DIRECTIONAL CORRELATIONS OF GAMMA RAYS IN THE DECAY OF 36 hr ^{82}Br

By S. L. Gupta* and M. M. Bajaj*

[*Manuscript received May* 14, 1968]

Summary

Coincidence and gamma–gamma directional correlation measurements are made for the 10 cascades of ^{82}Kr: 1648–777, 1008–1044, 1317–777, 619–1475, 555–1317, 555–619, 828–1044, 828–(1044)–777, 698–777, and 619–698 keV, of which the cascade 1008–1044 keV has been attempted for the first time. The results permit a unique spin assignment of 5 for the 2829 keV level from the directional correlation of the 1008–1044 keV cascade and a spin of 3 to the level at 2425 keV from that of the 1648–777 keV cascade. Multipole character and admixture are determined for the transitions 1648, 1475, 1044, 1008, 555, 828, 698, 619, and 1317 keV. Computed E2 partial half-lives for the last two transitions are compared with the predictions of the single-particle estimate and the nonaxial rotor model.

I. Introduction

The 36 hr β-decay of ^{82}Br and the positron decay of ^{82}Rb^{m} into ^{82}Kr have been the subject of many investigations since 1941. Even the earlier results showed a rather complicated disintegration scheme and a high multiplicity of the cascades in the level structure of ^{82}Kr. Recent studies on the γ-transitions in ^{82}Kr using more refined techniques (Gfirtner, Reiser, and Schneider 1965; Kenney and Raman 1965; Koch *et al.* 1965; Mo, Hsu, and Wu 1965; Nieschmidt, Mandeville, and Ellsworth 1965; Reidy and Wiedenbeck 1965; Beard 1966; Etherton and Kelly 1966; Raman 1967) helped to construct an acceptable level scheme of ^{82}Kr (Fig. 3), which could also account for some of the earlier data. Some uncertainties, however, still exist. Etherton and Kelly (1966) using a permanent magnet electron spectrometer investigated the decay scheme of ^{82}Br and assigned three possible spin values 2, 3, or 4 to the 2425 keV level. On the other hand, Koch *et al.* (1965) had put forward a spin value of 3 for the same level from the study of the directional correlation of the 1648–777 keV gamma–gamma cascade. Recent correlation measurements of Hsu and Wu (1967) on the same cascade, however, favour a spin value of 3 or 4. In view of these uncertainties, a redetermination of the directional correlation of this cascade with sufficient accuracy is considered necessary for fixing the spin value of the 2425 keV level. The work of Etherton and Kelly (1966) also gave three possible spin values 4, 5, or 6 for the 2829 keV level. No unique spin assignment for this level is possible from the presently available data. An attempt is therefore made from the present directional

* Department of Physics and Astrophysics, University of Delhi, Delhi-7, India.

Aust. J. Phys., 1968, **21**, 649–60

correlation measurement of the 1008–1044 keV cascade to assign a spin to this level uniquely. The quadrupole admixture in the 1008 keV transition is also determined.

The internal conversion coefficient of $\gamma 1648$ has not been measured so far and therefore the multipolarity of the transition is not definitely known. Koch *et al.* (1965) reported a predominantly dipole character for $\gamma 1648$ from the directional correlation study of the 1648–777 keV cascade. As $\gamma 1648$ is an extremely weak transition, further investigation of the directional correlation of the above cascade appears to be worth while. Again, Waddell and Jensen (1956), Simons *et al.* (1963), and Simons, Bergström, and Anttila (1964) measured the directional correlation of the 555–619 keV cascade. The coincidence rate observed for this cascade is strongly influenced by the Compton contributions of the neighbouring high energy γ-rays. Simons *et al.* (1963) estimated the percentage of the interfering coincidences, but did not apply the necessary correction to their correlation function. Waddell and Jensen (1956), on the other hand, seem to have neglected the interfering effects on their correlation function. Reinvestigation of the directional correlation of the 555–619 keV cascade, taking into account the contribution of the interfering cascades, is therefore considered desirable.

In addition to the above-mentioned cascades, seven other interfering cascades have also been re-examined here in order to make cross-checks on the multipole admixtures of the γ-transitions involved. Finally the partial lifetimes of the 619 and 1317 keV transitions obtained from the experimental data are compared with the single-particle Weisskopf estimates as well as with the nonaxial rotor model, as this may help in understanding the origin of the low-lying excited states of ^{82}Kr.

II. Experimental Procedure

(a) *Source Preparation and Details of Procedure*

The ^{82}Br (36 hr) source was produced by the irradiation of natural bromine ($50 \cdot 5\%$ ^{79}Br and $49 \cdot 5\%$ ^{81}Br) in the form of NaBr with the pile neutrons in the Apsara Reactor of the Bhabha Atomic Research Centre, Bombay. As ^{80}Br^{m}, with a half-life of $4 \cdot 5$ hr, was produced together with the 36 hr ^{82}Br, the source was allowed to decay for several hours to reduce the ^{80}Br^{m} activity to a very low level.

All coincidence and directional correlation measurements were carried out using a fast–slow coincidence scintillation spectrometer having an effective resolving time of about 30 nsec. In coincidence measurements both the detectors were shielded from each other with anti-Compton graded cones and the spectra were analysed using standard line shapes. The coincidence counting rates were measured in 30° increments from 90° to 270°. The total number of coincidences collected at each angular position was about 15 000. The singles counting rates in the movable and fixed detectors and the coincidences were recorded simultaneously in all the runs at each angle. The ratio of true to chance coincidences was about 100 : 1. The singles counting rate at different angular positions was constant to within 1%. In the directional correlation measurements, the data were corrected for the source decay, chance coincidences, geometry, and the interfering cascades.

(*b*) *Gamma Ray Spectrum and Coincidence Measurements*

The observed γ-ray scintillation spectrum of ^{82}Br is reproduced in Figure 1. It does not indicate the presence of any impurity activity in the source.

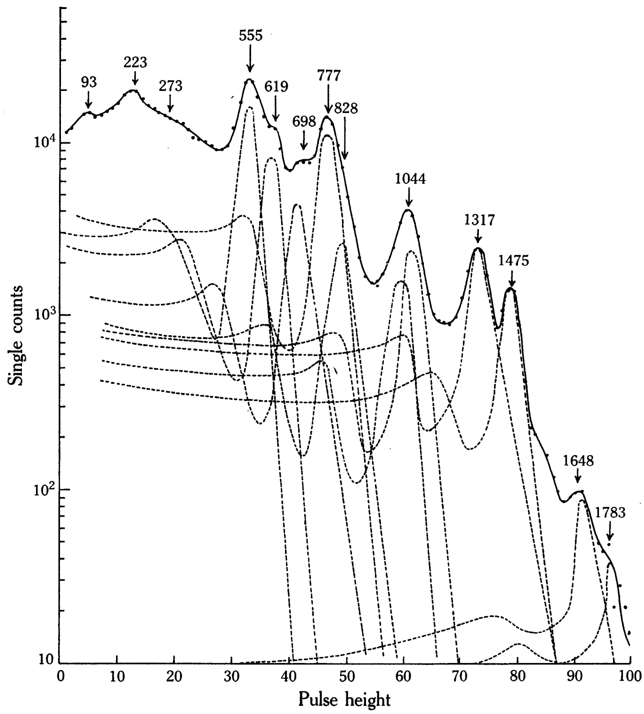
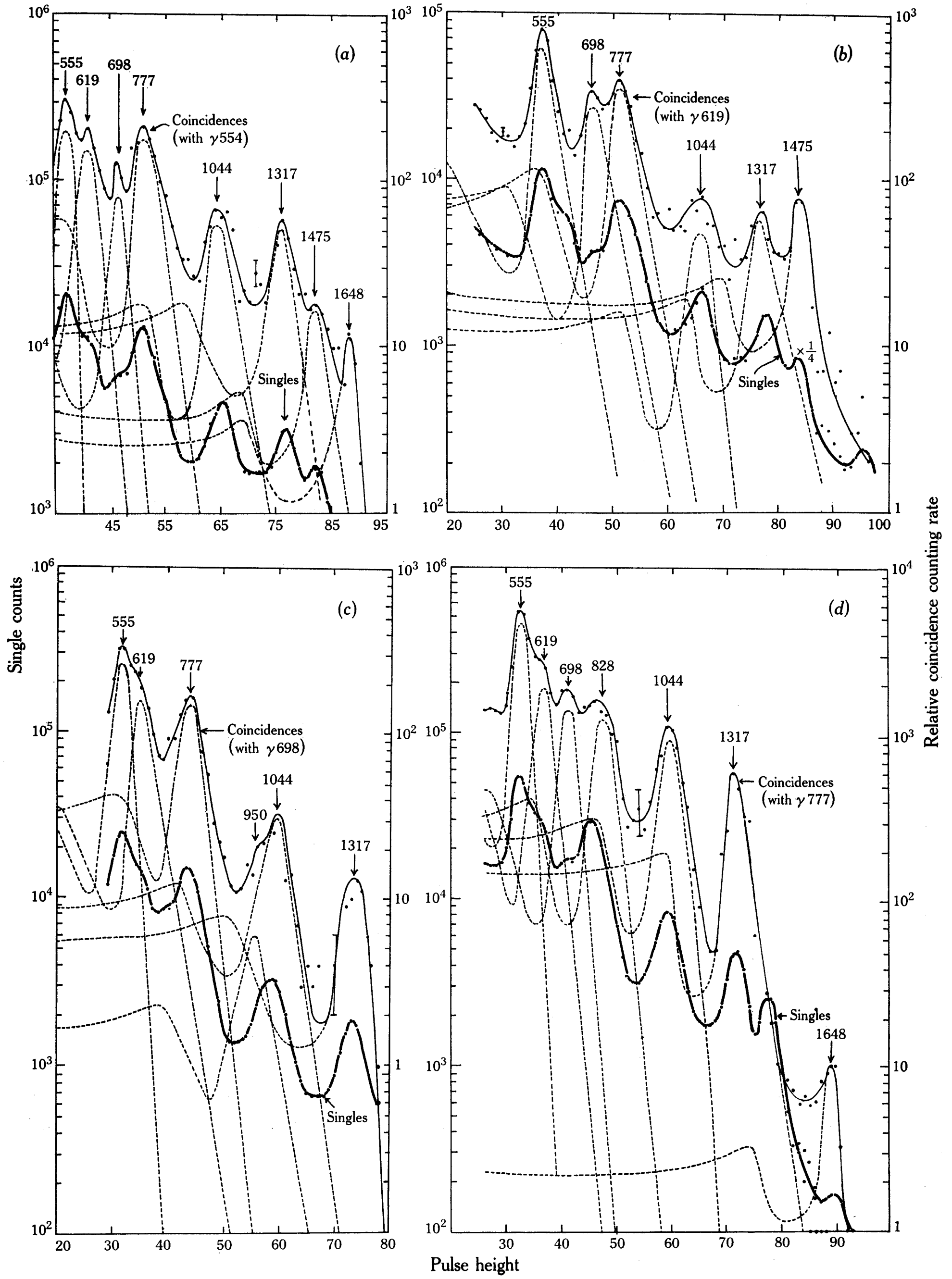


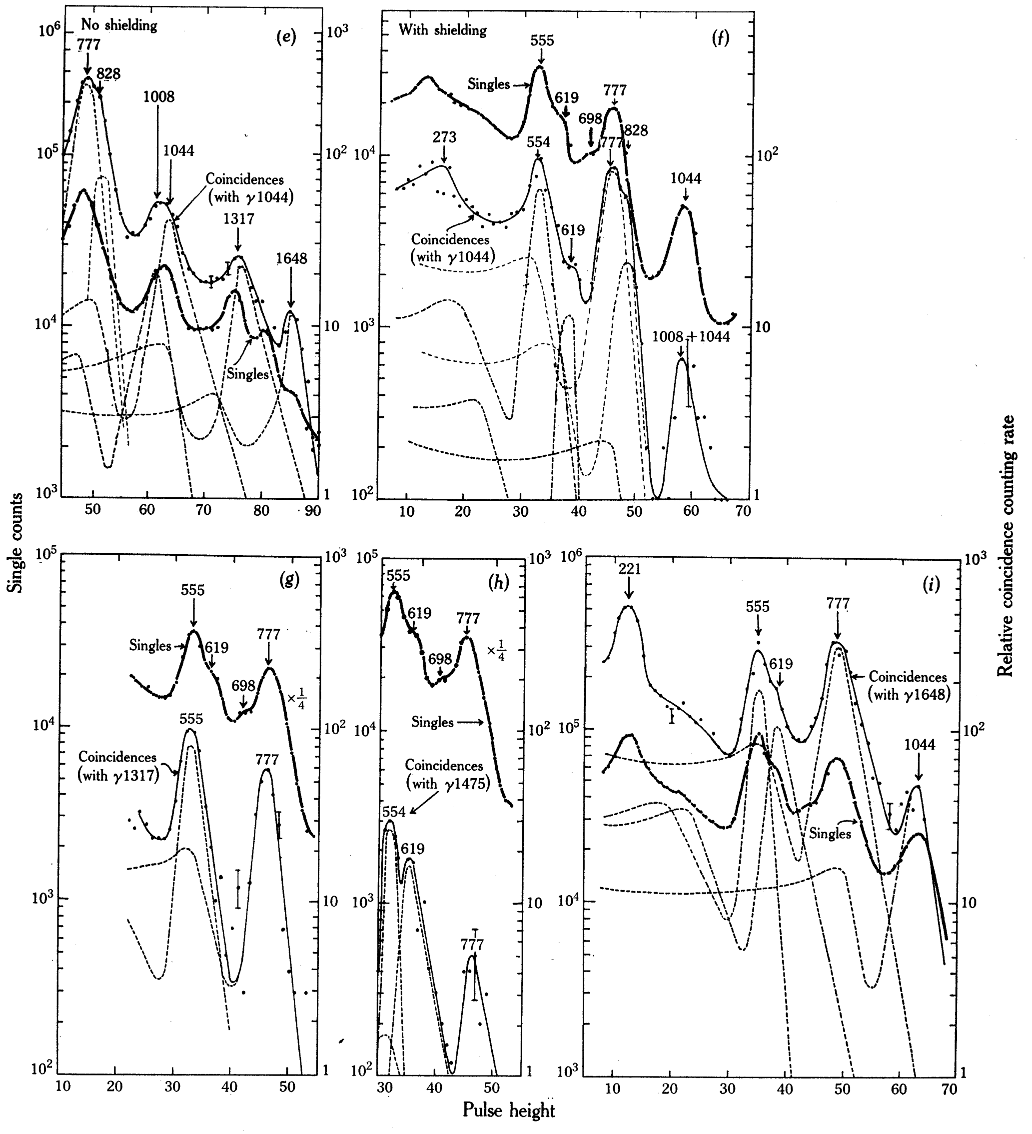
Fig. 1.—Gamma ray scintillation spectrum of 36 hr ^{82}Br.

Figures 2(*a*)–2(*i*) show the coincidence spectra recorded by setting one of the spectrometers successively around the 555, 619, 698, 777, 1044 (with and without conical shielding), 1317, 1475, and 1648 keV energy regions. Results confirm the earlier conclusions (Etherton and Kelly 1966) regarding the coincidence relationships between the various γ-rays. The results of the spectra have been used in correcting the directional correlation data of several cascades for interfering effects of neighbouring cascades.

All the correlation functions reported below, were obtained by fitting the experimental data by a least-squares method, following the treatment given by Breitenberger (1956), and were corrected for the finite geometry of the crystal using the correction factors given by Yates (1965).



Figs. 2(*a*)–2(*i*).—Gamma ray spectra in coincidence with (*a*) 555 keV photopeak; (*b*) 619 keV region; (*c*) 698 keV region; (*d*) 777 keV photopeak; (*e*) 1044 keV region, recorded without conical shielding; (*f*) 1044 keV region, with conical shielding; (*g*) 1317 keV photopeak; (*h*) 1475 keV photopeak; and (*i*) 1648 keV region.



Figs. 2(*e*)–2(*i*)

III. Results

(*a*) *Directional Correlation of 1648–777 keV Cascade*

The solid-angle corrected directional correlation function for the 1648–777 keV cascade was found to be

$$W(\theta) = 1+(0\cdot0427\pm0\cdot0152)P_2(\cos\theta) - (0\cdot0517\pm0\cdot0308)P_4(\cos\theta). \qquad (1)$$

This cascade has also been studied by Koch *et al.* (1965) and Hsu and Wu (1967). It is practically free from all interfering contributions. The reason is that the high energy γ-ray of energy 1783 keV also cascading with $\gamma777$ is extremely weak in intensity. The spin and parity of the ground state and the first excited state of even–even ^{82}Kr are well established as 0^+ and 2^+ respectively. A spin assignment of 2, 3, or 4 follows for the 2425 keV state from the γ-decay of this state to the 1475 (2^+) and 777 keV (2^+) states and the de-excitation of the 2649 keV (4^-) state to the 2425 keV state. The possible spin sequences for the above cascade are then (i) $2(D,Q)2(Q)0$, (ii) $3(D,Q)2(Q)0$, and (iii) $4(Q)2(Q)0$. The observed A_2 coefficient appears to be consistent with the sequence (i) only with an admixture in the 1648 keV transition of either $\sim 93\%$ dipole and $\sim 7\%$ quadrupole or $\sim 98\%$ quadrupole and $\sim 2\%$ dipole radiations. However, in both these cases, the finite negative value ($-0\cdot0517\pm0\cdot0308$) of the observed A_4 coefficient cannot be accounted for. Therefore, the only possible spin sequence that could be assigned to this cascade is $3(D,Q)2(Q)0$. Mixing ratio analysis of the observed A_2 expansion coefficient in terms of this spin sequence leads to a quadrupole content of $Q_{1648} = 0\cdot0210\pm0\cdot0035$ or $0\cdot9025\pm0\cdot0125$ for the 1648 keV radiation. As the internal conversion coefficient of this radiation is not known, nothing definite can be said about its multipolarity. However, a similar analysis of the A_4 coefficient favours a predominantly quadrupole character for the 1648 keV γ-radiation. This conclusion is in contrast with the results of Koch *et al.* (1965), who prefer a predominantly dipole character for this transition from their directional correlation measurements. The work of Hsu and Wu (1967) does not discuss the multipolarity of the 1648 keV transition.

(*b*) *Directional Correlation of 1008–1044 keV Cascade*

The directional correlation of this cascade appears to be isotropic within the statistical accuracy of the measurement. Interference due to neighbouring cascades was found to be extremely small and was therefore not taken into account.

Orbitals of the 777 and 1821 keV levels have been established to be 2^+ and 4^+ respectively. Etherton and Kelly (1966) obtained the value $\log ft = 5\cdot7$ for the β-decay from the ground state of ^{82}Br to the 2829 keV state in ^{82}Kr. Therefore, the β-transition of 264 keV (3%) energy is either an allowed normal transition having $\Delta I = 0$ or 1 and no parity change, or a first forbidden transition characterized by the same change in angular momentum but having a parity change. The spin of the ground state of ^{82}Br is 5^-, and thus the probable spin values for the 2829 keV level are 4^-, 4^+, 5^-, 5^+, 6^-, or 6^+. These values are also consistent with the γ-decay of this state to the 2649 (4^-) and 1821 (4^+) keV states. Consequently, there are three possible spin sequences for the 1008–1044 keV cascade, namely, (i) $4(D,Q)4(Q)2$, (ii) $5(D,Q)4(Q)2$, and (iii) $6(Q)4(Q)2$. Assuming that $\gamma1008$ is a pure dipole transition in the first two cases and a pure quadrupole in the third, the theoretical A_2 expansion coefficients for the above three spin sequences are found to be $+0\cdot1964$, $-0\cdot0714$, and $+0\cdot1021$ respectively. The spin sequence (iii) is thus out of the question, while (i) and (ii) can possibly account for the isotropic distribution only if the 1008 keV transition is assumed to have quadrupole admixtures of $\sim 23\%$ and $\sim 1\cdot1\%$ respectively. The spin sequence (ii) appears to be more sensitive to multipole mixing and we therefore conclude that the spin of the 2829 keV level is 5. As the conversion coefficient measurements have not been carried out so far for the 1008 keV transition, nothing can be decided about its multipole character or about the parity of the 2829 keV level.

(c) *Directional Correlations of 1317–777, 619–1475, and 555–1317 keV Cascades*

The measurement on the 1317–777 keV cascade is affected by the interfering contribution of the 1648–777 keV cascade. The interference due to the latter cascade has been estimated to be $\leqslant 2\cdot5\%$ from a careful analysis of the singles and coincidence spectra. As this is quite negligible, we have made no correction for it.

In the case of the 619–1475 keV cascade, both the γ-rays were gated on their high energy sides to minimize interfering effects. With the channel settings and energy windows used, the contribution of each of the four interfering cascades 555–(619)–1475, 555–1317, 1317–777, and 1648–777 keV to the investigated one has been estimated to be $\leqslant 2\%$ and can be neglected.

In the 555–1317 keV cascade, with the gates fixed around the 555 and 1317 keV energy regions, the interfering coincidences are recorded in particular between (i) γ1317 and the Compton electrons of γ777, (ii) the Compton electrons of γ1475 and those of γ619, (iii) the Compton electrons of γ1648 and those of γ777, and (iv) γ555 and the Compton electrons of γ1475 (through the unobserved intermediate radiation γ619). Contributions due to (i) and (ii) are found to be $21\%\pm4\%$ and $6\%\pm4\%$ respectively (Figs. 1 and 2(*a*)); the percentage of interference due to (iii) and (iv) has been estimated to be quite negligible.

True correlation functions for these three cascades and the conclusions derived from them about the multipolarities of the γ-transitions 1317, 619, and 555 keV are given in Table 1. The results obtained are in excellent agreement with those reported by other authors (Benczer-Koller 1958; Simons *et al.* 1963; Simons, Bergström, and Anttila 1964; Etherton and Kelly 1966).

(d) *Directional Correlation of 555–619 keV Cascade*

Evaluation of the experimental data yields

$$W(\theta) = 1-(0\cdot0663\pm0\cdot0029)P_2(\cos\theta)+(0\cdot0110\pm0\cdot0059)P_4(\cos\theta)\,. \tag{2}$$

This cascade is influenced by all other high energy cascades and needs further correction. Waddell and Jensen (1956), Simons *et al.* (1963), and Simons, Bergström, and Anttila (1964) have made directional correlation measurements on this cascade and have reported the correlation functions without taking into account the interfering contributions. Their uncorrected functions compare well with our equation (2).

The major contributions in this cascade are from the 1317–777, 1044–777, and 555–1317 keV cascades, which are estimated to be $12\cdot2\%\pm4\cdot0\%$, $4\cdot4\%\pm4\cdot0\%$, and $24\cdot3\%\pm4\cdot0\%$ respectively (Figs. 1 and 2(*a*)). As we did not measure the correlation function for the 1044–777 keV cascade, the expansion coefficients for this cascade were taken from the work of Etherton and Kelly (1966) and were used in applying the correction to the 555–619 keV cascade. Corrections for the interfering contributions from the 1317–777 and 555–1317 keV cascades were applied by using

TABLE 1

CASCADE DATA

Cascade (keV)	A_2	A_4	Possible Spin Sequence	Multipole Mixing in γ-transitions (%)
1317–777	$-0\cdot0301\pm0\cdot0069$	$-0\cdot0452\pm0\cdot0140$	$3(D,Q)2(Q)0$	γ1317: $95\cdot5\pm0\cdot5$ E2, $4\cdot5\pm0\cdot5$ M1
619–1475	$-0\cdot0992\pm0\cdot0029$	$-0\cdot0022\pm0\cdot0061$	$3(D,Q)2(Q)0$	γ 619: $84\cdot5\pm0\cdot5$ E2, $15\cdot5\pm0\cdot5$ M1
555–1317	$-0\cdot0915\pm0\cdot0084$	$+0\cdot0500\pm0\cdot0123$	$4(D,Q)3(D,Q)2$	γ1317: $90\cdot5\pm2\cdot5$ E2, $9\cdot5\pm2\cdot5$ M1 γ 555: pure E1 and γ 555: $99\cdot95\pm0\cdot05$ E1, $0\cdot05\pm0\cdot05$ M2 γ1317: $95\cdot5\pm0\cdot5$ E2
828–1044	$+0\cdot2005\pm0\cdot0295$	$-0\cdot0074\pm0\cdot0667$	4(E1)4(E2)2	γ 828: pure E1 γ1044: pure E1
828–(1044)–777	$+0\cdot1244\pm0\cdot0253$	$-0\cdot0162\pm0\cdot0436$	4(E1)4(E2)2(E2)0	γ 828: pure E1 γ1044: pure E2 γ 777: pure E2
698–777	$-0\cdot247\pm0\cdot066$	$+0\cdot191\pm0\cdot064$	2(E2, M1)2(E2)0	γ 698: 86 ± 11 E2
619–698	$+0\cdot0688\pm0\cdot0206$	$+0\cdot0975\pm0\cdot0464$	3(E2, M1)2(E2, M1)2	γ 698: 82 ± 8 E2

the results given in Section III(c). The contributions due to the cascades 698–777, 828–1044, 1008–1044, 555–(619)–1475, 555–(619)–698, 619–1475, 619–698, and 1648–777 keV were estimated to be negligible. The true correlation function for the 555–619 keV cascade then turns out to be

$$W(\theta) = 1-(0\cdot1370\pm0\cdot0142)\mathrm{P}_2(\cos\theta)+(0\cdot0050\pm0\cdot0072)\mathrm{P}_4(\cos\theta)\,. \tag{3}$$

From considerations based on the level structure of ^{82}Kr (Simons *et al.* 1963; Koch *et al.* 1965; Etherton and Kelly 1966) the levels concerned here are 1475(2$^+$), 2094(3$^+$), and 2649(4$^-$) keV. Equation (3) was therefore analysed in terms of the spin sequence $4(D,Q)3(D,Q)2$. Using the result (0·155 M1 +0·845 E2) for the multipolarity of γ619 from Table 1, the mixing ratio analysis shows that the 555 keV transition is predominantly E1 having a very small M2 admixture ($Q_{555} = 0\cdot0005\pm0\cdot0005$).

This cascade provides another check on the multipole character of the 555 keV radiation and supports the results for the cascade 555–1317 keV given in Section III(c).

(e) *Directional Correlations of 828–1044, 828–(1044)–777, 698–777, and 619–698 keV Cascades*

The true correlation functions for these four cascades, after applying all corrections, are also given in Table 1.

The importance of the triple cascade 828–(1044)–777, with the intermediate radiation being unobserved, lies in deciding the placement of the 828 and 1044 keV transitions. If we regard the 828 keV transition to be the first and the 1044 keV transition to be the second, the measured correlation function between the 828 and 777 keV transitions will correspond to the triple cascade 828–(1044)–777 keV. If, however, we reverse this order then it will correspond to the simple gamma–gamma cascade 828–777 keV.

In the first case, we may explain the measured correlation function in terms of the spin sequence 4(E1)4(E2)2(E2)0. The theoretical A_2 coefficient for this spin sequence is $+0\cdot0994$, which agrees fairly well with the experimental A_2 expansion coefficient ($+0\cdot1244\pm0\cdot0253$). In the second case, the measured correlation function will have to be considered as that for the 828–777 keV gamma–gamma cascade. Mixing ratio analysis for the A_2 expansion coefficient ($+0\cdot1244\pm0\cdot0253$) in terms of the spin sequence 2(1, 2)2(2)0 shows that the quadrupole content in γ828 is $0\cdot0115+0\cdot0035$ ($\delta_{828} = -0\cdot108\pm0\cdot017$). If the same expansion coefficient is analysed in terms of the spin sequence 3(1, 2)2(2)0, the quadrupole content in γ828 becomes $0\cdot075\pm0\cdot025$ ($\delta_{828} = -0\cdot285\pm0\cdot051$). Both these values of Q_{828} are, however, inconsistent with the conclusions drawn from the analysis of the 828–1044 keV cascade discussed above and that of the 1044–777 keV cascade reported by Etherton and Kelly (1966). We therefore conclude that the successive placement of the transitions is 828–1044–777 keV (Fig. 3). This conclusion strongly favours the analysis reported by Etherton and Kelly.

The multipole admixture of the 698 keV transition has been calculated from both the cascades 698–777 keV and 619–698 keV. The two results, as shown in Table 1, agree well within the experimental error.

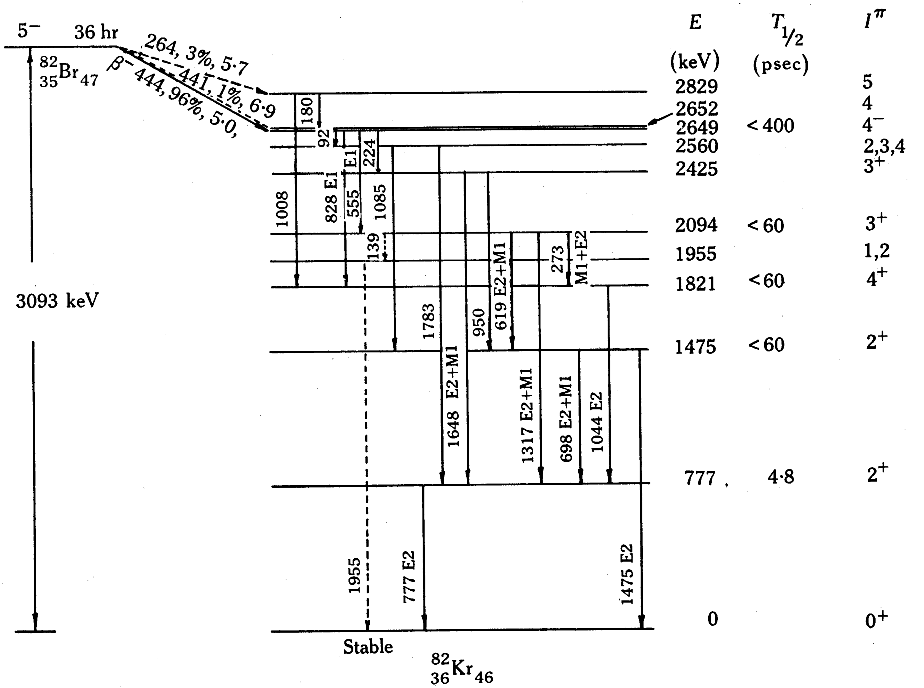


Fig. 3.—Decay scheme of ^{82}Br based on the results of earlier workers and on those obtained in the present investigation.

IV. Discussion

The 180 keV radiation originating from the 2829 keV level feeds the level at 2649 keV, which is populated by the 444 keV extremely intense beta group. The 2649 keV level decays to 2425, 2094, and 1821 keV states with the emission of 224, 555, and 828 keV γ-radiations. The level at 2652 keV, which is populated by an extremely weak ($\sim$ 1%) beta group of 441 keV energy, decays to a 2560 keV state with the emission of an extremely weak ($\sim$ 1%) γ-radiation of 92 keV. There is no evidence for any other γ-ray that originates from or feeds this level. The possible existence of the 2652 keV level therefore does not interfere with the gamma–gamma cascades under consideration.

We have computed the E2 lifetimes, τ_{γ}, for the 619 and 1317 keV γ-transitions, using the measured values of δ^2, the experimental $T_{\frac{1}{2}}$ values, and the known α_K values and they are given in Table 2. The E2 component in the case of γ619 appears to be enhanced by a factor of about 2, whereas in the case of γ1317 it is retarded by a factor of about 10 with respect to corresponding single-particle estimates. The E2 lifetime values seem to follow the order of the single-particle values and thus do not reflect the many-body collective behaviour of even–even nuclei.

As has been pointed out by Etherton and Kelly (1966), the nonaxial rotor model of Davydov and co-workers (Davydov and Filippov 1959; Davydov and Chaban 1960) predicts more or less correctly the ordering and spacing of the strongly excited states of ^{82}Kr, and, further, that the rotation–vibrational interaction does not

TABLE 2

E2 LIFETIMES FOR 619 AND 1317 keV γ–TRANSITIONS

Energy of Transition (keV)	Mixing Ratio δ	A $\tau_\gamma(\text{E2})_{\text{expt}}$ (10^{-11} sec)	B $\tau_\gamma(\text{E2})_{\text{W}}$ (10^{-11} sec)	E2 Enhancement (B/A)
619	$-2\cdot34\pm0\cdot05$	$<23\cdot52$	$41\cdot67$	$\geqslant 1\cdot8$
1317	$-4\cdot61\pm0\cdot26$	$<11\cdot22$	$0\cdot96$	$\geqslant 0\cdot09$

affect the reduced E2 transition probabilities of even–even nuclei, provided the nonadiabaticity parameter $\mu \leqslant 0\cdot5$. Using our computed values of $\tau_\gamma(\text{E2})$ for γ619 and γ1317 we have evaluated the ratio of the reduced E2 transition probabilities for the transitions from the 2094 keV (3^+) state to the 1475 keV (2^+) and 777 keV (2^+) states. The resulting ratio is

$$B(\text{E2};619)/B(\text{E2};1317) = 0\cdot011\,,$$

which corresponds to the nonaxiality parameter $\gamma = 27\cdot9°$. This is in good agreement with the corresponding value ($\gamma = 29\cdot0°$) reported by Klema, Mallmann, and Day (1961) on the basis of energy considerations.

V. ACKNOWLEDGMENTS

The authors wish to express their sincere thanks to Professor F. C. Auluck, Head of the Department of Physics and Astrophysics, University of Delhi, for providing facilities for this work. Thanks are also due to Professor N. K. Saha for his guidance throughout the course of the work. One of the authors (M.M.B.) is indebted to the Council of Scientific and Industrial Research, India, for financial support.

VI. REFERENCES

BEARD, G. B. (1966).—*Phys. Rev.* **145**, 862.
BENCZER-KOLLER, N. (1958).—Univ. California Rep. No. CU–177.
BREITENBERGER, E. (1956).—*Proc. phys. Soc.* A **69**, 489.
DAVYDOV, A. F., and CHABAN, A. A. (1960).—*Nucl. Phys.* **20**, 499.
DAVYDOV, A. F., and FILIPPOV, G. F. (1959).—*Soviet Phys. JETP* **8**, 303, 488.
ETHERTON, R. C., and KELLY, W. H. (1966).—*Nucl. Phys.* **84**, 129.
GFIRTNER, H., REISER, W., and SCHNEIDER, H. (1965).—*Z. Naturf.* **20a**, 1727.
HSU, F. H. H., and WU, C. S. (1967).—*Nucl. Phys.* A **94**, 205.
KENNEY, E. S., and RAMAN, S. (1965).—*Bull. Am. phys. Soc.* **10**, 588.
KLEMA, E. D., MALLMANN, C. A., and DAY, P. (1961).—*Nucl. Phys.* **25**, 266.

Koch, J., Münnich, F., Schaare, W., Fischer, K., and Fricke, K. (1965).—*Z. Naturf.* **20a**, 845.

Mo, L., Hsu, F., and Wu, C. S. (1965).—*Bull. Am. phys. Soc.* **10**, 81.

Nieschmidt, E. B., Mandeville, C. E., and Ellsworth, L. D. (1965).—*Bull. Am. phys. Soc.* **10**, 129.

Raman, S. (1967).—*Nucl. Phys.* A **90**, 508.

Reidy, J., and Wiedenbeck, M. L. (1965).—*Bull. Am. phys. Soc.* **10**, 1131.

Simons, L., Bergström, S., and Anttila, A. (1964).—*Nucl. Phys.* **54**, 683.

Simons, L., Nystén, K. E., Holmberg, P., Junger, H., Anttila, A., Bergström, S., and Hagebø, E. (1963).—*Acta polytech. scand.* **Ph 22**.

Waddell, R. C., and Jensen, E. N. (1956).—*Phys. Rev.* **102**, 816.

Yates, M. J. L. (1965).—*In* "Alpha-, Beta- and Gamma-ray Spectroscopy". (Ed. K. Siegbahn.) p. 1691. (North-Holland: Amsterdam.)