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STUDIES IN THE DECAY OF ^{62}Zn

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Abstract: The decay of ^{62}Zn to ^{62}Cu has been studied using a double-focussing iron yoke beta spectrometer for the electron and positon spectra and a Ge(Li) solid state detector for the gamma ray measurements. Energies and relative intensities were deduced from the spectra for the gamma transitions and conversion lines belonging to the decay. A level scheme for ^{62}Cu with spin and parity assignments is given.

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RADIOACTIVITY ^{62}Zn [from ^{63}Cu(p, 2n)]; measured $T_{\frac{1}{2}}$, E_{β}, E_{γ}, I_{γ}, I_{ce}. ^{62}Cn deduced levels, J, π, log ft. Natural target, Ge(Li) detector.

1. Introduction

The ^{62}Zn isotope was first identified by Miller *et al.* [1]) who reported a half-life of 9.5 h and an orbital electron capture decay. Later the beta spectrum of ^{62}Zn was investigated by Hayward [2]) who found a positon-branch of end-point energy 0.66 ± 0.01 MeV with a half-life of 9.33 h. He also observed internal conversion lines consistent with a transition energy 41.8 ± 0.8 keV. The K/L ratio found by Hayward [2]) was 6.4 which indicates E1 or M1 multipolarity for this transition.

Nussbaum *et al.* [3]) reported that $(36 \pm 3)\%$ of the ^{62}Zn disintegrations proceed to a 41.3 ± 0.3 keV level in ^{62}Cu. The K-conversion coefficient and the K/(L+M) ratio of the 41 keV transition were determined to be 0.52 ± 0.08 and 8.0 ± 1.5 respectively, indicating M1 multipolarity. The half-life reported for ^{62}Zn was 9.3 ± 0.2 h.

The first level scheme for ^{62}Cu was presented by Brun *et al.* [4]), who reported five additional transitions. Coincidence measurements as well as angular correlation studies were carried out providing the basis for their proposed level scheme. The coincidence measurements indicated no positon feeding to the 41 keV level; the upper limit for such a positon branch was found to be 0.45 % of the total disintegrations of ^{62}Zn.

When the experiments described in this paper were completed, Roulston and Becker [5]) reported on a study of the ^{62}Zn decay. The gamma-ray spectrum was investigated with a Ge(Li) detector and some additional weak transitions were found. The gamma-ray intensities reported are, however, in rather bad agreement with those of Brun *et al.* [4]) and those reported in this paper.

When this investigation was initiated no high resolution experiment had been performed, nor had any experiments been reported concerning the internal conversion intensities except for the 41 keV transition. It was therefore decided to reinvestigate the ^{62}Zn decay using a combination of high resolution beta spectroscopy and solid state detector techniques for the gamma-ray measurements. Furthermore the 9 h activity could be easily produced in the nearby synchro-cyclotron.

2. Instrumentation and source preparation

The gamma-ray spectra were observed using a Ge(Li) solid-state detector (RCA SJGG-1) with a depletion layer depth of 2 mm and an active area of 80 mm^2. The detector was incapsulated in a steel cap with a wall thickness of 0.5 mm. The incident radiation had to pass this wall as well as the 0.5 mm lithium diffused layer of the diode before it entered the active volume of the detector. The intensity discrimination caused by this 1 mm window was severe below a gamma-ray energy of 50 keV and no accurate intensity determination was possible in this region. The detector was operated at liquid nitrogen temperature with a reverse bias of 150 V. The detector was directly coupled to a charge sensitive preamplifier of the Goulding-Landis [6]) type, followed by a linear amplifier and a multichannel analyser. The resolution obtained was typically 4 keV at 500 keV gamma-ray energy for moderate counting rates. A fairly high counting rate was, however, necessary in many of the runs causing a worsening of the resolution to between five and six keV at 500 keV due to shifts in the linear amplifier base line.

An energy calibration was performed in each run using standard sources. The experimental determination of the relative gamma-ray intensities requires knowledge of the relative efficiency of the Ge(Li) detector as a function of the gamma-ray energy. This efficiency function cannot be calculated accurately as in the case of NaI crystals mainly because the active volume and its homogeneity is not accurately known. The efficiency function is instead obtained by calibration with standard sources and the result of such a calibration is shown in fig. 1. This figure is based upon data recorded in a fixed geometry by Norlin *et al.* [7]) kindly put at our disposal prior to publication. As can be seen from the figure the data fit to a straight line in the log-log diagram within a fairly broad energy region in accordance with results obtained by e.g. Easterday *et al.* [8]). The slope of this line might be a little different, depending on how the background is subtracted from the lines in different energy regions, and for different types of background slopes. The error arising from difficulties in background subtraction, being the main error contribution in the relative intensity determination, can be reduced by applying the same principles for the background subtraction in both the calibration and the measured spectra. For the strongest lines in the decay studied this error in the relative intensity determination was about 8 %. It should be pointed out that the efficiency function of fig. 1 deviates from the straight line for lower gamma-ray energies due to the above mentioned window absorption.

The electron spectra were observed in a 50 cm radius iron yoke double-focussing beta spectrometer of the Hedgran [9]) type. The spectrometer was operated automatically as described by Pettersson *et al.* [10]). The slit geometry of the spectrometer was chosen to give a resolution of typically 0.25 % at a solid angle of 0.3 %. A GM tube having an entrance window covered with a 0.55 mg/cm^2 mylar foil was used as the detector. The transmission of this mylar window must be determined as a function of the electron kinetic energy as the relative electron line intensities must be determined even at low energies. To investigate this transmission function the well-known

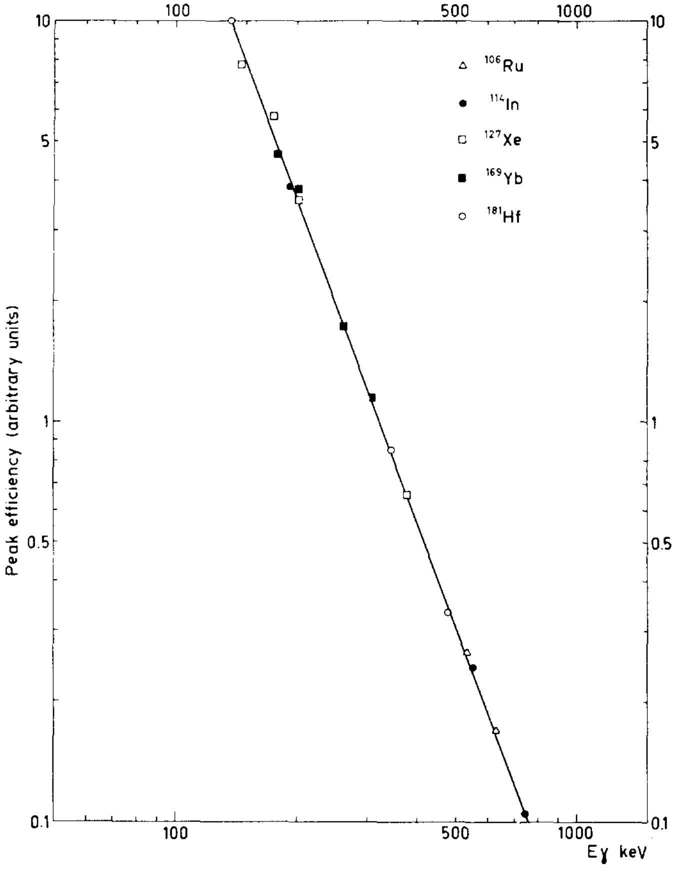

Fig. 1. Relative peak efficiency as a function of gamma-ray energy for the Ge(Li) solid state detector (RCA SJGG-1).

continuous beta spectrum of ^{35}S was recorded. Special care was taken to obtain an extremely thin source. The ^{35}S activity was hardly visible on the 100 μg/cm^2 carbon backing. The spectrum was transformed to a linear energy dependent function through a Fermi-Kurie plot. A deviation from this straight line could be observed below 40 keV and the relative transmission as a function of electron energy was calculated. The transmission curve is shown in fig. 2.

The zinc activity was produced by bombarding a natural copper target with protons at the synchro-cyclotron of the nearby Gustaf Werner Institute. The target was usually irradiated for five hours with a beam current of 0.1–0.2 μA. According to the work of Ghoshal [11]) a proton energy of 32 MeV yields a maximum activity of ^{62}Zn through the (p, 2n) reaction on ^{63}Cu. The desired activity was chemically separated from the target and the gamma spectra were recorded immediately after the irradiation and throughout the various stages of the chemical separation using the Ge(Li) detector. The spectra from the unseparated target material showed weak traces of ^{63}Zn and ^{65}Zn activities as well as other weak contributions from unidentified isotopes in the gamma energy region up to 1.5 MeV.

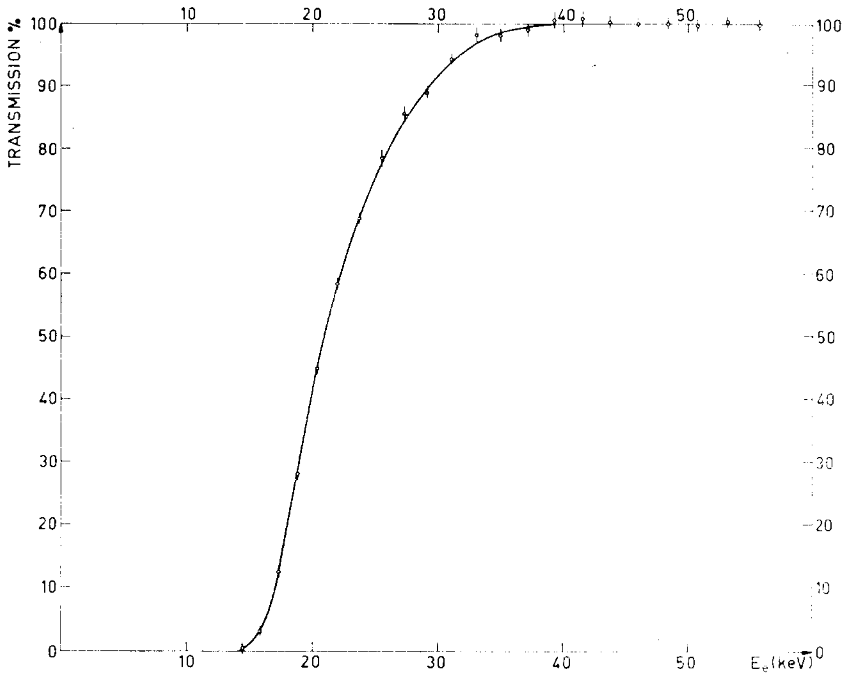

Fig. 2. The transmission as a function of the electron energy for the entrance window of the GM-counter used as detector in the beta spectrometer. The window used was a 0.55 mg/cm^2 mylar foil.

Both the separated and the unseparated sources used in this investigation contain of course ^{62}Cu activity, the active daughter in the decay of ^{62}Zn. ^{62}Cu decays to ^{62}Ni with a very intense beta branch to the ground state with only about 1 % of the disintegrations yielding excited states in ^{62}Ni. Consistent with this, no conversion line and no gamma ray belonging to transitions in ^{62}Ni was observed.

The chemical separation proceeded in the following way. The metal copper target was dissolved in conc. HNO_3. A few drops of conc. HCl was then added and the solution was slowly heated to speed up the process. HNO_3 was removed by repeated evaporations to dryness with 6*N* HCl. The residue was dissolved in 1.6*N* HCl and added on the top of a carefully washed ion exchange column (Resin Dowex 1–X8, size: 0.5 cm in diameter and 10 cm long). Under these conditions the copper passed through and the zinc was retained by the resin. The column was then washed with 1.6N HCl until no copper was detected in the effluent. The zinc was eluted with pure water or faster with 0.05N HNO_3. The solution was evaporated to suitable volume and the activity was electroplated onto a 5 mg/cm^2 copper foil forming a 2×20 mm^2 rectangular source area. These kinds of sources were used for the positon and electron measurements.

3. Gamma ray measurements

Gamma-ray spectra were taken at repeated time intervals for half-life assignment to each line for the separated sources and the unseparated target material as well. One ex-

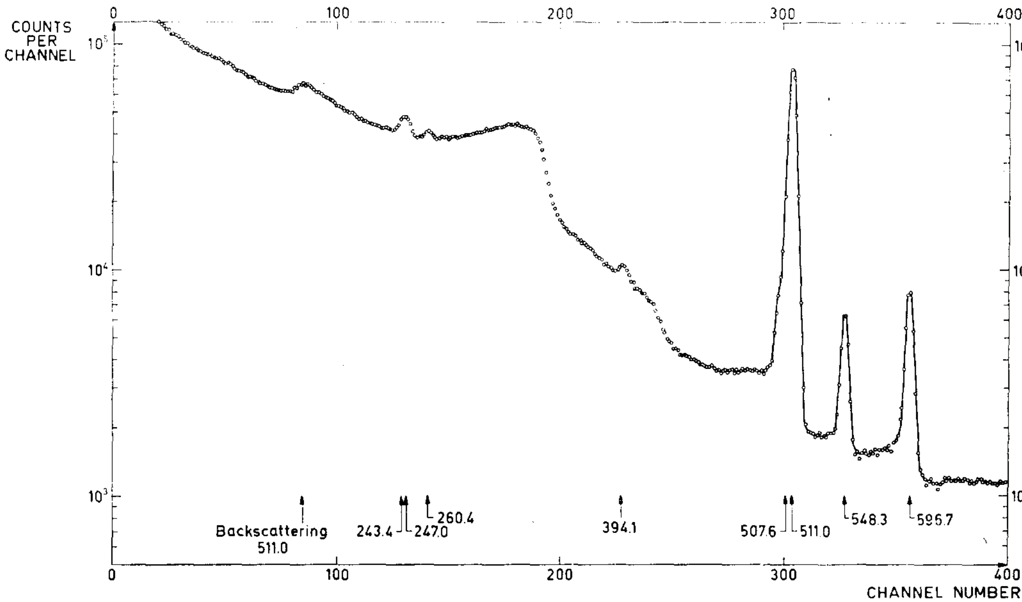

Fig. 3. Example of the spectra recorded with the Ge(Li) solid state detector. The counting time was in this case 40 minutes, and at this high counting rate the resolution has deteriorated to about 6 keV FWHM at about 500 keV.

ample of such a spectrum recorded for forty minutes using an unseparated source is shown in fig. 3. The energies obtained in calibration runs were consistent with the more accurate energy determinations from the internal conversion spectra. Intensities were measured for each line by determining the line area and applying the efficiency function discussed above. The results of these measurements are summarized in table 1, where the results of Brun *et al.*[4]) are also given for comparison. No gamma ray was observed above 650 keV using chemically separated sources although special efforts were undertaken to search for high-energy transitions belonging to the decay of ^{62}Zn. As mentioned above, no accurate intensity determination was possible for the 40.88 keV line. The intensity, calculated from the assumption of M1 multipolarity of this transition is, however, in good agreement with the value reported by Brun *et al.* [4]). The 243.4 keV and 247.0 keV lines were not completely resolved because of the fairly high counting rate necessary to measure intensities above the intense Compton background from the annihilation line. Careful graphical analysis showed, however, that both transitions must contribute to the total intensity of the complex line and from the line shape it could be deduced that the 243.4 keV transition is somewhat stronger. The weak 349.7 line is found on the steep slope of the Compton distribution and the intensity determination is difficult. A rough value was obtained using graphical methods. The 507.6 keV transition is fairly intense but the corresponding line is located on the low-energy side of the strong 511.0 keV line from annihilation quanta. The intensity of the 507.6 keV transition was approximately determined by applying graphical resolving methods.

It should also be mentioned that the assignment of the lines in the gamma ray spectrum to transitions in ^{62}Cu from half-life data might be erroneous because of the radioactive equilibrium in the decay chain. But as mentioned above the excited states of ^{62}Ni are fed in the decay of ^{62}Cu with very low intensity and no gamma ray in the spectra could be identified as the strongest transition in ^{62}Ni considered to be around 1170 keV [12]). Furthermore the K–L distance in the internal conversion spectra provides a basis for correct element assignment.

4. Positon and negaton measurements

The positon spectrum of the ^{62}Zn decay was measured. As the daughter nucleide ^{62}Cu is also a positon emitter, the spectrum was complex, and it was of course very difficult to make assignments of the different branches. The high-energy branch of ^{62}Cu was, however, determined and was found to have an end-point energy of 2934 ± 7 keV, which is somewhat higher than the hitherto best determination by Nussbaum *et al.* [3]), who reported 2.91 ± 0.01 MeV. For the other branches in the spectrum it was not possible to make the assignments definite.

The half-life of ^{62}Zn was determined from different runs on the most intense internal conversion lines. A weighted mean value of these determinations gave the result 9.2 ± 0.1 hours.

The energy region from 15 keV to 700 keV was scanned with a resolution of 0.25 %. It was not found worthwhile to search for conversion lines in the high-energy region where the conversion coefficients are small and the sensitivity of the Ge(Li) detector used in the gamma ray experiments was higher.

The internal conversion spectrum from the decay of ^{62}Zn obtained in this investigation is partly reproduced in figs. 4–6. All earlier reported transitions were found except the low intensity 305 keV transition reported by Roulston and Becker [5]). From fig. 5 it is also clear that the earlier reported 0.25 MeV transition actually consists of two gamma rays with energies of 243.40 and 247.02 keV. It should be pointed out that the doublet character of this line is essential in constructing the level scheme of

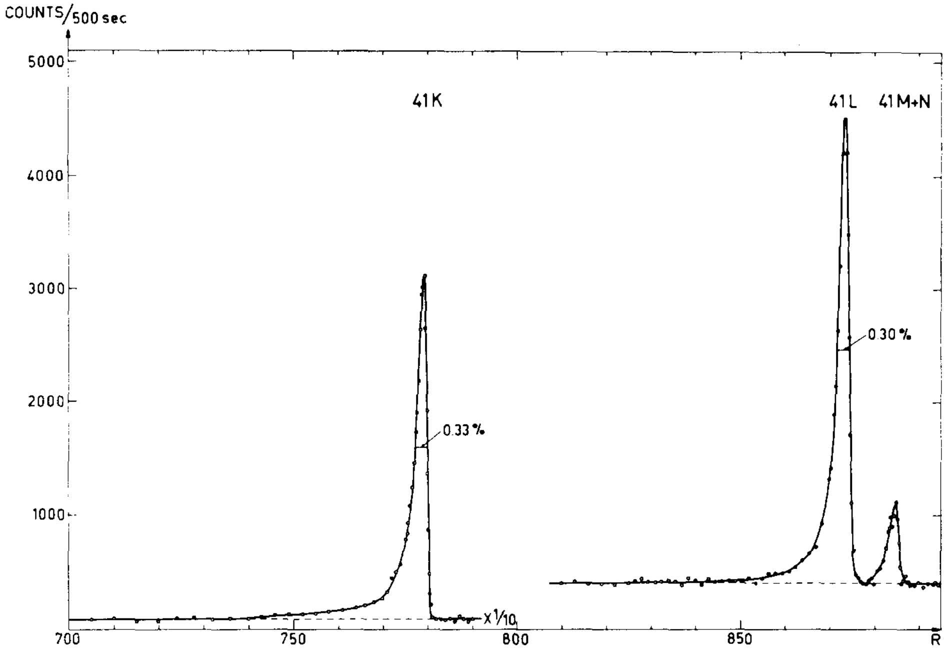

Fig. 4. The internal conversion lines from the 40.88 keV transition. The points are corrected for decay.

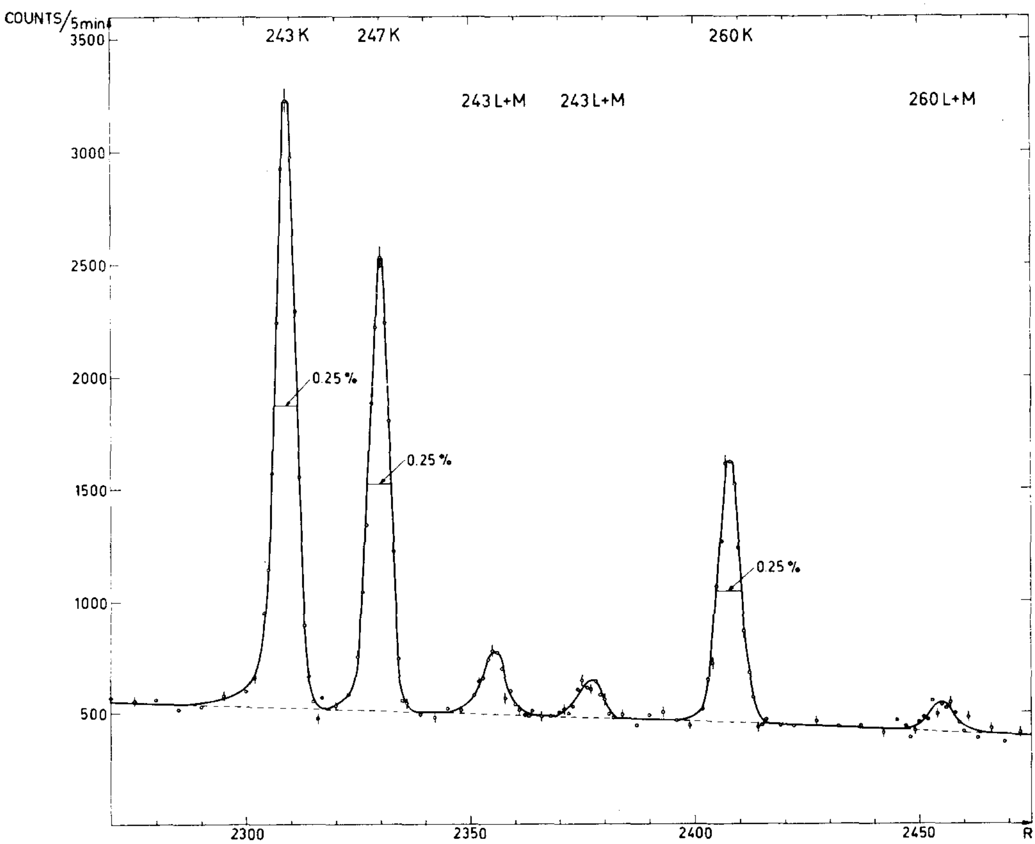

Fig. 5. The three internal conversion line groups showing the earlier reported 250 keV transition split into two transitions. The points are corrected for decay.

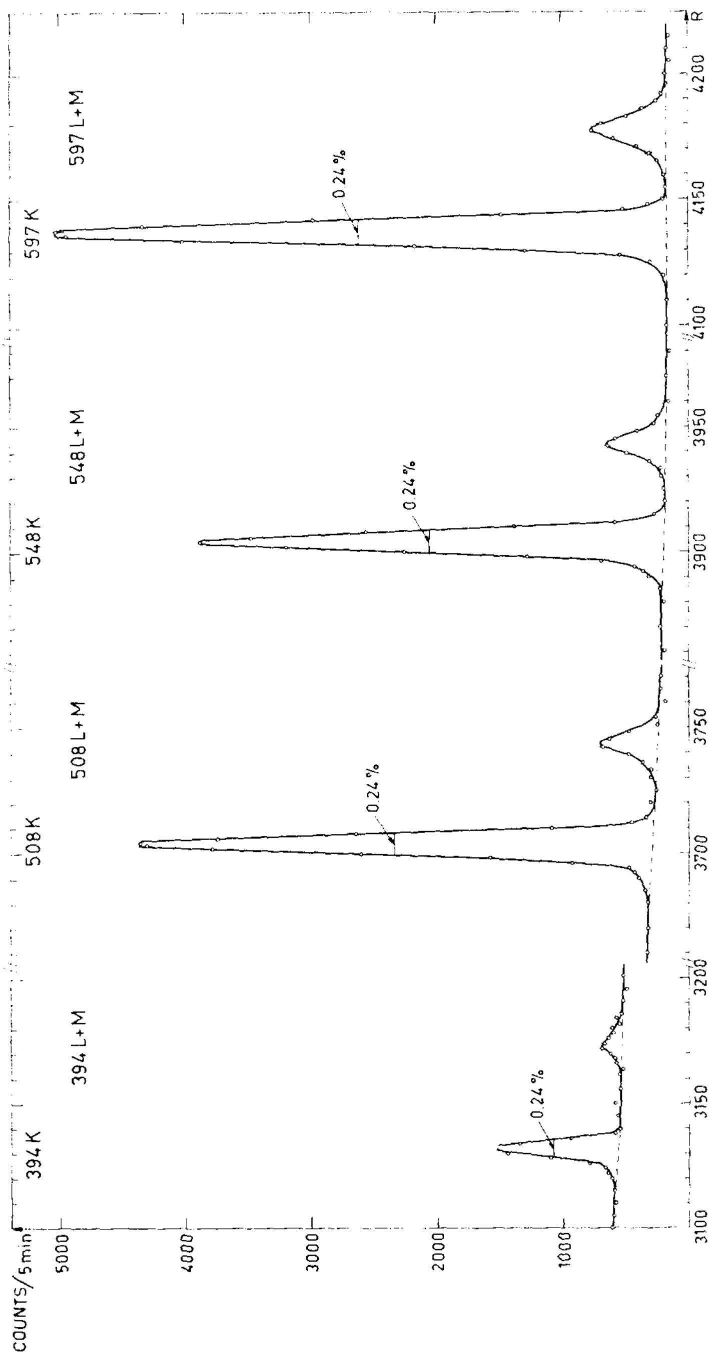

Fig. 6. The high-energy part of the internal conversion spectrum. The points are half-life corrected.

^{62}Cu. The assignments of these lines to transitions in ^{62}Cu were made through half-life studies and K–L distances. Every line was measured with at least two different sources, and all the lines were followed for at least three half-lives.

The intensities of the conversion lines were determined by measuring the line areas after half-life corrections of each point of the line. Correction for the absorption in the GM-tube entrance window (fig. 1) was needed only for the conversion lines from the 40.88 keV transition. The errors in the relative intensity measurements of lines measured with different sources include the errors obtained in the normalization procedure.

TABLE 1

Energies, internal conversion and gamma-ray intensities of the transitions belonging to the decay of ^{62}Zn to ^{62}Cu

Transition energy (keV)		Relative photon intensity Present work		Brun *et al.* [c]		Normalized K-conversion line intensity		Total intensity (%)	K-conversion coefficient		Multi-polarity
40.88	9	102 [a]		95	5	60.2	8	35.2	0.59 [b]		M1 [b]
243.40	5	≈7 } 11.0	9			0.0480	14	1.4	≈0.007		M1–E2
247.02	9	≈4 }		13	4	0.0313	9	0.8	≈0.008		M1–E2
260.44	10	2.6	5			0.0203	14	0.6	0.0078	21	M1–E2
349.69	25	≈1		–		0.0068	10	0.2	0.007		
394.12	18	6.2	10	5	3	0.0217	24	1.2	0.0035	9	E2
507.57	13	60	15	–		0.0693	20	12.4	0.0012	3	M1–E2
548.33	22	54	5	≦34		0.0528	12	10.9	0.00098	12	M1–E2
596.68	20	100	8	100		0.0590	13	20.7	0.00059 [b]		M1 [b]
636.9	5	≦1		≦5		0.0015	7	0.2	–		–

Conversion coefficients and transition multipolarities are deduced from the fact that the 40.88 and 596.68 keV transitions are of M1 character arrived at in the discussion.

[a]) Calculated from the adopted value for M1 transition.

[b]) Adopted values.

[c]) See ref. [3]).

ThB and ^{137}Cs sources were used for the energy calibration. The calibration energies were taken from reference [13]). Only the stronger lines were energy calibrated, the energies of the weaker lines were obtained by interpolations in spectra with other sources. The final values of the transition energies and the K-conversion line intensities are listed in table 1.

5. Results and discussion

The decay scheme of ^{62}Zn was established mainly on the basis of energy and intensity considerations using the data gained in this investigation. However, some data from earlier works were also taken into account.

As a first step, energy relationships of the type $E_1 + E_2 = E_3$ were studied. Two cascade cross-over combinations $41+508 = 548$ and $41+597 = 637$ involve the 41 keV transition, and determine the excited states at 41, 548 and 637 keV in agreement with the levels of Brun *et al.* [4]) and Roulston and Becker [5]). The relationships 247+260 = 508 and 247+350 = 597 define an excited state at 288 keV. Furthermore 243+394 = 637 gives a new cascade cross-over combination. The order of this cascade is not uniquely determined from the intensity data. However, Roulston and Becker [5]) reported a transition of 305 keV, and by taking this transition into account another energy relationship is obtained, namely 243+305 = 548, which determines an excited state at 243 keV.

From the relationships quoted above it can be seen that all reported transitions are placed in the level scheme. To check the level scheme obtained in this way the total intensities of the transitions were used. No conflicting data arise from this control and all the intensities seem to fit quite well within the proposed scheme. According to Brun *et al.* [4]), the upper limit for the intensity of a positon feeding to the first excited state of ^{62}Cu is 0.45 % which is also consistent with our data.

By comparing the obtained level scheme with the coincidence data of Brun *et al.* [4]) strong support is gained for most levels. The only disagreement is that the 400 keV gamma ray is reported to be in coincidence with the 42 keV gamma ray. The relative intensity of this coincidence is given as 0.2 ± 0.2 which implies that the coincidence is not completely definite.

The spin and parity of the ground state of the doubly even nucleus ^{62}Zn is 0^+. The spin of the ground state of ^{62}Cu has been determined by atomic beam measurements to be 1 (see e.g. ref. [14])) and the parity is even since the $\log ft$ value of the 2.9 MeV positon branch of ^{62}Cu indicates an allowed transition.

The end-point energy of the positon branch from ^{62}Zn to the ground state of ^{62}Cu is determined to be 0.66 ± 0.01 MeV (ref. [2])) and 0.675 ± 0.10 MeV (refs. [3,12])) which yields a Q-value of 1.69 MeV. Nussbaum *et al.* [3]) measured the ratio $\beta^+(^{62}\text{Zn})/\beta^+(^{62}\text{Cu})$ to be 0.14. Furthermore the decay of ^{62}Cu is known [12]) to feed the ground state of ^{62}Ni with almost 100 %. From the theoretical K-capture to positon emission ratios of 2.9 and 0.022 for the allowed transitions of ^{62}Zn and ^{62}Cu, respectively, it is found that 53 % of the total ^{62}Zn disintegrations proceed to the ground state. This makes it possible to normalize the total transition intensities relative to 100 % of the total decay (compare table 1 and fig. 7). The $\log ft$ values of the feeding transitions can thus be obtained [15]) and the results are 5.0 for the ground state transition and 4.7 to the levels at 548 and 637 keV, indicating allowed transitions in all three cases.

From the measured K/L ratio of the 41 keV transition it was not possible to distinguish between E1 and M1 multipolarities. However, the $L_I/(L_{II}+L_{III})$ ratio is much more sensitive in this energy region. This ratio was measured in this investigation to be certainly greater than 10, which excluded the E1 multipolarity. Thus the multipolarity of the 41 keV transition is M1 and as the 41 keV state is not fed directly in the ^{62}Zn decay, spins of 0 and 1 must be excluded and the remaining possibility is spin 2 and even parity.

According to the decay scheme (fig. 7) the 637 keV level must be fed in the decay of ^{62}Zn. The $\log ft$ value obtained above indicates an allowed transition and as the ground state of ^{62}Zn is a 0^+ state the spin and parity of the 637 keV level must be 0^+ or 1^+. This implies that the possible multipolarities of the 597 keV transition are M1 and E2. If M1 is assumed to be correct, the measured K-conversion line intensities from table 1 combined with the theoretical [13]) K-conversion coefficients yield very closely

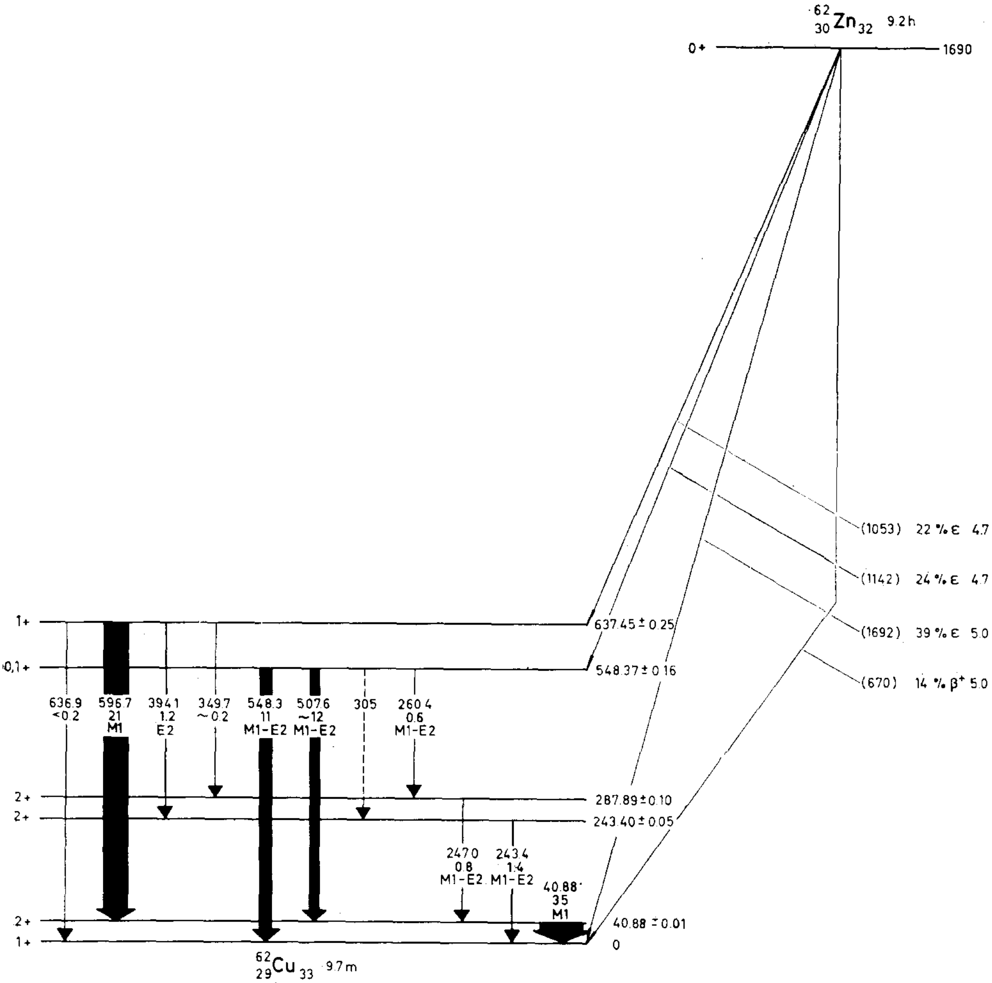

Fig. 7. The deduced decay scheme of ^{62}Zn. The total intensities of the transitions are given in per cent of the total decay rate below the transition energies. To the right the electron capture or positon energies are given in brackets and the figures to the extreme right denote the log *ft* values.

the same gamma-ray intensities for both the 597 and the 41 keV transitions, the latter being an M1 transition as deduced above. This is actually observed by Brun *et al.* [4]) as can be seen from table 1. A similar discussion for an assumed E2 multipolarity of the 597 keV transition yields a gamma-ray intensity much too low for this transition when compared to the intensity of the 41 keV transition. Thus the 597 keV transition must be an M1 transition and the spin-parity assignment of 1^+ is the only remaining possibility for the 637 keV state. The theoretical [13]) K-conversion coefficient for the 597 keV M1 transition is $5.90 \cdot 10^{-4}$ and has been used to normalize the internal K-conversion intensities of table 1.

The 548 keV excited state has a log *ft* value of 4.7, which indicates an allowed transition. Since ^{62}Zn has a spin of 0 and even parity, the most probable spin of the 548 keV state is 0 or 1 with even parity. None of these alternatives can be excluded since the de-exciting transitions are of M1 and/or E2 character.

No direct feeding to the excited states at 243 and 288 keV has been observed which is also in agreement with the intensity balance of the proposed decay scheme. Thus the spin-parity assignments of 0^+ and 1^+ are eliminated. The K-conversion coefficient of the 260 keV transition indicates a mixed M1–E2 transition. A pure E2 transition is however excluded. Accordingly, the 2^+ assignment is the only remaining alternative for the 288 keV state. The same arguments are true concerning the 243 keV transition, which determines the 243 keV state to be of 2^+ character. The 2^+ assignments of these states are in agreement with the other transitions involved, which are of M1 and/or E2 character.

Thus spins and parities are assigned to all the levels in the decay scheme into which all the experimental data fit consistently.

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References

1) D. R. Miller, R. C. Thompson and B. B. Cunningham, Phys. Rev. **74** (1948) 347
2) R. W. Hayward, Phys. Rev. **79** (1950) 541
3) R. H. Nussbaum *et al.*, Physica **20** (1954) 571
4) E. Brun, W. E. Meyerhof, J. J. Kraushaar and D. J. Horen, Phys. Rev. **107** (1957) 1324
5) K. I. Roulston and E. H. Becker, Bull. Am. Phys. Soc. **11** (1966) 458 and private communication
6) F. S. Goulding and D. A. Landis, Proc. of Conf. Instrumentation Techniques in Nuclear Pulse Analysis, Monterey, April 1963, N.A.S.-N.R.C. publ. 1184
7) L. O. Norlin and S. Gustafsson, private communication
8) H. T. Easterday, A. J. Haverfield and J. M. Hollander, Nucl. Instr. **32** (1965) 333
9) A. Hedgran, K. Siegbahn and N. Svartholm, Proc. Phys. Soc. **A63** (1950) 960;
A. Hedgran Ark. Fys. **5** (1952) 1
10) H. Pettersson *et al.*, Ark. Fys. **29** (1965) 61
11) S. N. Ghoshal, Phys. Rev. **80** (1950) 939
12) Nuclear Data Sheets, National Academy of Science, Washington D. C.
13) Alpha-, beta- and gamma-ray spectroscopy, ed. by K. Siegbahn, (North-Holland Publ. Co., Amsterdam, 1965)
14) I. Lindgren, in Perturbed angular correlations, ed. by E. Karlsson, E. Matthias and K. Siegbahn (North-Holland Publ. Co., Amsterdam, 1964) appendix 1
15) A. H. Wapstra, G. J. Nijgh and R. van Lieshout, Nuclear spectroscopy tables (North-Holland Publ. Co., Amsterdam, 1959)