the 9–40-MeV region for protons, deuterons, and alpha particles. Figure 19 illustrates the data of Refs. 8, 18, 16, 23, 11, and 17 as well as our data and the optical-model data,[6] where the last two have been averaged over the natural abundances. It then is easy to discern the minimum occurring. This evidence shows that the nickel reaction cross section is small because of the presence of comparatively light ^{58}Ni as the prevalent isotope in nickel which reduces the value of σ_R for the element relative to neighboring elements by about 10%.

ACKNOWLEDGMENTS

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Search for Members of the Two-Phonon Triplets in ^{80}Se and ^{80}Kr

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The γ rays emitted in the decay of ^{80}Br have been investigated with Ge(Li) and NaI(Tl) spectrometers. γ rays (relative intensities are in parentheses) of 616.2±0.5(100), 639.2±0.7(3.6), 665.6±0.5(17.2), 704.0±0.7(2.9), 812.0±1.5(0.8), and 1256.4±1.5(1.0) keV have been observed. Coincidence and γ-γ directional correlation measurements were performed with two NaI detectors, a fast coincidence system, and a multiparameter analyzer to record the data. The coincidence studies indicated levels at 616.2±0.5, 1255.6±0.6, and 1320.2±0.9 keV in ^{80}Kr, and 665.6±0.5 and 1477.6±1.6 keV in ^{80}Se. The experimental directional correlation coefficients of the 639.2–616.2-keV, 704.0–616.2-keV, and 812.0–665.6-keV cascades are $A_2=-(0.12\pm0.04)$, $A_4=+(0.38\pm0.10)$; $A_2=+(0.38\pm0.06)$, $A_4=+(1.28\pm0.18)$; and $A_2=+(0.29\pm0.13)$, $A_4=+(1.32\pm0.37)$, respectively. These values are compatible with spin assignments of 0^+ for the 1477.6-keV level in ^{80}Se, and of 2^+ and 0^+ for the 1255.6- and 1320.2-keV ^{80}Kr levels, respectively.

I. INTRODUCTION

In recent years there has been considerable interest in the low-lying states of spherical even-even nuclei. In many cases these states have been found to have a collective nature in that they possess many of the properties of quadrupole surface vibrations about a spherical equilibrium shape. Particular interest has centered around the 0^+, 2^+, and 4^+ members of the "2-phonon state." However, it is only in a very limited number of cases that all three members of the triplet have been identified. In most cases it is the 2^+ and 4^+ members that are observed. Even in the cases where the 0^+ state is seen, it is not always clear that it has the same character as the other two members of this triplet. It has been pointed out by Kisslinger[1] that if one includes in perturbation theory the parts of the interaction which are dropped in the quasiparticle random-phase approximation, it is found that the 0^+ state is affected much more than the other states. Numerous other investigators have dealt with the nature of these states at about twice the energy of the first 2^+ state in medium-weight even nuclei, but certainly the recent work of Kregar and Mihailovic[2] lends credence to the assertion that in some cases they cannot be described as members of a vibrational triplet. They[2] show that the second 0^+ states of several even nuclei in the germanium-selenium region can be interpreted by means of the nonadiabatic model of Davydov[3] as belonging to the

* Work supported in part by a grant from the National Science Foundation.
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‡ Research contract sponsored by the U. S. Atomic Energy Commission under contract with the Union Carbide Corporation.

[1] L. S. Kisslinger, in *Internal Conversion Processes*, edited by J. H. Hamilton (Academic Press Inc., New York, 1966), p. 285.
[2] M. Kregar and M. V. Mihailovic, Nuklearni Institut Jozef Stefan, Ljubljana (Yugoslavia), Report No. R-484, 1966 (unpublished).
[3] A. S. Davydov, Nucl. Phys. **24**, 682 (1961).

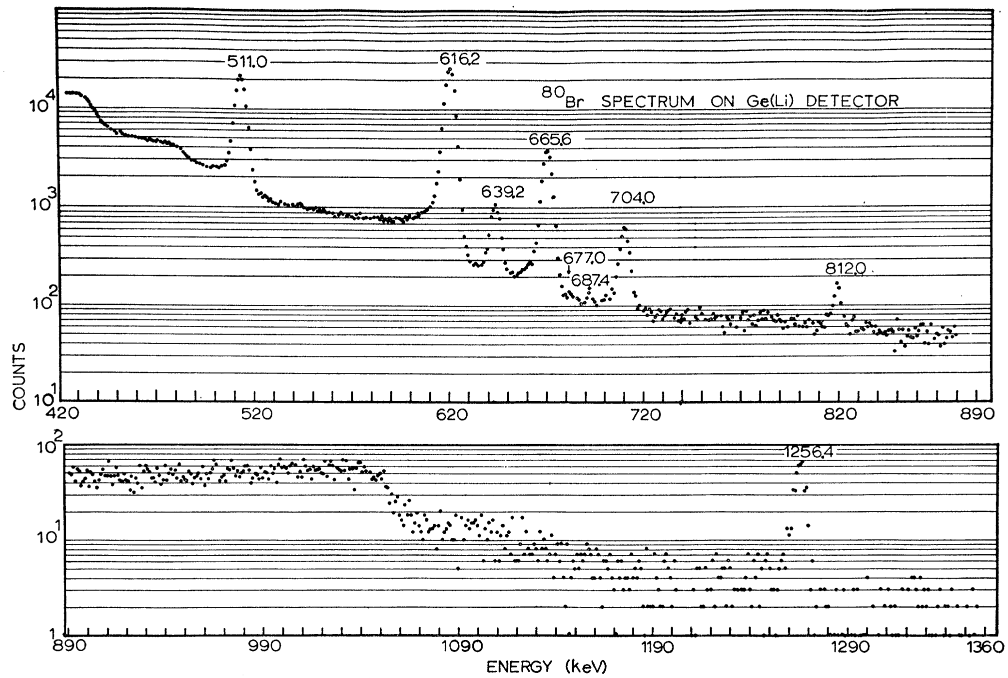

FIG. 1. γ-ray spectrum of ^{80}Br taken with a Ge(Li) detector.

oblate-shaped ellipsoid. With the result that the general description of the second 0^+ level in spherical even-even nuclei as a member of the two-phonon triplet is open to question, there is an obvious need for detailed experimental information on such nuclei.

Both Coulomb excitation and inelastic scattering experiments have proved useful probes for the study of members of one- and two-phonon states. Selected radioactive nuclei, namely, those decaying from a 1^+ state, also provide an excellent means for studying these states inasmuch as β decay should be allowed to both one- and two-phonon levels as well as to the ground state. The decay of 18-min ^{80}Br which has a ground-state spin[4] of 1^+ is such a case and it is a study of this nucleus that is reported in the present paper.

The 18-min ground state of ^{80}Br decays[5] by negatron emission to ^{80}Kr and by positron emission and electron capture to ^{80}Se. The first excited level in ^{80}Kr was established at 620 keV by Scharff-Goldhaber and McKeown.[6] Coulomb-excitation studies of ^{80}Se by Temmer and Heydenberg[7] indicated the presence of a 654-keV γ ray which they assigned to the first 2^+ level in ^{80}Se. From (p,p') studies of ^{80}Se, Carter[8] reported the levels in ^{80}Se at 661, 1444, and 1470 keV. It was shown by McGowan and Stelson[9] that a second 2^+ level exists at 1455 ± 12 keV in ^{80}Se. The γ-ray measurements by Trehan and Van Patter[10] showed that levels at 618, 1258, and 1333 keV occur in ^{80}Kr, and a 2^+ 667-keV level in ^{80}Se. However, they were unable to make definite spin parity assignments for the 1258- and 1333-keV levels of ^{80}Kr. The (p,p') studies of ^{80}Se by Darcey *et al.*[11] indicated the existence of 660-, 1430-, 1470-, and 1690-keV levels. They were able to assign the levels at 0.66 and 1.43 MeV as 2^+ states. However, it was only by a comparison with the systematic trends in ^{76}Se and ^{78}Se and by the similarities in the angular distributions with those observed in ^{76}Se that they were able to assign probable spins of 0^+ and 4^+ for the levels at 1.47 and 1.69 MeV. In recent measurements of the inelastically scattered deuterons on ^{80}Se, Lin[12] reports low-lying levels at 0.66, 1.44, 1.48, and 1.69 MeV, in general agreement with Darcey *et al.*[11]

In an effort to more clearly identify and establish the properties of the low-lying states in ^{80}Kr and ^{80}Se we

[4] E. Lipworth, H. L. Garvin, and T. M. Green, Bull. Am. Phys. Soc. 4, 11 (1959).

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[11] W. Darcey, D. J. Pullen, and N. W. Tanner, in *Proceedings of the International Symposium on Direct Interactions and Nuclear Reaction Mechanisms*, edited by E. Clementel and C. Villi (Gordon and Breach Science Publishers, Inc., New York, 1962), p. 795.

[12] E. K. Lin, Nucl. Phys. **73**, 613 (1965).

have remeasured the γ-ray spectrum of ^{80}Br by means of high-resolution Ge(Li) detectors. γ-γ coincidence measurements have also been performed with a multiparameter analyzer, and the angular correlations have been determined for all coincident γ cascades.

II. SOURCE PREPARATION

The ^{80}Br sources were prepared by the reaction ^{79}Br$(n,\gamma)^{80}$Br in the Oak Ridge research reactor. The starting material was sodium bromide enriched to 99.75% in ^{79}Br. After the irradiation, the target material was dissolved and a silver bromide precipitation was carried out. Further purification was achieved by dissolving the silver bromide precipitate in ammonium hydroxide and then reprecipitating it in the presence of sodium "hold-back" carrier. This step was repeated and finally ^{80}Br sources for analysis were prepared in the form of silver bromide precipitate mounted on thin Mylar film backing.

For the γ-γ angular correlation measurements, the sources consisted of ~50 microliters of silver bromide dissolved in ammonium hydroxide. The solution was contained in a $\frac{1}{8}$-in.-diam fluorethene thimble.

III. SINGLE-CRYSTAL γ-RAY MEASUREMENTS

Singles γ-ray measurements were carried out with both NaI(Tl) and Ge(Li) spectrometers. The germanium detector, which had a 2-cm^2 surface area and 3-mm depletion depth, was coupled to a Tennelec 100-C preamplifier. Pulses from the preamplifier were amplified and then stored in a Victoreen 1600-channel analyzer. The resolution of this system was about 5 keV for the 661.6-keV line of ^{137}Cs.

The efficiency calibration of the spectrometer was accomplished in the following way. Sixteen sources emitting prominent γ rays ranging in energy from 87.7 keV (^{109}Cd) up to 2753.9 keV (^{24}Na) were counted at known geometry using an efficiency calibrated NaI(Tl) crystal. From these measurements, emission rates of the γ rays for the various sources were determined. The sources were then measured at fixed geometries with the Ge(Li) detector in order to determine appropriate efficiency curves.

The ^{80}Br source was placed at a distance of approximately 5 cm from the detector and a 1.33-g/cm^2 polystyrene absorber was inserted between the source and detector to absorb electrons. Several runs each of about 35-min measuring time were taken in order to check the half-lives of the γ rays appearing in the spectrum. These measurements were repeated until essentially all of the remaining activity could be attributed to ^{82}Br. The earlier spectra from three freshly prepared ^{80}Br sources, (these were relatively free of ^{82}Br contamination) were added to increase the statistical accuracy. The spectrum thus obtained is shown in Fig. 1. From the intensity of the 778-keV γ ray (relative intensity 100%) emitted in the decay of ^{82}Br we calculate that this isotope contributes less than 0.2% to the spectrum of Fig. 1 at 778 keV.

TABLE I. Energies and relative intensities of ^{80}Br γ rays.

Energy (keV)	Singles [Ge(Li)] relative intensity	Relative intensity, spectra in coincidence with γ rays of energies (keV): 616.2	665.6	704.0
616.2±0.5	100			3.6±0.9
639.2±0.7	3.6±0.3	4.2±0.6		
665.6±0.5	17.2±1.4			
677.0±1.0[a]	0.12±0.04			
687.4±1.0[a]	0.18±0.05			
704.0±0.7	2.9±0.4	4.0±1.0		
812.0±1.5	0.8±0.2		0.9±0.2	
1256.4±1.5	1.0±0.1			

[a] The intensity of this γ ray was so small that it was not possible to accurately determine its half-life. Therefore, it cannot be said with certainty that the transition belongs to the decay of ^{80}Br.

The energies and relative intensities of the γ rays assigned to the decay of ^{80}Br are presented in Table I. The two weak γ rays with energies of 677.0±1.0 and 687.4±1.0 keV could not be assigned definitely to the decay of ^{80}Br because their extremely low intensities made it impossible to check their half-lives.

IV. γ-γ COINCIDENCE EXPERIMENTS

γ-γ coincidence measurements were performed by means of two 3-in.×3-in. NaI(Tl) detectors making an angle of 120° with each other. A 1.7-cm lead plate covered with thin layers of copper and cadmium was inserted between the crystals to minimize crystal-to-crystal scattering. Electrons were absorbed by 1.33 g/cm^2 polystyrene disks placed between the source and detectors. Amplifier outputs of the scintillation crystals were coupled to the X and Y analog-to-digital converters of a Victoreen 100×200 channel multiparameter analyzer. The analyzer was provided with an external gate signal from a fast coincidence system having a resolving time of $2\tau = 80$ nsec. The singles spectra from the X and Y detectors were accumulated on a time sharing basis with the coincidence spectra and were stored in the memory planes provided for this purpose. During a typical cycle of counting, the X and Y singles spectra were each stored for 1 sec and the X-Y coincidences were accumulated for 10 sec. The first experiment on a freshly prepared ^{80}Br source usually consisted of about 200 such cycles. The accumulated data were then read onto magnetic tape and the measurement repeated. With several such measurements on a given source it was possible to search for contributions from 4.5-h ^{80}Br and 35-h ^{82}Br. The early measurements from several freshly prepared ^{80}Br sources were summed.

The necessary random coincidence corrections, as well as the real coincidence corrections from ^{82}Br, were accomplished by a computer program. It was unnecessary to consider corrections to the early spectra for 4.5-h ^{80}Br. If either the 677.0- or the 687.4-keV transition resulted from direct population from the 5-

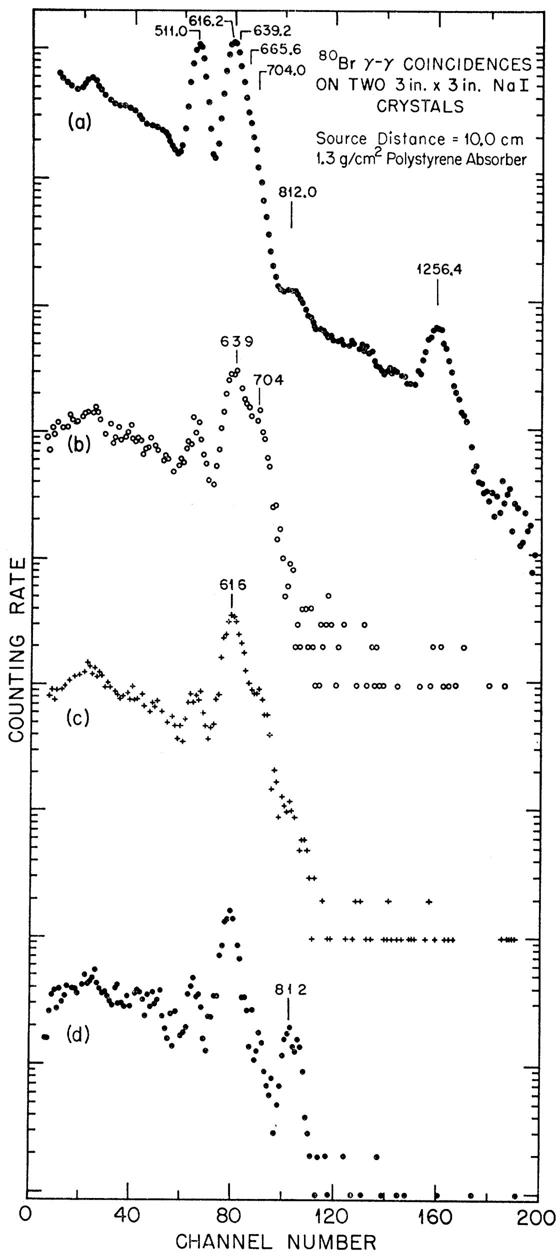

FIG. 2. Curve (a) shows ungated γ-ray spectrum of ^{80}Br taken with a 3 in.×3 in. NaI(Tl) crystal. Curves (b), (c), and (d) are coincident spectra with 16-keV-wide gate settings at 605, 636, and 670 keV, respectively.

isomeric state of ^{80}Br, this would place an upper limit of 0.01% for direct decay from the isomer.

The principal features observed in these experiments were coincidences between the 616.2-, 639.2-, and 704.0-keV γ rays and between the 665.6- and 812.0-keV transitions. These features are illustrated quite clearly in Figs. 2 and 3, in which we show coincidence planes in the X direction generated by the selected Y gates which most clearly emphasize the coincidence relationships.

Curve (a) in Fig. 2 is the ungated spectrum of ^{80}Br. Curves (b), (c), and (d) in Fig. 2 are spectra coincident with $Y=39$, 41, and 43 which correspond to a gating window width of ~16 keV centered at 605, 636, and 670 keV, respectively. From curve (b) we easily see that the 639.2- and 704.0-keV γ rays are in coincidence with the 616.2-keV transition. Now, by comparing curves (b) and (c), we notice the reduced intensity of the 704-keV transition in curve (c) as the gate setting is moved from 605 to 636 keV, which illustrates that the 639.2- and 704.0-keV transitions are not coincident with each other. As the gate position is moved to 670 keV [curve (d)], we notice the appearance of the 812.0-keV γ ray, which indicates that the 812.0-keV transition is coincident with the 665.6-keV γ ray and possibly with the 704.0-keV transition which also has events falling within the gating channel.

Curve (a) in Fig. 3 is again the ungated spectrum of ^{80}Br. Curve (b) in Fig. 3 is the coincidence spectrum corresponding to the gate centered at 709 keV. Actually this curve is the result of adding two X planes generated by gate settings of $Y=45$ and 46. The near absence of the 812.0-keV γ ray in this curve implies that this transition is not in coincidence with the 704.0-keV transition but is only coincident with the 665.6-keV γ ray. The absence of the 511.0-keV line in this curve, which is present in all the previous curves shown, is due to the fact that positrons are only in coincidence with the 665.6-keV transition. Curve (c) in Fig. 3 is the result of adding X planes generated by the gate settings of $Y=52$, 53, and 54 which correspond to the gate setting covering the three top channels of the 812.0-keV photopeak. In this curve we see only the 665.6-keV line, which confirms our previous conclusion that the 812.0-keV line is coincident with the 665.6-keV γ ray.

We were unable to detect any coincidence relationships between the weak 677.0- and 687.4-keV γ rays and any other transitions. Possibly this was due to the large coincidence background effects from the more intense transitions in this energy region.

The pertinent coincidence spectra were shape-unfolded and a quantitative determination of the coincidence quotients q was made in a manner similar to that described previously.[13] From the q values and the singles intensities in column 2 of Table I we calculated the intensities of the transitions coincident with the grating γ ray of interest. These data which are shown in columns 3–5 of Table I substantiate the decay scheme of Fig. 5.

V. γ-γ DIRECTIONAL CORRELATION MEASUREMENTS

The same equipment as described in Sec. IV was used in the directional correlation experiments. As

[13] N. R. Johnson, E. Eichler, G. D. O'Kelley, J. W. Chase, and J. T. Wasson, Phys. Rev. 122, 1546 (1961).

before, the source-to-crystal distance was 10.0 cm for both detectors, and polystyrene disks of 1.33 g/cm^2 were placed between the source and the scintillation crystals to absorb electrons. However, the anti-Compton absorber was used to minimize crystal-to-crystal scattering in the 90° geometry only. The source was centered with an accuracy of about 1%. Coincidences were collected at three angles: 90°, 135°, and 180°. The angle was changed every 10 min. Data were taken for approximately 60 min covering the sequence of angles 90°, 135°, 180°, 180°, 135°, 90°; then the source was replaced by another one made from a freshly bombarded sample and a similar sequence of measurements was taken beginning at 180°. The two sets of data were added and normalized by the ungated spectra stored in the $X=0$ and $Y=0$ planes. Measurements were also carried out on the 4.5-h ^{80}Br activity. No change in results could be observed when compared with those obtained for the 18-min ^{80}Br activity. This is due to the fact that the 4.5-h isomeric level almost entirely decays to the 18-min ^{80}Br ground state. When the data were corrected for the contribution of accidental coincidences, the following results were obtained.

The 812.0–665.6-keV cascade. The coincidence spectra (X planes) belonging to those gating Y channels which correspond to the top of the 665.6-keV photopeak were added to improve the statistical errors. None of the other γ rays falling in this gating window are in coincidence with the 812-keV transition. After correction for finite solid angles of the detectors, we obtain $W(\theta)=1+A_2P_2(\cos\theta)+A_4P_4(\cos\theta)$ with $A_2=+(0.29\pm0.13)$ and $A_4=+(1.32\pm0.37)$. These results are consistent only with a spin of 0 for the 1477.6-keV level in ^{80}Se.

The 704.0–616.2-keV cascade. Those coincidence spectra (X planes) gated by Y channels corresponding to the top of the photopeak of the 616.2-keV transition were summed. The contribution from the 812.0–665.6-keV cascade was subtracted; however, there exist the weak 677.0- and 687.4-keV γ rays one of which (or both) might be in coincidence with the 812.0- or 665.6-keV transitions. No attempt was made to correct for an eventual contribution from this (these) cascade(s) because the intensity of the 677.0- and 687.4-keV γ rays is at least one order of magnitude less than that of the 704.0-keV γ ray. The anisotropy coefficients for the 704.0–616.2-keV cascade are (finite solid-angle correction applied): $A_2=+(0.38\pm0.06)$ and $A_4=+(1.28\pm0.18)$ which uniquely determine the spin of the 1320.2-keV level in ^{80}Kr as 0.

The 639.2–616.2-keV cascade. The same summing procedure as in the preceding case was followed. Contributions from the 812.0–665.6-keV and the 704.0–616.2-keV cascades were subtracted. After correcting the results for the finite solid angles of the counters, we obtain $A_2=-(0.12\pm0.04)$ and $A_4=+(0.38\pm0.10)$ which is in agreement only with a spin of 2 for the 1255.6-keV level in ^{80}Kr. In Fig. 4, the A_2 and A_4 coefficients of the Legendre polynomials are plotted as a function of δ. Reference to this plot shows that the 639.2-keV γ ray for the $2^+\rightarrow2^+$ transition consists of 98% or more $E2$ radiation ($\delta\leq-9$).

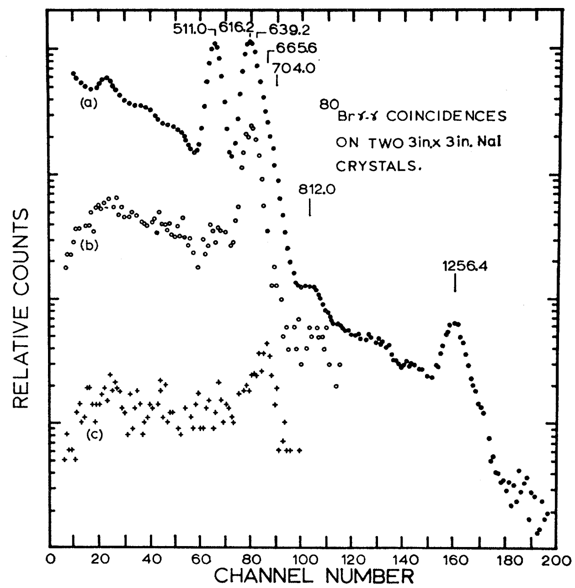

FIG. 3. Curve (a) shows the ungated γ-ray spectrum of ^{80}Br taken with a 3 in.×3 in. NaI(Tl) crystal. Curves (b) and (c) are coincident spectra with 16-keV-wide gate settings at 709 and 812 keV, respectively.

VI. DISCUSSION

A decay scheme of ^{80}Br consistent with our experimental data is presented in Fig. 5. The 812.0-keV transition is in coincidence with the 665.6-keV γ ray which establishes an excited level at 1477.6±1.6 keV in ^{80}Se. The 1477.6-keV level apparently corresponds to the level seen at about this energy in various proton and deuteron scattering experiments.[6,9,10] The results of the 812.0–665.6-keV directional correlation measurements lead to a spin assignment of 0 for this level. The log*ft* value of the electron capture feeding to the 1477.6-keV level is 5.7 as calculated from our relative γ-ray intensities, the ratio of the intensity of the 616.2-keV γ ray to that of positron emission,[10] the ratio of positron to negatron emission,[14] and the ratio of positron emission plus electron capture to negatron emission.[15] Therefore this electron capture transition is probably allowed and even parity is assigned to the 1477.6-keV level.

Neither the singles γ-ray spectra nor the γ-γ coincidence data showed any evidence for population of a second 2^+ level at about 1450 keV as observed in (p,p'), (d,d'), and (α,α') experiments.[8,9,11,12] We can set an upper limit for the intensity of an approximately 780-keV γ ray in our spectra (representing a $2^+\rightarrow2^+$ transition) as about 20% of that of the 812.0-keV transition.[8]

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[15] J. H. Reynolds, Phys. Rev. **79**, 243A (1950); **79**, 789 (1950).

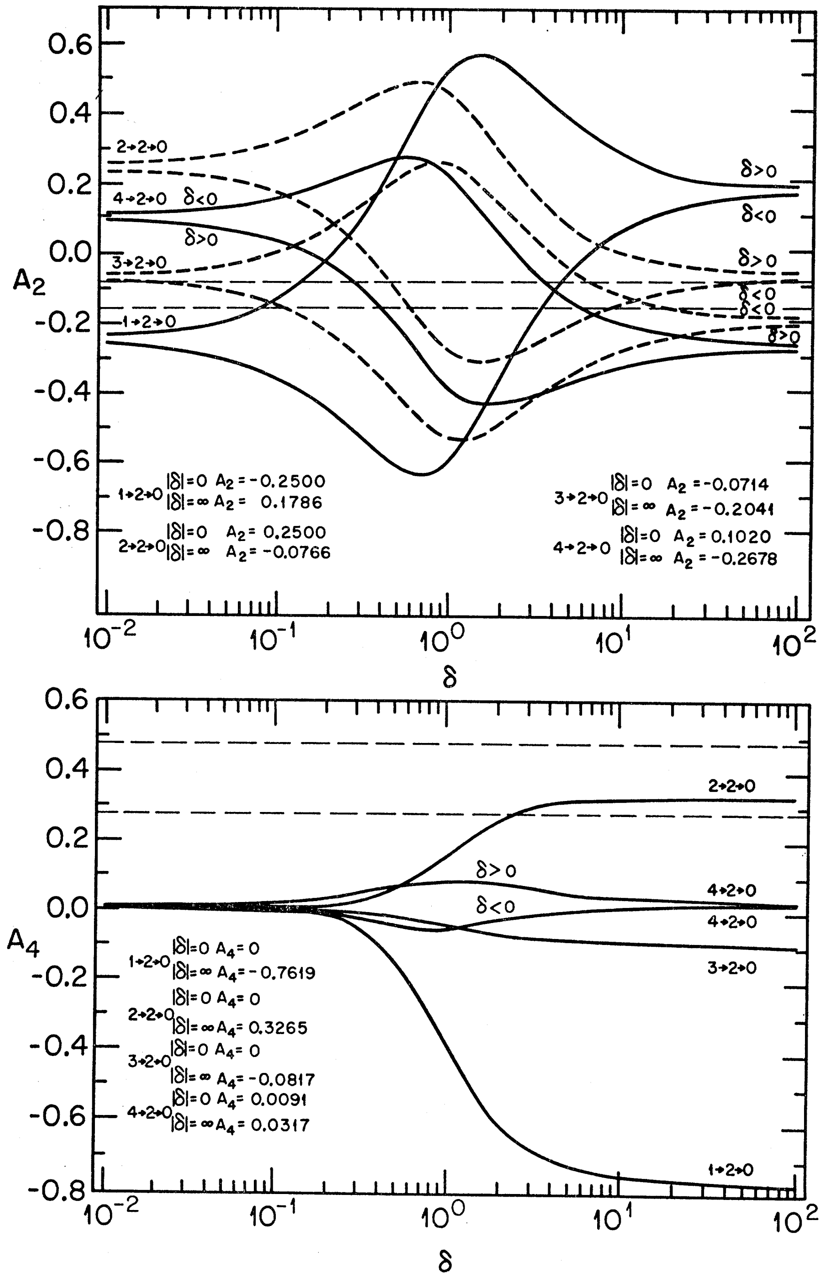

FIG. 4. Theoretical correlation coefficients of A_2 and A_4 versus $I_i=4$, 3, 2, and 1. The horizontal dashed lines are the experimental values of A_2 and A_4 and clearly indicate the predominantly $E2$ character of the 639.2-keV transition in the $2^+ \rightarrow 2^+$ transition in ^{80}Kr.

Our single-crystal and coincidence results establish levels at 1255.6±0.6 keV and at 1320.2±0.9 keV in ^{80}Kr. According to the directional correlation results, the spins of these levels are 2 and 0, respectively. Although the logft values of the β branches feeding these levels are each 6.3 and do not permit an unambiguous classification of the transitions, it is reasonable to assign even parity to the 1255.6- and 1320.2-keV levels. Even parity is implied by the quadrupole character of the 639.2-keV transition which is best explained by an $E2$ assignment. The above spin assignments also agree with the fact that a 1256.4-keV ground-state transition is observed whereas a 1320.2-keV transition is not. The latter result disagrees with the findings of Trehan and van Patter,[10] who reported a crossover γ ray of 1333 keV having an intensity of 0.3 units relative to the 616.2-keV transition as 100. A transition of such intensity should have shown up in our spectra. It is conceivable that the 1333-keV γ ray observed by them was due to summing of 616.2- and 704.0-keV γ rays.

The 677.0- and 687.4-keV γ rays observed in the singles spectrum are too weak to show up in the coincidence spectra. In fact, their extremely low intensities made it impossible to check the half-lives of these lines,

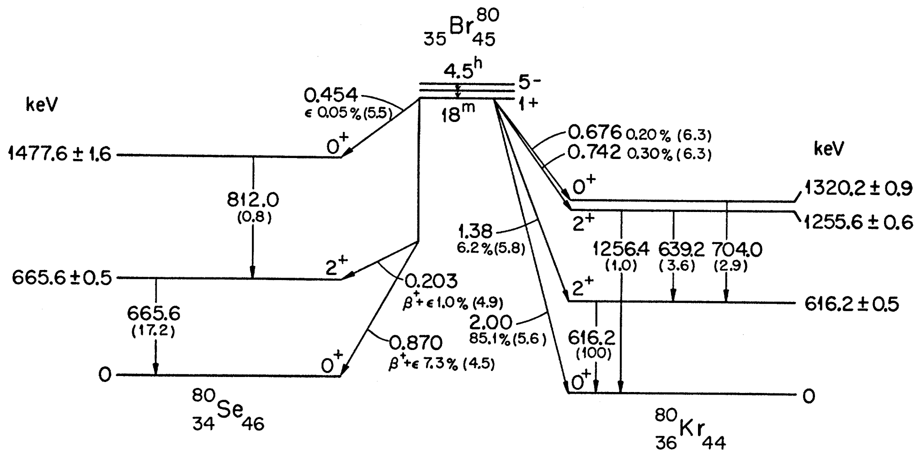

FIG. 5. Decay scheme of ^{80}Br. Relative γ-ray intensities deduced from the measurements with a germanium detector are given in parentheses beneath the γ-ray energies. These intensities were used in conjunction with the existing information on the positron plus electron capture and negatron decays of ^{80}Br to determine the logft values shown in parentheses on the respective decay branches.

and consequently we are not sure that they occur in the decay of ^{80}Br. Thus, these two transitions have not been placed in the decay scheme shown in Fig. 5.

The increasing degree of forbiddenness for the β transition from ^{80}Br (1^+) to the ground, one-phonon, and two-phonon states of ^{80}Se and ^{80}Kr fits the theoretical calculations of Futami and Sakai.[16] Using a microscopic discription, they obtained for transitions, to the ground and first-excited state, logft values of 4.9 and 5.8 to ^{80}Se and 5.7 and 6.2 to ^{80}Kr. It appears, however, that electron capture decay to what has been attributed[11,12] as the second 2^+ state in ^{80}Se is more hindered than is the average case, i.e., if we set a reasonable upper limit of 0.005% for an electron capturing branch to the 2^+ state in ^{80}Se, the lower limit on the logft is 6.4 whereas from the general pattern for such cases a somewhat lower value of about 6 would be expected. On the other hand, the β branch feeding the 2^+ state in ^{80}Kr at 1255.6 keV shows an opposite deviation from the general pattern in that it has a logft value identical with the β-ray branching feeding the second 0^+ level. It is not known whether this behavior results from basic properties of the structures of the second 2^+ states in ^{80}Se and ^{80}Kr or whether this is due to accidental cancellations in the wave functions of these states and the ground state of ^{80}Br. Detailed calculations are needed to clarify this point.

From our measured value of 98% or greater, $E2$ radiation for the 639.2-keV transition and from the γ-ray intensity values of Table I, the reduced $E2$ transition probability ratio $B(E2; 2'^+ \rightarrow 2^+)/B(E2; 2'^+ \rightarrow 0^+)$ is found to be 97. It is interesting to compare this large value with the corresponding ratio in ^{82}Kr and ^{84}Kr. As the closed shell of 50 neutrons is approached, the ratio becomes 51 and 14 in ^{82}Kr and ^{84}Kr, respectively,[17,18] indicating what may be a change in the collective nature of the low-lying states of the latter nucli.

In conclusion, we feel that accurate energy and spin assignments for the second 0^+ level in ^{80}Se and the second 0^+ and 2^+ levels in ^{80}Kr have been firmly established in the present measurements. These assignments are important and necessary for a better understanding of the character of the group of levels at about twice the energy of the first-excited state in such even nuclei. However, the present experiments have not included a measurement of the lifetimes of these 0^+ states. A knowledge of these lifetimes is important to establish if the 0^+ states are collective as are their close-lying 2^+ and 4^+ neighbors or if their character is more of a quasiparticle nature. We hope to include some of these more difficult measurements in the near future.

ACKNOWLEDGMENT

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[18] Branching ratio taken from N. R. Johnson and G. D. O'Kelley, Phys. Rev. **108**, 82 (1957).