as transitions in ^{75}Br. The energies and intensities are given in Table I. The possible 474.6 keV line (see level scheme below) is masked by a background line and only a maximum limit for its intensity was established.

These γ rays were fitted into a level scheme on the basis of γ-ray energy combinations, γ-intensity balance, γ-γ coincidence relationships, lifetime measurements, and γ-ray angular distributions.

D. Coincidence measurements

The coincidence spectrometer consisted of the Ge(Li) detector of 7% efficiency and the small x-ray detector. A conventional coincidence circuit

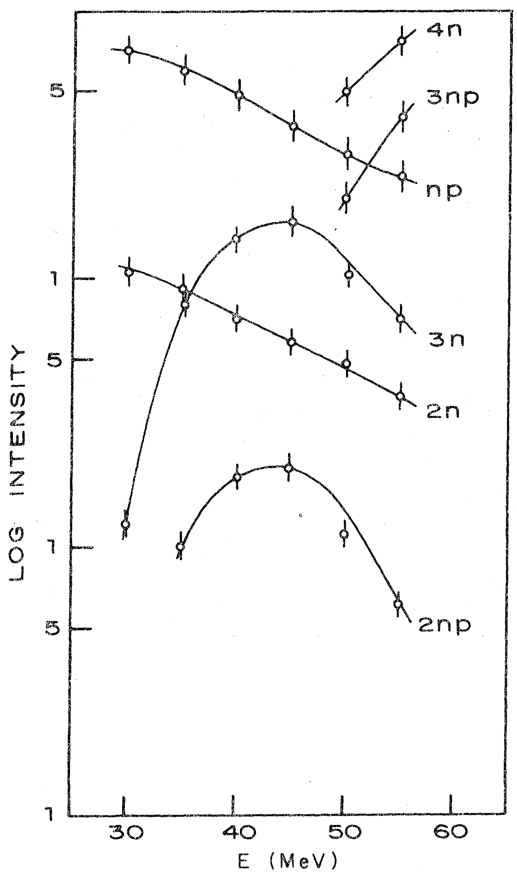

FIG. 2. Excitation functions for the different reactions observed from the bombardment of ^{75}As with α particles of energies between 30 and 55 MeV. The curves correspond to the most intense γ rays in each reaction. They are plotted in relative scale.

of $2\tau = 40$ nsec resolution time was used in conjunction with a 4096 Intertechnique multichannel analyzer. Gates were set on the 66.4, 87.8, and 132.2 keV γ rays. Results are given in Table II.

E. Angular distribution measurements

To obtain angular distributions, γ-ray spectra were taken at seven angles (75, 90, 100, 110, 120, 130, and 140°) with respect to the beam direction. The target area was reduced to a circular form with a diameter of 3 mm.

The movable detector was placed 15 cm from the target. To normalize the spectra taken at different angles the output of a pulser triggered by pulses from a monitor detector was fed into the preamplifier of the moving detector.

The results of our angular distributions measurements are shown in Fig. 3. The solid curves represent the fit to the data. The experimental results are shown in Table I.

TABLE I. Summary of the results of the present experiments.

Energy[a] (keV)	Intensity[b]	Spin sequence	A_2	A_4
66.4	60	$\frac{5}{2}-\frac{3}{2}$	-0.22 ± 0.09	-0.01 ± 0.09
87.8	16	$\frac{7}{2}-\frac{5}{2}$	0.00 ± 0.06	···
132.2	60	$\frac{5}{2}-\frac{3}{2}$	0.01 ± 0.04	···
360.3	42	$\frac{7}{2}-\frac{5}{2}$	-0.13 ± 0.06	0.03 ± 0.06
427.1	12	$\frac{7}{2}-\frac{3}{2}$	0.30 ± 0.17	-0.15 ± 0.20
474.6	≤7	$\frac{9}{2}-\frac{7}{2}$	···	···
562.4	35	$\frac{9}{2}-\frac{5}{2}$	0.26 ± 0.08	-0.11 ± 0.09

[a] Energies are accurate to ±0.30 keV.
[b] Typical intensity error is about 10%.

F. Half-life measurements

A search of isomeric states with lifetimes longer than a few nsec was carried out, observing the time correlation between the beam burst and the γ radiation. The low energy γ spectrum was detected with the small x-ray detector, taking advantage of its good time resolution. For the high energy γ spectrum the Ge(Li) detector was used. The data were accumulated in the analyzer memory in a 64×64 channel format and the slope of the prompt distribution was, respectively, 5 and 8 nsec.

In the present experiment the time distributions corresponding to the 66.4, 87.8, 132.2, 360.3, 427.1, and 562.4 keV γ-ray transitions were measured. It is interesting to note that all of them except the 562.4 keV transition show a flat background in the time distribution spectra. Figure 4 shows the timing data for the 87.8 and 360.3 keV γ ray after subtracting the time spectra corresponding to the Compton background. In both cases the existence of a long lived component is apparent. After this component is subtracted, a short lifetime of 12 ± 3 nsec remains in the case of the 87.8 keV γ ray but none larger than 8 nsec (the instrumental limit) was observed for the 360.3 keV

TABLE II. The γ-γ coincidence results from the present experiment. The letter W denotes weak coincidence.

Gate E_γ	66.4	87.8	132.2
87.8			X
132.2		X	
360.3	X		
474.6		W	W
562.4			X

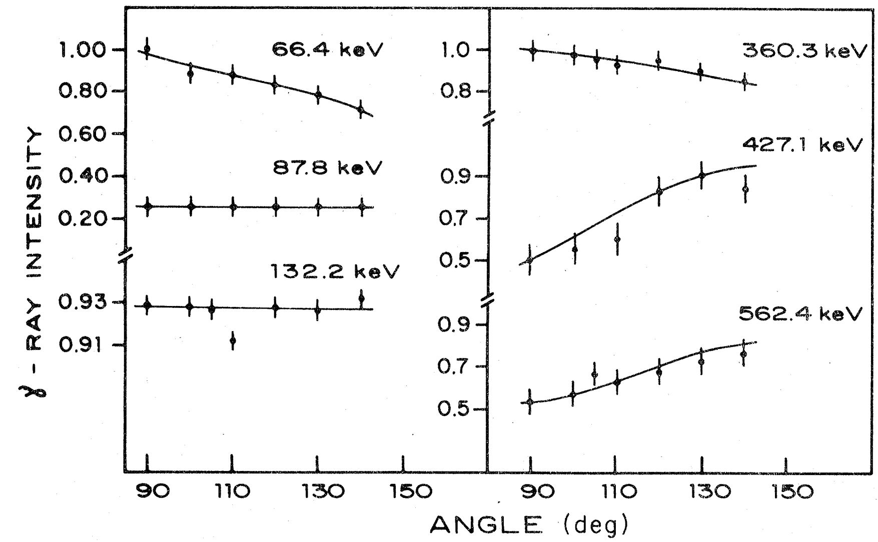

FIG. 3. Angular distribution results for the γ rays assigned to ^{75}Br. The solid curves represent the best theoretical fit to the experimental points.

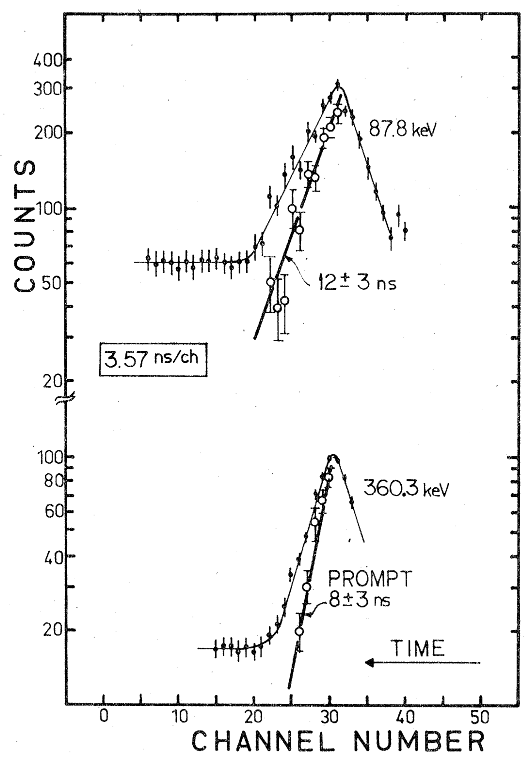

FIG. 4. Time distributions of the 87.8 and 360.3 keV γ rays. When the time distribution of the Compton background has been subtracted (solid dots) a flat time background appears in both time distributions. The open circles are the experimental results with this flat background discounted. The 87.8 keV transition shows a half-life $T_{1/2} = 12 \pm 3$ nsec and the 360.3 keV shows only a prompt time distribution within the time resolution of our detectors (~8 nsec).

γ ray.

On the other hand, our time measurements confirm the previous value for the half-life of the 132.2 keV transition ($T_{1/2} = 6.6$ nsec) while all the other γ transitions show a prompt distribution when the time background is discounted.

The observation of a flat time distribution in all observed lines but one, indicates the existence of an isomeric state with a lifetime longer than 100 nsec which feeds the 220.0 and 427.1 keV states. By comparing the relative contribution of this isomeric feeding with the total intensity, it is possible to speculate on the position of the unobserved long lived state. Within errors, such contribution is the same (~60%) for the 427.1, 360.3, and 87.8 keV transitions. This is also the case for the 132.2 keV transition once the long lived delayed intensity from the feeding 87.8 keV transition is subtracted. From these results one can conclude that the isomeric state should lie above 1 MeV because: (a) No transition of energy between 60 and 1000 keV has been observed in either single spectrum or the coincidence spectra with both the 132.2 and 360.3 keV lines, with an intensity comparable to the deduced long lived intensities; (b) If the isomeric state is near the 427.1 keV state, one should not expect a similar branching from such state to the 132.0 and 427.1 keV levels as is the present case.

III. ANALYSIS AND DISCUSSION

A. Energy levels and decay scheme

The energy levels of ^{75}Br and their decay scheme are shown in Fig. 5. The scheme was constructed

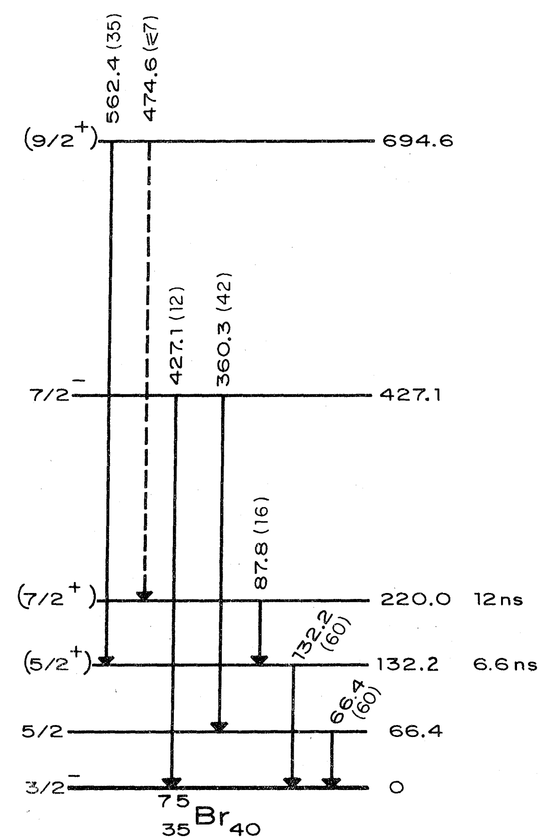

FIG. 5. Level scheme of ^{75}Br obtained with the ^{75}As-$(\alpha, 4n)$ reaction at 55 MeV.

on the basis of the relative γ-ray intensities, energy combinations, coincidence experiments, and timing results.

The 132.2 and 220 keV levels were previously known.[2] Our measurements clearly show that the 562.4 keV line is in coincidence with the 132.2 keV γ ray and not with the 87.8 keV γ ray. Thus the 694.6 keV level is unambiguously determined.

It is known that the spin-parity of the ^{75}Br ground state is $\frac{3}{2}^-$.[5] The lack of ground state transition from the 220 keV level indicates that the spin of this state is $\frac{7}{2}$ or larger. On the other hand, the $\Delta I = 0, 1$ character of the angular distribution of the 132.2 and 87.8 keV transitions limits the spin of the 220 keV level to $I \leq \frac{7}{2}$. Consequently we propose $I = \frac{5}{2}$ and $\frac{7}{2}$ for the 132.2 and 220 keV levels respectively. The positive parity of the 132.2 keV level is determined by the measured $E1$ multipolarity[2] of the ground state transition.

It is interesting to note that our timing measurements concerning the 220 keV level lead to the conclusion that the 87.8 keV state has dipole character in agreement with the angular distribution measurements. However, this result is in contradiction to the electron conversion data of Ref. 2. This disagreement can be attributed to the presence of a ^{74}Br contaminating line reported[2] at 89.6 keV.

The angular distribution of the 562.4 keV line is characteristic of a $\Delta I = 2$ stretched transition. This result together with the measured time distribution ($T_{1/2} \leq 8$ nsec) leads us to the conclusion that the spin and parity of the 694.6 keV level is $I^\pi = (\frac{9}{2}^+)$.

The 427.1 level deexcites into the 66.4 keV and ground states via the 360.3 and the 427.1 keV γ transitions. The last one exhibits an angular distribution that is only consistent with a $\Delta I = 2$ stretched transition, while the 66.4 keV γ-ray angular distribution exhibits $\Delta I = 1$ character. Consequently the spins $\frac{5}{2}$ and $\frac{7}{2}$ are assigned to the 66.4 and 427.1 keV levels, respectively. Moreover, the 66.4 keV angular distribution is consistent with the above mentioned assignments. The measured time distribution of the 427.1 keV γ transition ($T_{1/2} \leq 8$ nsec) is consistent with an $E2$ character. Thus a negative parity is assigned to the 427.1 keV level.

B. Discussion

In Fig. 6 the excitation energies of the known $\frac{9}{2}^+$ states for the odd-Z nuclei are shown together with the 2^+ state energies of the even-even nuclei for $28 < N < 50$. The systematics presented by Murray *et al.* has been completed with the data on ^{71}As and the Ga and Cu isotopes. The result of the present measurement is shown with a solid circle. It is seen that the existence of a minimum at $N \sim 42$, as suspected from the As data, is fully confirmed for the Br isotopes. Moreover, the validity of the assumed correlation between the $\frac{9}{2}^+$ and 2^+ states is strengthened. A closer inspection of the trend exhibited by the $\frac{9}{2}^+$ states in both the As and Br isotopes suggests that the actual minimum may show a smooth dependence with Z, shifting towards higher N as Z increases.

Recently Scholz and Malik,[6] by considering the Coriolis force plus a residual interaction of the pairing type, have successfully accounted for several experimentally observed features of the odd-proton nuclei in this mass range. In particular they have accounted for the occurrence of the low lying positive parity states in these nuclei. Although it is not possible to calculate the exact position of the $\frac{9}{2}^+$ states relative to the negative states, this model predicts that a positive deformation will produce a characteristic doublet of the positive parity states $\frac{5}{2}^+$, $\frac{9}{2}^+$, whose splitting diminishes with the deformation. Also from the model it can be concluded that the maximum of

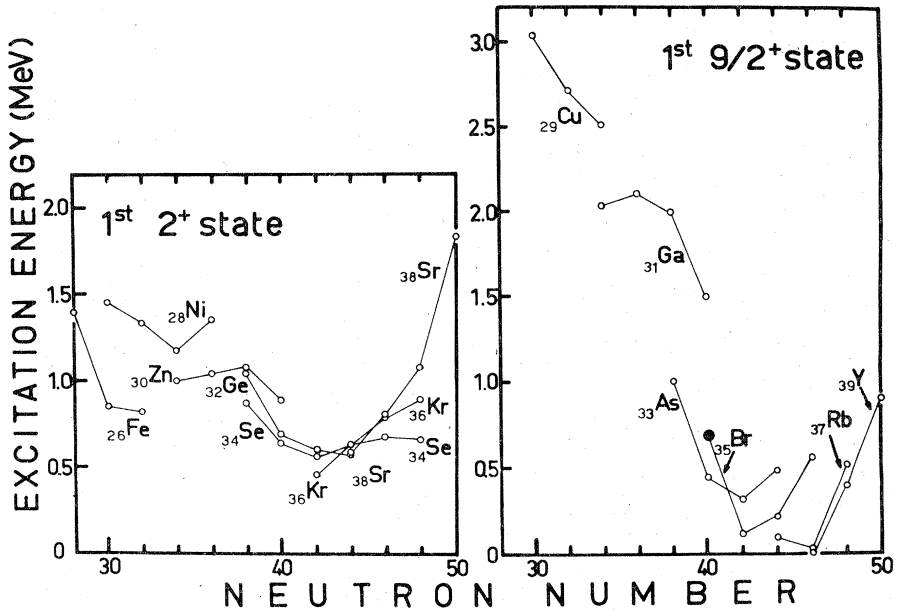

FIG. 6. Systematics of $\frac{9}{2}^+$ states for the As, Br, Rb, and Y isotopes compared with the 2^+ states of neighboring even-even nuclei. The solid circle corresponds to the $\frac{9}{2}^+$ state of ^{75}Br obtained in the present work.

deformation will correspond to the minimum of the excitation energy of the $\frac{9}{2}^+$ state. Experimentally the minimum of the splitting appears to coincide indeed with the minimum of $E_{9/2+}$ for ^{77}Br.

From the present experiment and according to this model several conclusions can be drawn:

(1) The odd-Z nuclei show a deformed structure which reaches its maximum for $N \simeq 42$. It is interesting to note in this connection that rotational bands have been found in neighboring isotopes like ^{73}Se,[7] ^{75}Se,[4] ^{76}Br,[8] and ^{77}Br.[9]

(2) The postulated correlation between the excitation energy of the $\frac{9}{2}^+$ and the first 2^+ levels is confirmed, showing a parallelism between the deformed structure of odd-A nuclei and their even-even cores.

(3) The existence of a close positive doublet ($\frac{5}{2}^+$, $\frac{9}{2}^+$) in the region indicates that the deformation is positive. This seems to be in contradiction to the results of a previous paper[10] which predicted oblate deformations around ^{72}Kr through potential energy surface calculations.

(4) The minimum excitation energy of the $\frac{9}{2}^+$ states in the Br isotopes occurs for N slightly larger than in the case of the As isotopes. In this regard it would be interesting to acquire the relevant data on the Rb and Y isotopes in order to determine the variation of this minimum with Z.

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