The level structure of ^{78}Kr (populated in ^{68}Zn(^{12}C,2n) reaction)

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The level structure of ^{78}Kr

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Abstract. States in ^{78}Kr have been excited by the decay of ^{78}Rb and by the reaction ^{68}Zn(^{12}C, 2n) and a level scheme has been built up from the observed γ-ray spectra. The presence of a number of states, previously reported, has been confirmed and four new levels at 2572·5, 2900·2, 3160·7 and 3723·8 MeV are identified. Firm spin and parity assignments are made for states at 1016·9 MeV (0^+) and 1147·5 MeV (2^+) and tentative assignments for states at 1564·4 MeV (3^+) and 1872·5 MeV (3^+, 4^+).

1. Introduction

Recent studies of the isotopes of Ge, Se and Kr (Lieder and Draper 1970, McCauley and Draper 1971, Nolte *et al* 1970) have shown that even–even nuclei with N and Z between 28 and 50 can possess quasi-rotational bands with strong collective properties. ^{78}Kr has one of the lowest first excited states for nuclei in this region and the transition between this state and the ground state has a very large B(E2), both of which facts indicate the existence of strong collective properties. It is therefore of interest to determine the level scheme and decay properties of this nucleus as completely as possible.

Nolte *et al* (1970) have identified a collective band based on the ground state with levels at 455 keV (2^+), 1119 keV (4^+) and 1977 keV (6^+), whilst McCauley and Draper have located, in addition, levels at 2991 keV and 4101 keV to which they assign spins and parities of 8^+ and 10^+ respectively on the basis of systematics and energies.

In this paper we present the results of a study of the level structure of ^{78}Kr when populated both by heavy ion (xn) reactions and by the β^+ decay of ^{78}Rb.

2. Experimental methods and results

2.1. *The decay of* ^{78}*Rb*

Sources of ^{78}Rb were produced by the reaction ^{65}Cu(^{16}O, 3n)^{78}Rb using an ^{16}O beam from the Manchester HILAC. The ^{65}Cu targets, with an isotopic purity greater than 99 %, were self-supporting foils 1 mg cm^{-2} thick. The targets were bombarded at six different energies between 38 MeV and 71 MeV. At each energy the bombardment took place for ten minutes. A further two minutes were required to remove the target and place it in front of the counter, at the end of which time counting commenced.

Singles γ-ray spectra were recorded for five consecutive three-minute periods using a 7 % efficiency Ge(Li) detector with a resolution of 2·4 keV FWHM at 1·3 MeV. Figure 1 shows the spectrum recorded in the first six minutes of such a run at 62 MeV. The γ rays

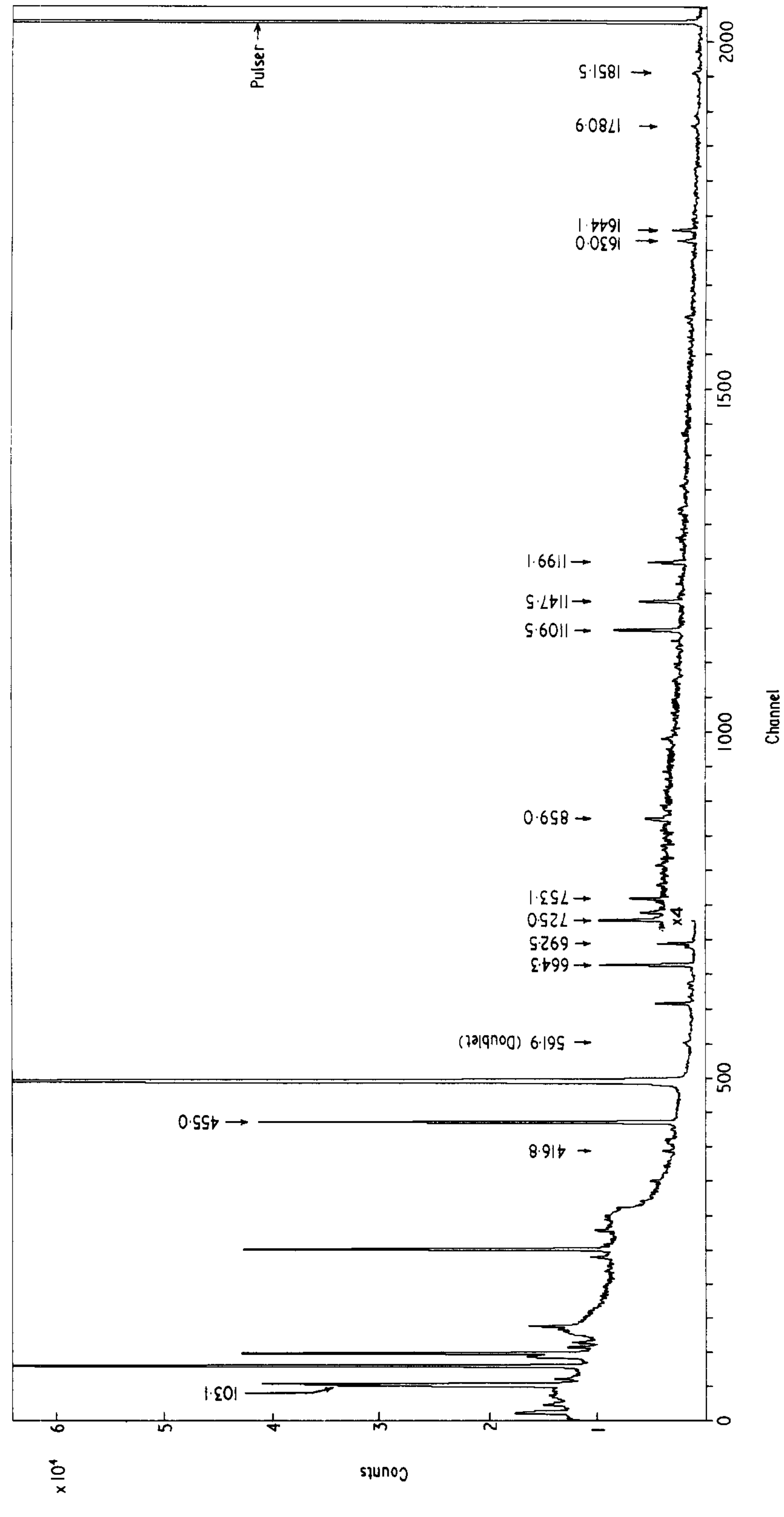

Figure 1. γ ray spectrum following the decay of ^{78}Rb. The lines, for which energies are given, have been assigned to levels of ^{78}Kr.

assigned to the decay of ^{78}Rb were identified on the basis of excitation functions and half-lives. The energy, intensity and half-life of the 103·1 keV γ ray were determined in a separate experiment using an 0·5 ml Ge(Li) detector with sufficient resolution to separate this line from the line at 105·7 keV. All the remaining γ rays in figure 1, with the exception of the 734·7 keV γ ray, can be identified as arising from the reactions (^{16}O, 2n), (^{16}O, αxn) and (^{16}O, xn, yp). Gamma–gamma coincidence measurements were also made on sources produced by the same reaction. An automated target transport system alternately positioned the target in the beam line and withdrew it through a distance of 3 m to a counting chamber shielded by concrete blocks. Coincidences were observed with two Ge(Li) detectors and a standard leading edge timing system with a time resolution of 30 ns FWHM. Coincident events were recorded on magnetic tape and could be recalled later for off-line analysis. Figure 2 shows the coincidence spectra obtained by setting windows on some of the γ rays. Background and chance coincidences have been subtracted in all these examples.

A list of the γ rays associated with the decay of ^{78}Rb is given in table 1, together with their relative intensities, decay half-lives and coincidence relationships. The energies and intensities of the higher energy γ rays were determined in a separate experiment using a large Ge(Li) detector. The level scheme deduced from these measurements is shown in figure 3; the results of the in-beam measurements, discussed in a later section, are also shown for comparison.

Two features stand out from table 1. Firstly the 103·1 keV γ ray is apparently not in coincidence with any other transition, and secondly the measured half-lives are not consistent with each other. These facts suggest that the decay of ^{78}Rb proceeds from an isomeric level, as well as from the ground state, and the complete absence of the 103·1 keV gamma ray, with a half-life of 4·7 min, from the coincidence spectra strongly suggests it is associated with a 4·7 min isomeric level in ^{78}Rb. The same suggestion has been made by Doron and Blann (1971) who found that the relative intensities of the 103·1 keV, 455·0 keV and 664·3 keV γ rays varied with time. Figure 4 shows the results of a half-life measurement in which γ rays from a ^{78}Rb source were recorded for sixteen consecutive three minute periods. It is clear that the 455 keV γ ray decays with two separate half-lives. The broken line is the result of a least-squares fit to the expression

$$N(t) = N_1\,\mathrm{e}^{-\lambda_1 t} + N_2\,\mathrm{e}^{-\lambda_2 t}.$$

The optimum value of the ratio N_1/N_2 is 2·3, and the two half-lives are $T_{1/2}(1) = 0{\cdot}693/\lambda_1 = 4{\cdot}4 \pm 0{\cdot}8$ min and $T_{1/2}(2) = 10{\cdot}6 \pm 3{\cdot}0$ min. The errors are not independent. While our results for the short half-life are in fair agreement with those of other investigators (Nolte and Shida 1972, Bakhru *et al* 1973), the value of $10{\cdot}6 \pm 3{\cdot}0$ min is substantially less than the lifetime of $17{\cdot}5 \pm 2{\cdot}0$ min for the longer lived state measured by Nolte and Shida. Clearly further experiments are required aimed at establishing accurately the two lifetimes. The fact that the 664·3 keV γ ray can be fitted adequately by a single component with $T_{1/2} = 5{\cdot}5 \pm 0{\cdot}1$ min indicates that the 1119·3 keV state is predominantly fed by the short-lived component. The partial half-life of the decay to this state is minimized if it is assumed that any decay to the ground state is weak, an assumption supported by the fact that after subtracting the contributions from other activities the strength of the 511 keV annihilation line in figure 1 is not significantly different from twice the 455 keV intensity. With this assumption the lg ft value for the transition to the 1119·3 keV level is found to be 6·75, suggesting a first forbidden transition. Direct transitions also occur to the 1016·9 level, which we later show to be 0^+,

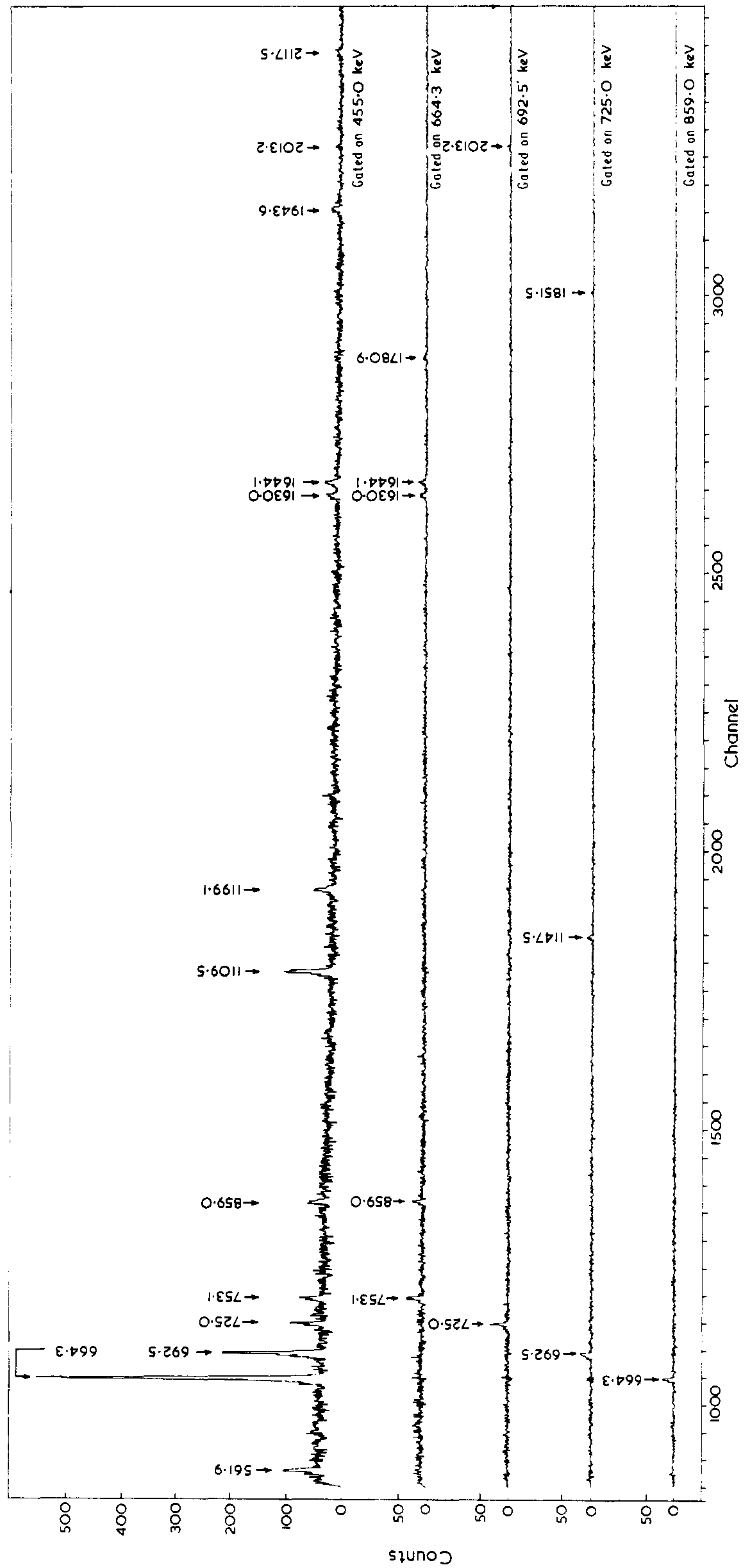

Figure 2. Examples of gamma–gamma coincidence spectra following the decay of ^{78}Rb.

Table 1. γ rays associated with the decay of ^{78}Rb.

Energy (keV)	Half-life (min)	Intensity	Measured in coincidence with
103·1 ± 0·1	4·7 ± 0·3	7·5 ± 0·6	Nothing
416·8 ± 0·2	7·7 ± 1·7	2·8 ± 0·3	
445·5 ± 0·5		1·0 ± 0·3	
455·0 ± 0·1	6·3 ± 0·1	100	416·8, 445·5, 511·0, 561·9, 664·3, 692·5, 725·0, 753·1, 859·0, 1109·5, 1199·1, 1630·0, 1644·1, 1943·6, 2013·2, 2117·5
561·9 ± 0·5		3·0 ± 1·0	
664·3 ± 0·2	5·4 ± 0·2	39·0 ± 3·0	445·0, 455·0, 511·0, 753·1, 859·0, 1630·0, 1644·1, 1780·9
692·5 ± 0·3	6·5 ± 0·4	15·0 ± 1·5	416·8, 455·0, 511·0, 725·0, 2013·2
725·0 ± 0·2	6·0 ± 0·6	6·5 ± 0·6	455·0, 511·0, 692·5, 1147·5, 1851·5
753·1 ± 0·2	6·0 ± 1·2	3·0 ± 0·3	455·0, 511·0, 664·3, 1851·5
859·0 ± 0·3	7·8 ± 2·3	4·8 ± 0·5	455·0, 511·0, 664·3
1109·5 ± 0·2	6·1 ± 0·4	13·2 ± 1·3	455·0, 511·0, 1199·1
1147·5 ± 0·2	7·3 ± 0·6	9·3 ± 0·9	416·8, 511·0, 725·0, 2013·2
1199·1 ± 0·2	6·1 ± 0·4	7·5 ± 0·7	416·8, 445·0, 455·0, 511·0, 664·3, 692·5, 1147·5, 1109·5
1630·0 ± 0·3	9·3 ± 2·8	4·7 ± 0·5	
1644·1 ± 0·3	6·5 ± 1·1	6·5 ± 0·6	
1780·9 ± 0·4		2·7 ± 0·3	
1851·5 ± 0·3		3·3 ± 0·3	
1943·6 ± 0·3		6·2 ± 0·6	
2013·2 ± 0·3		3·2 ± 0·3	
2117·5 ± 0·5		2·1 ± 0·3	

and to the level at 1978·3 keV, which is known to be 6^+. It is not possible for these two levels to be fed from the same level in ^{78}Rb with the measured half-lives.

Nolte and Shida (1972) have shown that the 1016·9 keV level is fed by a decay with a single half-life which they measure to be 17·5 ± 2 min. It is therefore safe to assume that the 1978·3 keV level is fed solely by the fast component, leading to a lg *ft* value of 7·2, again implying a first forbidden transition. Similarly the intensity of the β decay to the 1016·9 keV level implies a lg *ft* value of at least 7·7, suggesting that the long-lived decay is also first forbidden. It would thus appear that if both lifetimes are due to β decay there are two decaying levels in ^{78}Rb, both of negative parity with a substantial spin difference between them. It is extremely unlikely that the 103 keV γ ray directly connects these two levels, as the lifetime implies at least an E3 transition with an internal conversion coefficient of 9·4. This would make the total 103 keV transition strength at least 70% of the strength of the 455 keV transition, and a considerable rise and fall in the activity of this and other levels should be observed. This view is in contradiction to what is implied by Bakhru *et al* (1973), who propose that the 103·1 keV line is an M3 transition connecting the two states in ^{78}Rb, but present no supporting evidence for this assignment.

It is also possible that one of the lifetimes is due to an isomeric level in ^{78}Rb, which undergoes an electromagnetic transition to a lower level and which then decays by an allowed β decay.

The present results are in very good agreement with those reported by Nolte and Shida (1972) and Bakhru *et al* (1973) for the states below 2 MeV. The discrepancies with Nolte and Shida above 2 MeV are readily attributed to the fact that we observed

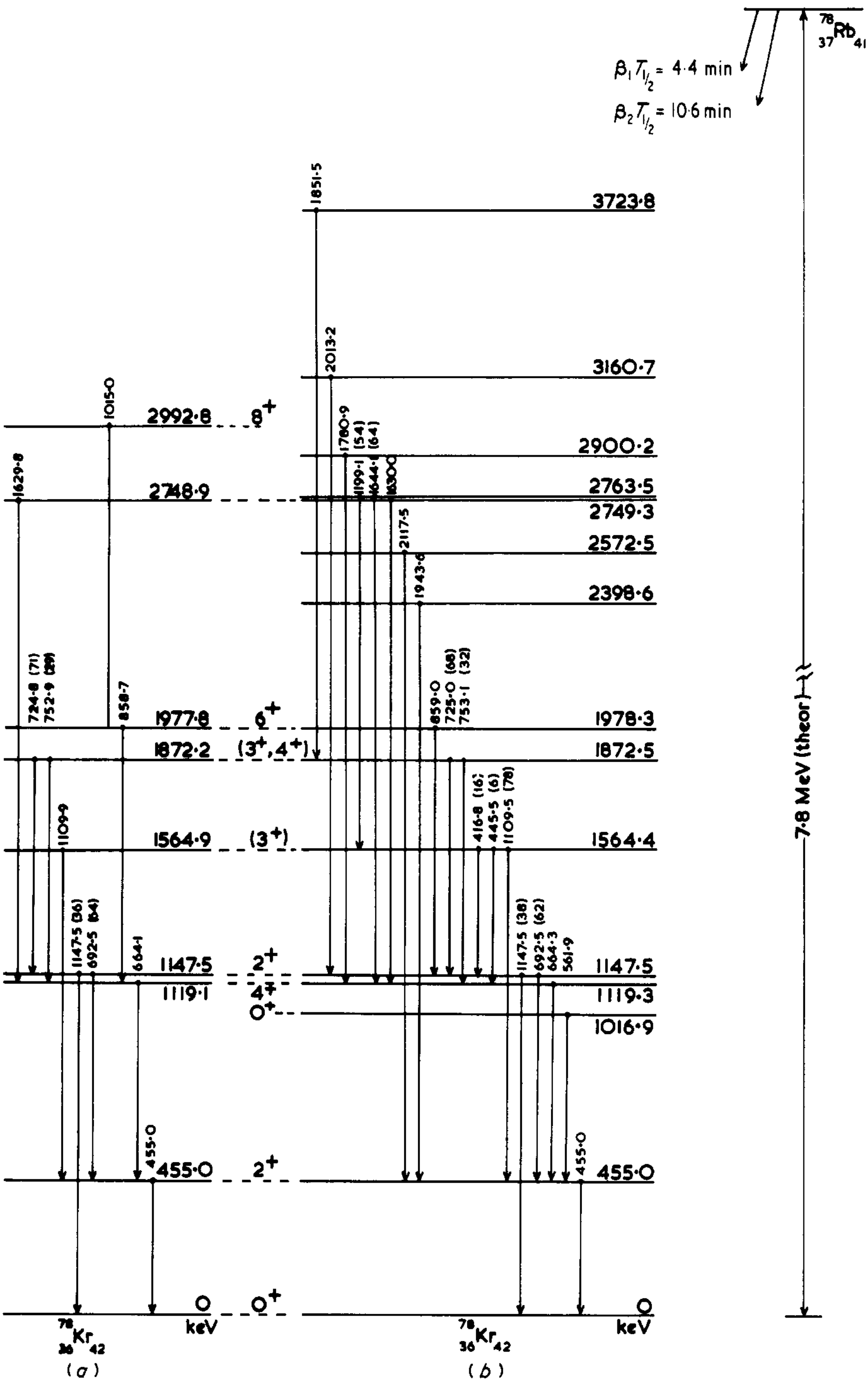

Figure 3. Level scheme of ^{78}Kr deduced from: (*a*) in-beam measurements and (*b*) the decay of ^{78}Rb.

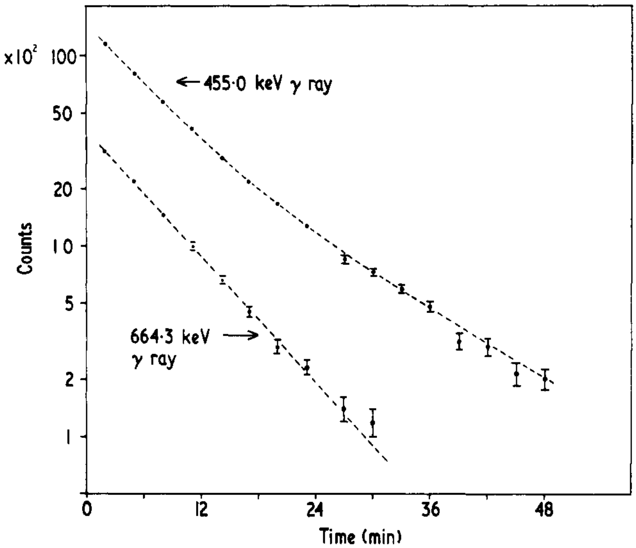

Figure 4. Intensities of the 455·0 and 664·3 keV γ rays, following the decay of ^{78}Rb, plotted as a function of time.

γ rays up to 2 MeV in our singles and coincidence spectra, while Nolte and Shida observed γ rays up to 5 MeV in their singles spectra but set a lower γ ray energy limit than us in their coincidence measurements (Nolte 1972, private communication). As a result our coincidence measurements identify a number of transitions between 1·5 and 2·2 MeV which Nolte and Shida would not have expected to observe. Consequently we find new states at 2572·5, 2900·2, 3160·7 and 3723·8 keV, but we do not observe the level reported by Nolte and Shida at 3723·8 keV. Also we do not report a level at 2300·1 keV. According to Nolte and Shida this level decays mainly by a 735·1 keV transition to the level at 1565·0 keV. We observed a γ ray of 734·7 keV in singles, but as it did not appear in any of our coincidence spectra we have not included it in our decay scheme.

2.2. *Angular correlations in the decay of ^{78}Rb*

The target transport system described in § 2.1 was also used to perform gamma–gamma angular correlation measurements. Two latching pins enabled the target to be accurately located both in the beam line and at the centre of the angular correlation table. Measurements were made at six different angles between the counters in the range from 90° to 180°. The data were recorded as described in § 2.1.

Although we collected data for 60 hours the statistics we obtained were generally poor, but in the case of the 664·3 keV–455·0 keV and the 561·9 keV–455·0 keV cascades, which involve the decay of the levels at 1119·3 keV and 1016·9 keV respectively, the angular correlations nevertheless provide useful spectroscopic information. The results of these measurements are shown in table 2 where the necessary angular correlation attenuation coefficients have been taken from Winn and Sarantites (1968). The angular correlation from the decay of the 1016·9 keV level fits a $J = 0$ assignment for this level with 70 % confidence. The next most favoured spin value is $J = 2$ at the 1 % confidence level, all other assignments being below the 0·1 % confidence limit. The high confidence level for the $J = 0$ assignment coupled with the absence of a ground state transition

Table 2. Angular correlation measurements.

Cascade	A_2/A_0	A_4/A_0
664·3 keV–455·0 keV	0·11 ± 0·04	0·03 ± 0·07
561·9 keV–455·0 keV	0·41 ± 0·21	0·73 ± 0·35

makes this assignment virtually certain. We assign positive parity in this case, as an M2 transition would have a lifetime of at least 10^{-7} s. The angular correlation of the γ rays following the decay of the 1119·3 keV level gives equally good fits for $J = 3$ or 4 ($\chi^2 = 0{\cdot}5$), in the latter case the primary radiation being pure quadrupole. We shall show in the next section that the $J = 4$ assignment is strongly preferred.

2.3. *In-beam measurements*

Further information on the level structure of ^{78}Kr has been acquired by studying the γ rays from the ^{68}Zn(^{12}C, 2n)^{78}Kr reaction. The ^{68}Zn targets (isotopic purity 99%) were in the form of self-supporting foils of thickness 1 mg cm^{-2}. Singles γ ray spectra were recorded at six bombarding energies between 32 MeV and 48 MeV. The spectrum recorded at 32 MeV is shown in figure 5, and those γ rays with similar excitation functions to that of the 455·0 keV γ ray are indicated. Angular distribution measurements for these γ rays have also been made by recording spectra at six different angles between 21° and 90° with respect to the beam axis. The measured A_2/A_0 and A_4/A_0 coefficients are given in table 3.

The γ rays of energy 455·0 keV, 664·1 keV and 858·7 keV, known from the work of the last section to form a cascade, have angular distributions which are in the range of values typically observed for members of ground state rotational bands populated in such reactions (Newton 1969). The 1015·0 keV γ ray also falls into this category, and the assignment of these four γ rays to the ground state quasi-rotational band of ^{78}Kr is in complete agreement with the results of McCauley and Draper (1971) and Nolte *et al* (1970). It is for this reason that we prefer the $J = 4$ assignment to the 1119·3 keV level. A γ ray of energy 1110 keV is also assigned by McCauley and Draper to be the $10^+ \rightarrow 8^+$ member of this band. Whilst a γ ray of energy 1109·5 keV is observed by us, its measured A_2/A_0 coefficient is smaller than would be expected for such an assignment.

Table 3. Angular distribution measurements of γ rays associated with the reaction ^{68}Zn(^{12}C, 2n)^{78}Kr.

Energy (keV)	Relative intensity	A_2/A_0	A_4/A_0
455·0 ± 0·5	100	0·23 ± 0·02	−0·01 ± 0·02
664·1 ± 0·5	66 ± 7	0·29 ± 0·01	−0·04 ± 0·02
692·5 ± 0·5	9 ± 2	0·01 ± 0·02	0·02 ± 0·03
725·0 ± 0·5	5·7 ± 0·6	0·32 ± 0·05	−0·08 ± 0·06
753·0 ± 0·5	2·4 ± 0·3	0·36 ± 0·08	−0·01 ± 0·1
858·7 ± 0·5	39 ± 4	0·27 ± 0·03	−0·08 ± 0·04
1015·0 ± 0·5	13 ± 1·3	0·29 ± 0·06	0·03 ± 0·09
1109·9 ± 0·5	14 ± 1·4	0·16 ± 0·04	0·05 ± 0·05
1147·5 ± 0·5	4·7 ± 0·5	0·12 ± 0·07	0·02 ± 0·09
1629·8 ± 0·5	7·5 ± 0·8	−0·24 ± 0·04	−0·01 ± 0·05

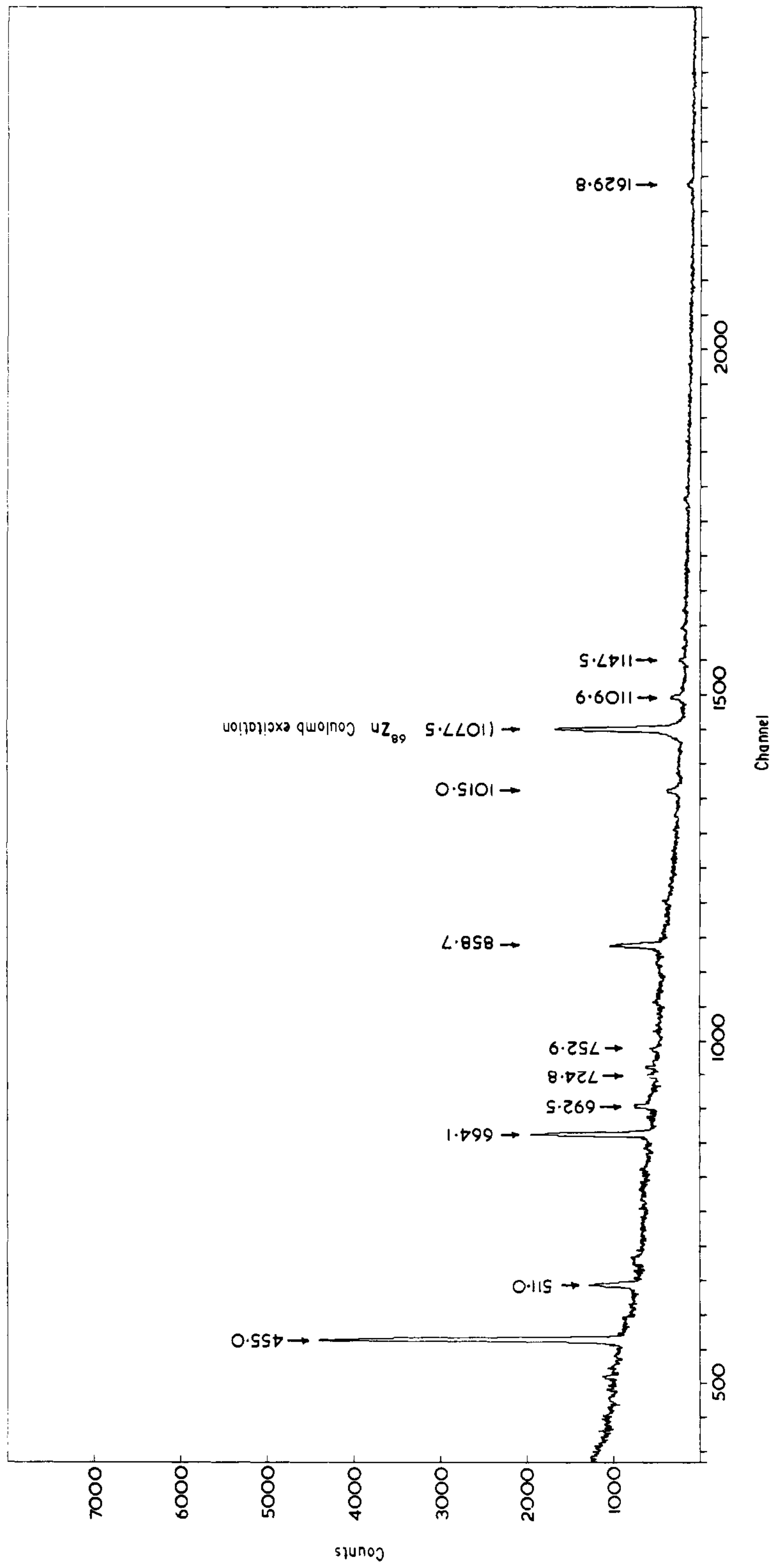

Figure 5. γ-ray spectrum from the reaction $^{68}Zn(^{12}C, 2n)^{78}Kr$ recorded at a bombarding energy of 32 MeV.

In addition, a γ ray of the same energy is observed following the β decay of ^{78}Rb, and in this case, the gamma–gamma coincidence results of § 2 show that it represents the decay of a state at 1564·4 keV.

In order to resolve this question, a gamma–gamma coincidence experiment has been undertaken on these transitions, excited by the reaction ^{64}Ni(^{16}O, 2n)^{78}Kr using an ^{16}O beam of energy 42 MeV from the Liverpool University EN Tandem Van de Graaff. The ^{64}Ni target (isotopic purity = 96%) was in the form of a self-supporting foil of thickness 5 mg cm^{-2}. Coincidences were recorded in the manner described in § 2.1. It is found that the 455·0 keV, 664·3 keV, 859·0 keV and 1015·0 keV γ rays form a cascade, whilst the 1109·5 keV γ ray is in coincidence only with the 455·0 keV γ ray. We conclude that the 1109·5 keV transition observed in the present work is associated with the decay of the 1564·4 keV state, but since high-spin states were relatively more strongly excited by McCauley and Draper (1971) our conclusions are not in conflict with their work. Furthermore, recent measurements of Nolte and Shida (1972) have confirmed the presence of the 10^+ state at 4105 keV.

3. Discussion

Spin and parity assignments have been made previously (Nolte *et al* 1970, McCauley and Draper 1971) to the levels at 455·0 keV (2^+), 1119·3 keV (4^+), 1978·3 keV (6^+) and 2992·8 keV (8^+). These results are confirmed by us and in addition we have assigned $J^\pi = 0^+$ to the 1016·9 keV state. There are reasons for ascribing 2^+ to the level at 1147·5 keV. Firstly, it would complete a two-phonon triplet. Secondly, it receives substantial direct feeding in the β decay of ^{78}Rb and should therefore be of the same parity as the other levels chiefly fed which are of positive parity. The angular correlation in the β decay of ^{78}Rb only limits the spin to be 1, 2 or 3. We can discard 3^+ as an assignment since the 1147·5 keV γ ray is seen in prompt coincidence with the 725·0 keV γ ray feeding this level, whereas the single-particle lifetime for an M3 transition of this energy is 10^{-4} s. If we assume the level possesses $J^\pi = 1^+$ the angular distribution of the ground state transition in the in-beam experiment requires the population of the $m = 0$ substate to be less than twenty-five per cent. This is a very unusual substate population for a heavy-ion reaction. On the other hand the observed distributions are entirely consistent with the distribution of known 2_2^+ states populated in heavy-ion reactions, eg ^{72}Ge(α, 2n)^{76}Se (Lieder and Draper 1970).

The level at 1564·4 keV decays to levels with spins of two and four, suggesting a spin value of 2, 3, 4. The absence of a ground state transition, which would be energetically favoured over a transition to the 4^+ state by a factor of over 500 for pure quadrupole transitions, speaks strongly against an assignment of 2^+. The in-beam angular distribution of the 1109·5 keV decay of this level is weak for a pure quadrupole 4^+ to 2^+ transition, which one expects to be strongly aligned as a result of direct feeding, and hence a 3^+ assignment is favoured.

The level at 1872·5 keV decays to the 2^+ level at 1147·5 keV and the 4^+ level at 1119·3 keV; it is also directly fed in the β-decay process. It may therefore be assumed to be 2^+, 3^+ or 4^+. The in-beam angular distribution of the 753·1 keV γ ray has an A_2 coefficient which is two standard deviations larger than the maximum theoretical value allowed for a 2^+ to 4^+ transition, this value occurring in the unlikely situation when only the $m = 0$ substate is populated. We therefore assign $J^\pi = 3^+$ or 4^+, the angular distribution being consistent with either of these values.

Some discussion of the β decay of ^{78}Rb has already been given in § 2.1 where it was pointed out that if both lifetimes are due to the β-decay process they correspond to first forbidden transitions, and that the 103·1 keV transition could not directly connect the two decaying states. The 0^+ state at 1016·9 keV would appear to be populated only by direct feeding from the long-lived level in ^{78}Rb. It is therefore reasonable to assume that the parent level has a low spin, not greater than two. It is difficult to say anything about the state in ^{78}Rb responsible for the short-lived activity until the status of the 103·1 keV transition has been resolved. However the existence of short-lived decays to the 4^+ and 6^+ states in ^{78}Kr but not to the 8^+ suggest that a moderately high-spin state is involved.

The original motivation for this work was the hope that ^{78}Kr might show a level scheme approaching that of a good rotor. This hope has not been fulfilled. The ground state quasi-rotational band can indeed be well fitted by the variable moment of inertia model of Mariscotti *et al* (1969), but this model does not account for the other levels. The parameters required are similar to those for other nuclei close to the vibrational region, and it is pertinent that there exists a 0^+, 2^+, 4^+ closely spaced triplet at only just over twice the excitation of the first 2^+ state. Our conclusion is that, although ^{78}Kr is a highly collective nucleus, it is not well explained by any of the simpler theoretical semi-empirical models now current, and may well require the solution of the full collective hamiltonian, as performed by Kumar and Baranger (1967) for a proper account.

Acknowledgments

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References

Bakhru H, Landenbauer-Bellis I M and Jones B 1973 *Phys. Rev.* C **7** 243
Doron T A and Blann M 1971 *Nucl. Phys.* A **161** 12
Kumar K and Baranger M 1967 *Nucl. Phys.* A **92** 608
Lieder R M and Draper J E 1970 *Phys. Rev.* C **2** 531
McCauley D G and Draper J E 1971 *Phys. Rev.* C **4** 475
Mariscotti M A J, Scharff-Goldhaber G and Buck B 1969 *Phys. Rev.* **178** 1864
Newton J O 1969 *Progress in Nuclear Physics* vol 11 p 53
Nolte E, Kutschere W, Shida Y and Moringa H 1970 *Phys. Lett.* **33B** 294
Nolte E and Shida Y 1972 *Z. Phys.* **256** 243
Winn W G and Sarantites D G 1968 *Nucl. Instrum. Meth.* **66** 61