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Q-VALUE FOR THE POSITRON DECAY OF ^{109}Sb AND THE LEVEL STRUCTURE OF ^{109}Sn

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Abstract

The Q_{EC} value for the decay of ^{109}Sb was determined to be 6380±16 keV from the analysis of mass-109 β-γ coincidence data accumulated using the on-line mass separator at GSI. Positron end-points were measured with a plastic scintillator telescope for the spectra in coincidence with γ-transitions to the ground state of ^{109}Sn. The decay scheme of ^{109}Sb has been established, and additional information about the level structure of ^{109}Sn obtained from in-beam measurements using the ^{106}Cd(α,n) reaction.

1. Introduction

The mass differences between ^{109}Sb and a number of other neutron-deficient nuclei in the tin region are known from observations on α-decays and β-delayed protons[1]. To link the mass differences of these nuclei to the known mass of ^{109}Sn, and thus to determine their absolute masses, the Q_{EC}-value for the decay of ^{109}Sb is required. In this paper we report on studies of the decay scheme of ^{109}Sb, and on measurements of positron spectra, which in conjunction with the decay scheme, lead to a value for Q_{EC}.

The decay scheme turns out to be well-suited to the Q-value measurement. The strongest γ-lines in the decay spectrum are ground-state transitions from levels at 664, 925 and 1062 keV which are populated directly in the β-decay and which have little or no feeding from higher levels. The positron spectra taken with a plastic scintillator in coincidence with these γ-lines lie in the energy range where the response of the scintillator is linear, and the end-point energies can be accurately measured by comparison with known standards.

The low-lying levels in ^{109}Sn populated in the β-decay are of interest in themselves, since ^{109}Sn is the lightest odd-A tin nucleus yet studied, and its level structure below 1 MeV excitation was not previously known. In order to obtain more information about these levels, we have also studied in-beam γ-transitions in the ^{106}Cd(α,n)^{109}Sn reaction, measuring angular distributions, γ-n and γ-γ coincidence spectra.

2. The Decay Scheme of ^{109}Sb

Sources of ^{109}Sb were produced in the ^{92}Mo + ^{20}Ne reaction at the Manchester heavy ion linear accelerator, and in the ^{58}Ni + ^{58}Ni reaction at GSI. At Manchester, the reaction products were transported by a helium jet system to a tape which moved at 40 second intervals to the counting position. Singles spectra were accumulated in multispectrum mode, and X-γ and γ-γ events recorded. Those γ-transitions which were in coincidence with tin X-rays, and were also later observed in a mass-separated A = 109 spectrum at GSI, have been assigned to transitions in ^{109}Sn. The energies of these transitions and their relative intensities are listed in Table I. Part of the mass-separated spectrum is shown in figure 1, with energies labelling the ^{109}Sn lines; many of the other lines are transitions in ^{109}In.

Table I
The relative intensity of γ-lines seen in the decay of ^{109}Sb. The numbers in parenthesis represent the the error in the last digit

Energy (keV)	Relative Intensity
246.7	1.9 (2)
261.0	2.0 (2)
544.8	10.6 (5)
664.5	63 (4)
678.6	19 (1)
925.4	100
950.6	2.0 (1)
1061.7	75 (5)
1078.0	3.9 (2)
1343.5	2.2 (2)
1495.8	30 (2)

The lines at 246.7, 261.0 and 950.6 keV are in coincidence with the ground-state transitions at 678.6, 664.5 and 544.8 keV respectively. All the other lines in Table I are ground-state transitions with no measurable feeding from higher levels. In particular, the intense lines at 925 and 1062 keV are populated only by the β-decay. The positron spectrum in coincidence with 664 keV γ-rays does include a component of feeding from the 925 keV level, but this is only 3% of the total intensity. The decay scheme deduced for ^{109}Sb is illustrated in figure 6.

Analysing the multispectrum intensities of ^{109}Sn in terms of a single exponential leads to a half-life of 16.67±0.15s. This result is taken from the helium jet measurement, for which production of the ^{109}Te precursor is expected to be small (about 3% of the ^{109}Sb) and which used a longer cycle time. The log ft values shown in figure 6 are derived from this half-life in conjunction with the branching ratios corresponding to the relative intensities in Table I and the ground state branching ratio of 2±1% found by fitting the positron spectrum.

3. Positron End-points

Positrons were detected with the plastic scintillator telescope shown in figure 2, which is described in detail elsewhere[2]. The energy calibration of the telescope was established using conversion electron lines from ^{137}Cs, ^{207}Bi and ^{208}Tl sources, and continuous β^--decay spectra from ^{90}Y,

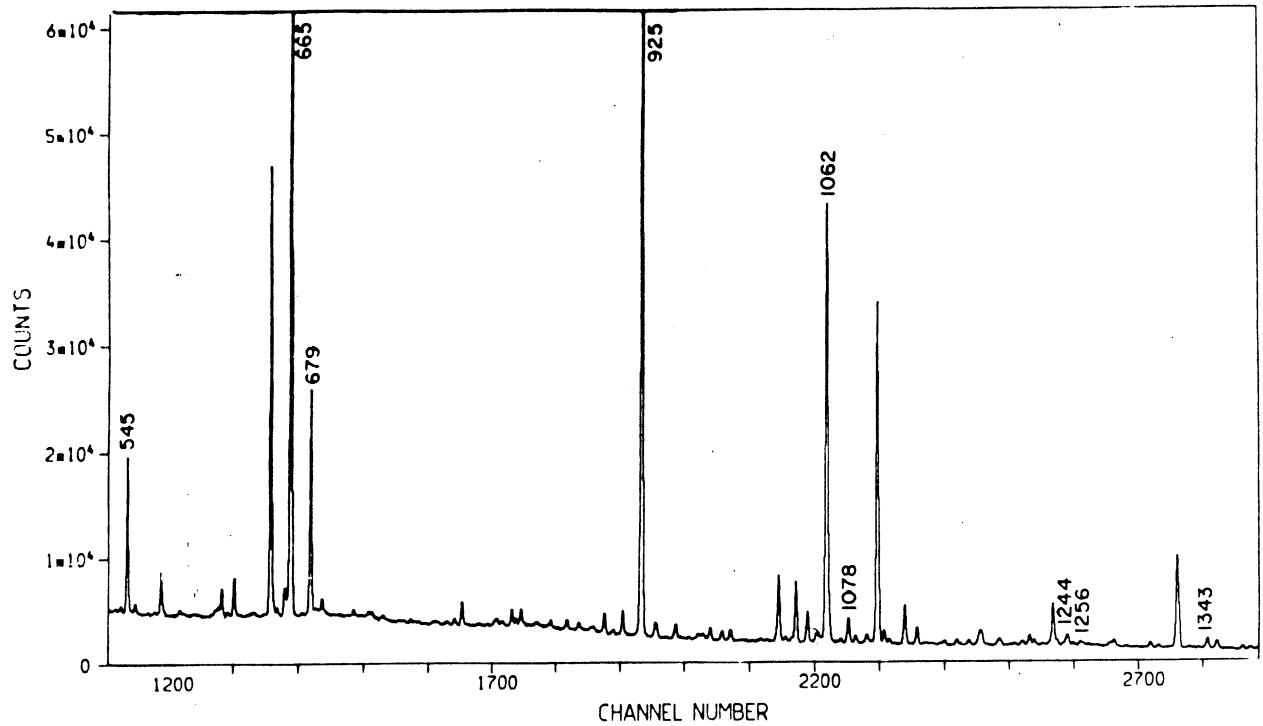

Fig. 1 Part of the mass-separated A = 109 γ-spectrum from the ^{58}Ni + ^{58}Ni reaction at a bombarding energy of 5.0 MeV. The peaks labelled in keV are assigned to transitions in ^{109}Sn.

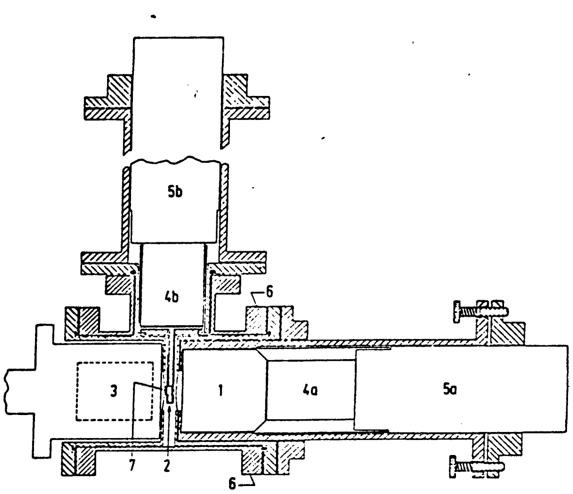

Fig. 2 The beta-gamma detector system. (1) E scintillator; (2) ΔE scintillator; (3) Ge(Li) detector; (4a,b) photomultipliers; (5a,b) photomultiplier bases; (6) vacuum chamber of the tape transport system at the mass separator; (7) source position.

^{144}Pr and ^{38}Cl sources. The detector response to electrons was assumed to be a Gaussian whose width increased linearly with energy. This assumption was made on the basis of computer fits to the conversion electron lines and in accordance with data taken from reference 2. The end-point channel of each continuous β^--spectrum was determined by comparing the experimental spectrum with a computer-generated theoretical spectrum obtained by folding the allowed spectrum shape with the Gaussian detector response. The range of the fit excluded low channels (where background might contribute) and channels near the end-point (where pile-up might become important). The fitted end-point showed very little sensitivity to the selection of fit range, and the close agreement between theory and experiment near the end-point showed that pile-up effects were small at the count-rates used in the measurements. Over the energy range up to 5 MeV the response of the E-detector scintillator was found to be linear, again in accordance with reference 2. (The ΔE-detector was only used to establish a coincidence, and hence to reduce the photon background; the ΔE and E signals were not summed).

The response of the E-detector scintillator to positrons is not the same as to negative electrons because of the possibility of an additional signal from one or both of the annihilation photons. In the plastic scintillator, photo-electric absorption is negligible for annihilation photons, and Compton scattering is the only important process leading to additional signals. The response function of the scintillator has been modified for positrons as follows. The average additional signal due to annihilation photons is assumed to be independent of positron energy. The response function is represented by the sum of three Gaussians: (i) the unmodified electron response function, with a variance increasing linearly with energy; (ii) a Gaussian at an energy increased by 230 keV, and a variance increased by 8300 keV^2, the values corresponding to a triangular approximation to the Compton scattered signal for annihilation photons; (iii) a Gaussian at an energy increased by 460 keV, and variance increased by 16000 keV^2, representing events in which both annihilation photons are Compton scattered.

Positron spectra from ^{66}Ga sources were fitted with this response function, using the probability of Compton scattering by a single annihilation photon as a parameter. The end-point energy obtained from this procedure agrees with the known ^{66}Ga end point[3]) when the probability of Compton scattering is 10.5%, corresponding to an average additional energy of 53 keV deposited by annihilation radiation for each positron stopped in the scintillator. It must be emphasised that the additional energy is the important quantity, and that this is rather well-known, since the end-point is very insensitive to the detailed shape of the response function. However, it lends confidence to the method of analysis that the value of χ^2 for the fit to the positron spectrum has a minimum at the same value of additional energy as is required to bring agreement with the β^--energy calibration.

The positron spectrum fitting procedure was tested on-line with mass-separated ^{112}Sb sources. A positron spectrum was collected in coincidence with the 1257 keV γ-transition following ^{112}Sb decay. This transition has a significant amount of feeding from higher levels. The intensity of ^{112}Sn γ-lines in the singles spectrum was in agreement with the published decay scheme for ^{112}Sb[4]). The relative intensities of β-transitions feeding the 1257 keV γ-line were taken from reference 3 in generating the β^+-spectrum, assuming that all these transitions have an allowed spectrum shape. The fitting procedure for ^{112}Sb leads to a value for Q_{EC} of 7.062±0.016 MeV in agreement with the previously measured value of 7.030±0.050 MeV[5]).

Fits to the positron spectra in coincidence with the 925 and 1062 keV γ-lines in ^{109}Sb decay are shown in figure 3. The end-points of these spectra, and of the spectrum in coincidence with the 664 keV transition, all lie between the ^{66}Ga end-point and the end-point of the ^{112}Sb end-point in coincidence with the 1257 keV line. The values of the end-points, directly from the fit, and converted to Q_{β^+} for the ground state transition by adding the γ-energy, are given in Table II.

Table II
End-point energies of positron spectra in coincidence with ^{109}Sn transitions of energy E_γ.

E_γ (keV)	End-point (keV)	Q_{β^+} (keV)
664	4674±22	5338±22
925	4416±21	5341±21
1062	4332±24	5392±24

The errors in Table II are statistical, derived from the goodness of fit. Since the annihilation photon correction has been taken from the ^{66}Ga spectrum, the end-points are referred to the ^{66}Ga end-point and in addition to the statistical errors there are the following sources of error: (i) uncertainty in the ^{66}Ga end-point (±8 keV), (ii) uncertainty in the keV/channel for the scintillator. This is 3%, but since the extrapolation from ^{66}Ga is from 180.7 to 523 keV, this error is smaller than the statistical error, (iii) A change in the average energy deposited by annihilation photons between ^{66}Ga and ^{109}Sb. Since the total energy deposited is estimated to be 53 keV, any change must be only a few keV, and this source of uncertainty has been neglected. Combining these errors leads to a final result Q_{β^+} = 5358±16 keV or Q_{EC} = 6380±16 keV.

An upper limit to the branching ratio for decay of ^{109}Sb to the ground state of ^{109}Sn has been obtained by analysing the singles positron spectrum. Assuming that all positrons above 4.8 MeV are due to ^{109}Sb decays with the end-point of 5358 keV derived above, the branching ratio is found to be 2±1%. The upper limit of 6.1 for the log ft value for the ground state shown in figure 6 corresponds to a 3% branch.

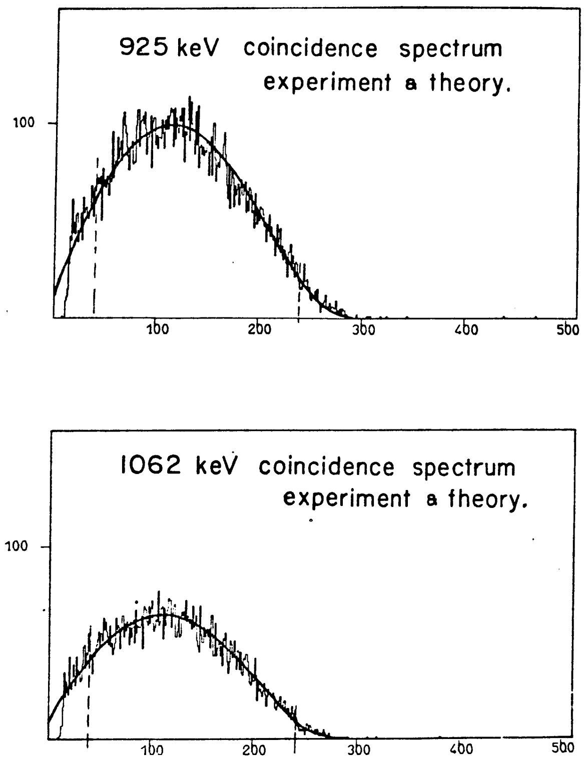

Fig. 3 Positron spectra in coincidence with transitions in ^{109}Sn. The dotted lines indicate the range over which the theoretical spectrum shapes were fitted to the data.

4. In-beam Measurements on ^{109}Sn Transitions

Transitions in ^{109}Sn have already been studied using the ^{106}Cd(α,n)[6]) and ^{108}Cd(α,3n)[7]) reactions. Madueme et al[6]) measured conversion coefficients as well as γ-spectra, but were unable to deduce the low-lying level structure of ^{109}Sn. Hashimoto et al[7]) were primarily interested in high-spin states: they found a number of high-spin bands, but did not observe transitions from levels below 1 MeV.

To obtain further information about the ^{109}Sn levels populated in ^{109}Sb β-decay, we studied γ-spectra in the ^{106}Cd(α,n) reaction, using n-γ coincidences as a signature for ^{109}Sn transitions. At bombarding energies below 17 MeV, (α,n) is the only compound nuclear reaction for which neutron emission is energetically possible. Using the tandem accelerators at Liverpool and Oxford, we have accumulated n-γ and γ-γ coincidences and γ-singles spectra at energies from 12.5 to 18.0 MeV and have measured angular distributions at 14.0 and 18.0 MeV.

The enriched ^{106}Cd target foil was mounted on a Pb backing just thick enough to stop recoil Sn nuclei at the highest bombarding energy. A Compton-suppressed Ge(Li) detector rotated in a horizontal plane about the target. Coincidence events were

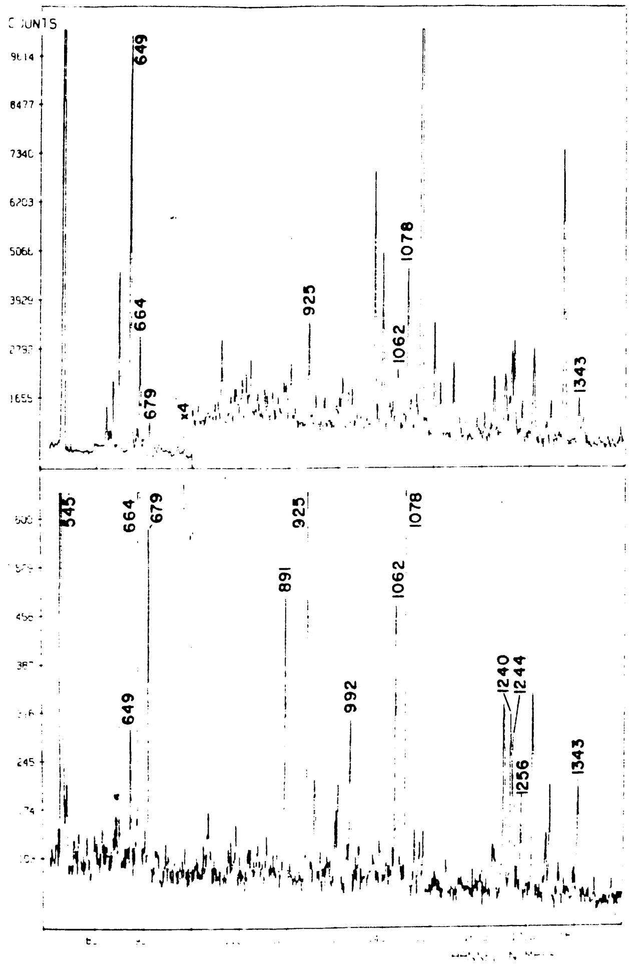

Fig. 4 A comparison of singles and n-γ coincidence spectra in the ($^{106}Cd + \alpha$) reaction at 14 MeV. Peaks are labelled in keV.

collected between this detector and a second, unsuppressed Ge(Li) detector in a fixed position. The second detector served as a monitor for the angular distributions. Below the threshold for direct ^{109}In production, all the ^{109}In lines are from the decay of ^{109}Sn, and hence have isotropic angular distributions. These lines checked that there was no significant anistropy arising from absorption or beam misalignment. Two liquid scintillators, with rise-time discrimination between neutrons and gammas, were used to select neutron coincidences in the Compton-suppressed detector. Singles and neutron coincidence spectra are compared in figure 4, in which the peaks labelled in the coincidence spectrum are assigned to ^{109}Sn. The peaks which are not strongly attenuated, but have not been labelled, are due to (α,n) contamination from cadmium isotopes other than ^{106}Cd in the target. All of the γ-lines observed in ^{109}Sb decay are also seen in-beam. On the basis of all the singles and coincident data from the in-beam and decay studies, we have built up the level scheme shown in figure 6.

A preliminary analysis has been made of part of the angular distribution data and Legendre polynomial coefficients extracted for some prominent γ-lines. Examples of the angular distribution data and fits are shown in figure 5. The values of the coefficients A_2 and A_4 in the Legendre polynomial expansion are listed in Table III, together with the multipolarity for transitions for which conversion coefficients are given in reference 6. The spin of the ground state of ^{109}Sn is known from atomic beam measurements[8]) to be $7/2$, and for transitions from higher levels to this state the spin of the upper level is in several cases uniquely determined by the angular distribution. We have made theoretical estimates of the angular distributions using optical model parameters taken from reference 9. Upper level spins which can yield the observed angular distributions are given in the last column of Table III. The spins in brackets are spins which give angular distributions of the right general shape, but outside the statistical range of the fits to the data.

Table III

Legendre polynomial coefficients A_2 and A_4 and allowed spins J for ground state transitions of energy E_γ in ^{109}Sn. The numbers in parenthesis following the coefficients represent the error in the last digit, the multipolarities are taken from reference 6.

E_γ (keV)	A_2	A_4	Multipolarity	J
545	-0.17(2)	0.03(2)		$5/2$, $9/2$
665	-0.33(2)	0.05(2)	E2 (M1)	$5/2$
679	0.05(3)	0.01(2)		$3/2$, $5/2$, $7/2$, $9/2$
891	-0.19(2)	0.21(2)		$9/2$
925	-0.03(1)	0.01(1)		$5/2$, ($3/2$)
992	-0.20(2)	0.02(2)		$5/2$, $9/2$
1062	-0.36(3)	0.10(3)		($5/2$), ($9/2$)
1078	-0.82(5)	0.22(5)		$9/2$
1240	0.24(1)	-0.19(1)		($11/2$+)
1244	0.25(1)	-0.18(1)	E2 (M1)	($11/2$+)
1256	0.15(1)	-0.20(1)	M2 E3	$7/2$, ($11/2$-)
1343	-0.23(3)	-0.02(3)		$5/2$, $9/2$

No Doppler shifts are observed in any of the γ-lines below 1500 keV. At 1200 keV, roughly the energy of the first 2+ vibrational states in the neighbouring ^{108}Sn and ^{110}Sn, the full Doppler shift at a bombarding energy of 14.0 MeV is 3.6 keV. The failure to observe a Doppler shift for the γ-lines near 1200 keV implies that their lifetimes are greater than 1 ps, or that the strength of an E2 transition is less than 5 Weisskopf units.

5. The Structure of the Low-lying Levels in ^{109}Sn

The combination of in-beam and decay measurements has led to information about a number of previously unknown levels at low excitation in ^{109}Sn. This information is summarized in figure 6. The ground state, which has spin $7/2$, is no doubt the $g_{7/2}$ state, and has been labelled with positive parity. Presumably all the states below the 1256 keV level have positive parity (the 1256 keV level is shown to be the $h_{11/2}$ state by the E3 multipolarity of the ground state transition). Most of the spin values consistent with the angular distributions are acceptable, and all the mixed M1, E2 transitions are required to be predominantly E2, with the exception of the $9/2$+ option for the 992 keV transition, which must be nearly pure M1. This is odd, since $5/2$+ seems an unlikely assignment for this state, as it is not populated in the β-decay.

There are some other unresolved puzzles.
(i) No spin $1/2$ state is observed. The $1/2$+ state is the ground state in ^{113}Sn and ^{115}Sn, and is at 255 keV in ^{111}Sn[4]). It may well have moved to a somewhat higher excitation in ^{109}Sn, and be by-passed in the decay of all other levels.
(ii) No state has the preferred assignment to $3/2$ from the angular distributions, although in ^{111}Sb, ^{115}Sb and ^{115}Sb the lowest log ft value is for the transi-

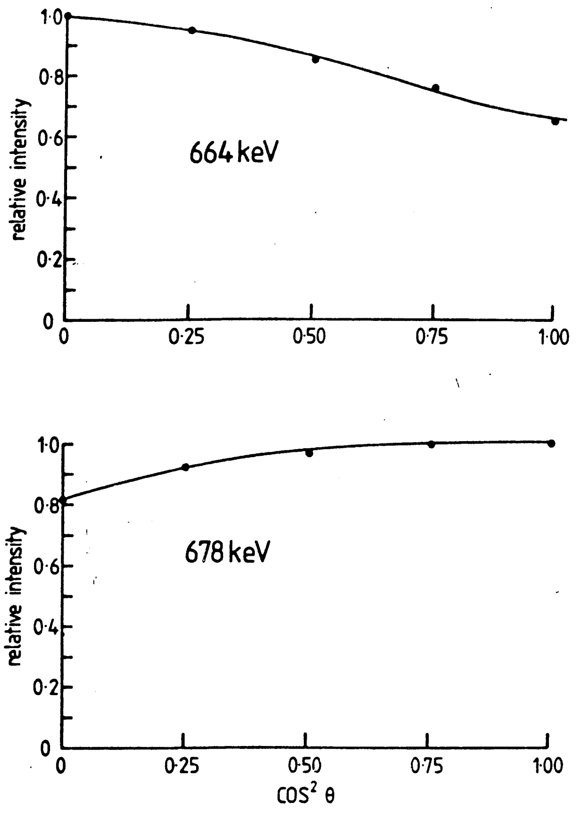

Fig. 5 Angular distributions of γ-transitions in ^{106}Cd(α,n)^{109}Sn. The lines are the fits given by the coefficients in Table III, and the error bars on each measurement are about the size of the data points.

tion to a $3/2^+$ state[4]). In ^{109}Sb decay the strongest transition is to the 925 keV level. The in-beam angular distribution of the 925 keV transition is essentially isotropic, and we recommend a $3/2^+$ assignment for this state, although the predicted A_2 is then +0.06, outside the limits of the data.
(iii) The 1078 keV transition has a strong anisotropy, which demands a $9/2^+$ assignment, inconsistent with the observation of this state in β-decay. The only explanation at present is a chance coincidence of two levels.
(iv) Hashimoto et al.[7]) propose $^{11}/_2$+ for the 1244 keV state, on the grounds that it is strongly populated in the de-excitation of high-spin bands. The 1240 keV and 1244 keV lines have almost identical angular distributions, suggesting that they are both transitions from $^{11}/_2$+ states. However, the expected values of A_2 and A_4 are then 0.38 and -0.13, outside the experimental limits.
(v) The 1256 keV transition must be an E3, M2 mixture because of its conversion coefficient. A predominantly E3 transition has a broadly similar angular distribution, but a statistically acceptable fit cannot be found.

The lower limit to the lifetime found for the states at about 1200 keV is a few times greater than the measured 2+→0+ lifetimes in the even tin isotopes[9]). The limit is not high enough to test whether there are states weakly coupled to the case excitation or whether the quasiparticle character of the states is largely retained at this excitation. It would be interesting to measure actual values for their lifetimes. Of course, the lowest states in ^{109}Sn will be rather pure quasiparticles; as in the other odd-A isotopes, the β-decay to the $7/2^+$ state has a high log ft value because $\Delta\ell = 2$ in the $d5/2 \rightarrow g7/2$ transition.

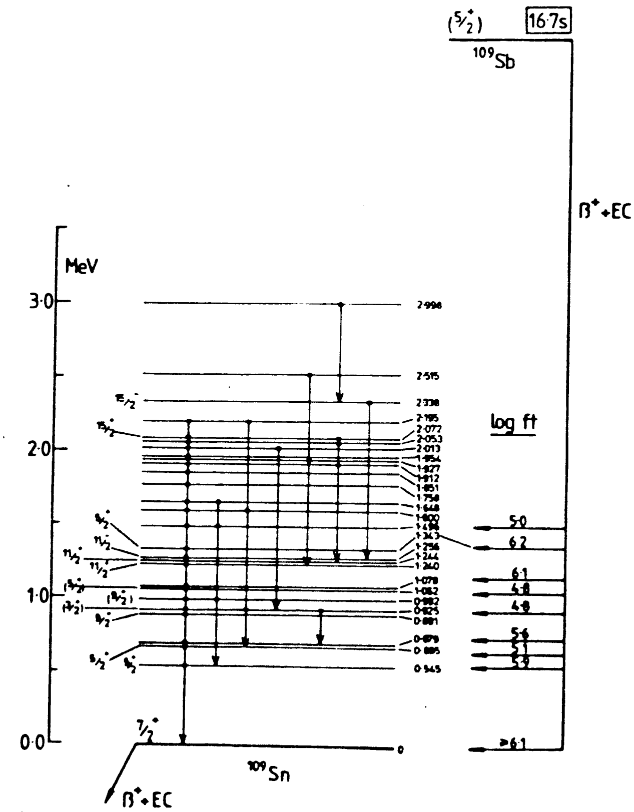

Fig. 6 The level diagram for ^{109}Sn.

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