DIRECTIONAL CORRELATIONS OF GAMMA RAYS IN ^{125}I

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Angular correlations of γ-rays in the decay of ^{125}Xe have been measured. The source was obtained by implanting Xe ions in aluminium foil. The results, together with the log ft values of electron capture transitions and the transition multipolarities, allow the assignment of spins and parities to the following levels: $\frac{7}{2}^+$ to 113.6 keV, $\frac{5}{2}^+$ to 372.1 keV and $\frac{3}{2}^+$ to 453.8 keV. They also suggest $\frac{3}{2}$ spin values for the 1090, 1180.5 and 1383 keV levels. The perturbation of the 74.9–113.6 keV correlation is discussed. The spin value for the 113.6 keV level and negative sign for the mixing amplitude of the 113.6 keV transition emerge from the analysis, irrespective of pertuibation of the angular correlation. Several new transition in coincidence with 453.8 keV γ quanta were observed.

1. *Introduction*

The energy levels of ^{125}I populated from the decay of 17.3 h ^{125}Xe have recently been investigated by means of Ge(Li) and NaI(Tl) detectors. Several new excited states were found, the total decay energy of ^{125}Xe to ^{125}I was measured, and the ft values of the electron capture feeding of the levels were determined [1, 2]. The multipolarity mixing ratios of the γ-transitions which depopulate the low-lying levels, and the spins of the second and third excited states of ^{125}I were found earlier [3] from the high-resolution conversion electron studies and from $\gamma-\gamma$ and $\gamma-e$ angular correlation measurements of the 55—188.4 keV cascade. These studies in combination with the life-time measurements of the first three excited states allowed the determination of the properties of the low-lying excited states [4, 5]. It was concluded that the states in question were mainly of a phonon character.

In order to investigate further the properties of the higher excited states and the nature of the γ-transitions from these states, $\gamma-\gamma$ directional correlation measurements were performed. Moreover, some additional information on the γ-transitions obtained from $\gamma-\gamma$ coincidence studies using NaI(Tl) detectors and from Ge (Li) γ-ray spectra, is included.

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2. *Experimental methods*

2.1. Preparation of the source

Sources of ^{125}Xe were produced by irradiating spectrally pure natural xenon in the Świerk reactor in a flux of 10^{13}n cm^{-2}s^{-1} for about 50 h. After irradiation in the special Al container placed near the reactor core [6], xenon was transferred to another vessel and used for preparing the metallic sources. The active natural xenon ions were embedded in Al foil using a simple accelerating device [7]. In some experiments mass-separated ^{125}Xe sources with Al backings prepared by means of the Lublin University electromagnetic mass separator were also used.

2.2. Experimental set-up

Angular correlations were measured using two 4.4 cm dia × 5.08 cm NaI(Tl) detectors coupled with EMI 6097F photomultipliers. The spectra were recorded with a two-parameter (40×40 channels) pulse-height analyser. A time-to-amplitude converter was used as a fast

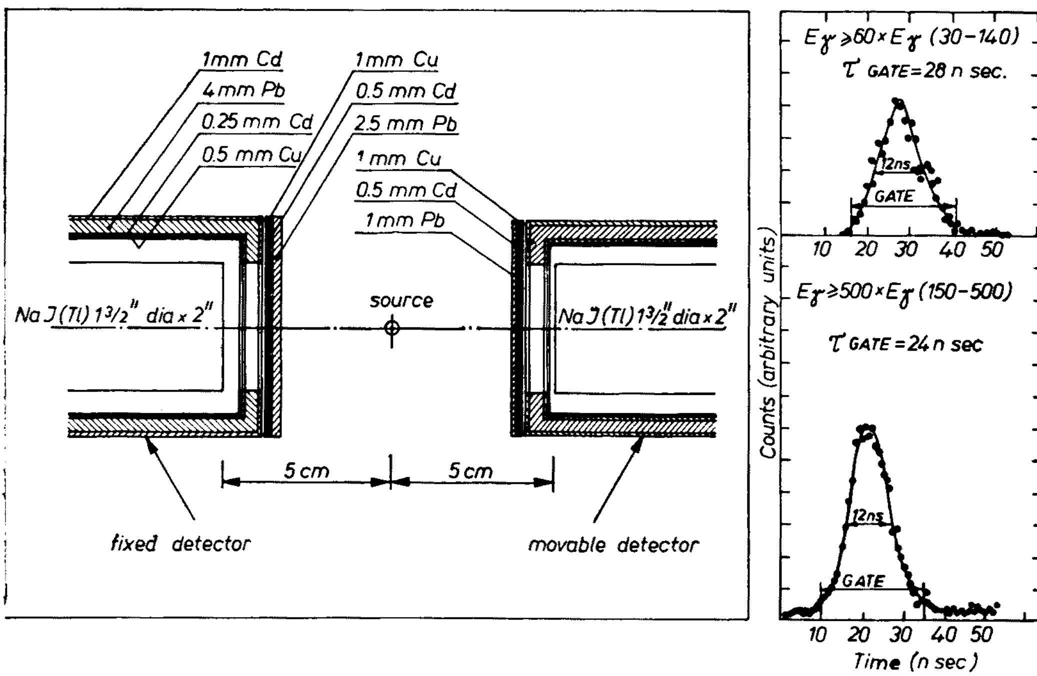

Fig. 1. Geometry of the $\gamma-\gamma$ directional correlation measurements and the spectra of the time-to-amplitude converter (on the right) for the given energy ranges

coincidence circuit. The experimental geometry, filters and the prompt coincidence curves obtained for the selected energy ranges are shown in Fig. 1. This figure also presents the half-width of the prompt curves and the width of the gates determining the resolving time of the arrangement.

3. *Results*

3.1. The 75 keV — 113.6 keV and 55 keV — 75 keV γ—γ correlations

The experiment was performed using the separated ^{125}Xe source. One axis of the two--parameter analyser was used for measuring the 0—140 keV energy range, while the other covered the 60—300 keV range. Because of the low-energies of the X and γ-rays, the filters normally placed in front of the detectors *cf.* Fig. 1 were removed. The coincidences were

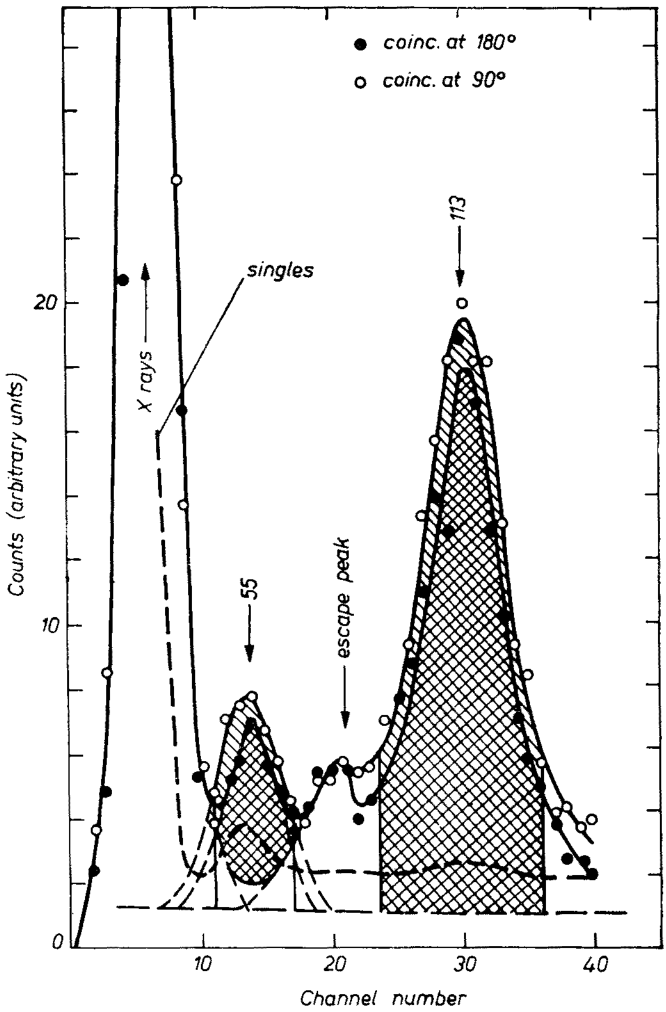

Fig. 2. Spectra coincident with the 75 keV transition. The dashed line at the bottom refers to the background coincidence

measured alternately at 90° and 180° positions at two hour intervals. The coincidence with the 75 keV transition for the two angles 90° and 180° as obtained from two-parameter spectra are shown in Fig. 2. The dashed line at the bottom refers to the background coincidences. The resulting values of anisotropy for the 75 keV — 113.6 keV and 55 keV — 75 keV $\gamma-\gamma$ cascades are given in Table 1. The corrections for the decay, position of the source, background coincidence and solid angle effects (*cf. e.g.* Ref. [8]) were taken into account.

The random coincidences under the 113.6 keV peak were obtained by normalizing them with respect to the 188.4 keV γ transition (the 113.6 keV transition is not coincident with the 188.4 keV γ-transition). A straight line was fitted to this background coincidence, and its extention gives the random coincidence under the 55 keV peak.

The total correction for the decay and for the position of the source was checked by the isotropic angular distribution of X-rays in coincidence with the 188.4 and 243.4 keV transitions. The accuracy of the correction factors was within 1%. The anisotropy of the 55—188.4 keV cascade, $A = 0.395 \pm 0.043$, was a check for the angular correlation measurement. This value is in very good agreement with the results obtained previously by Geiger and Brown [3].

3.2. Gamma-gamma correlations with the 188.4, 372 and 453.8 keV transitions

The $\gamma-\gamma$ directional correlation measurements for high-energy γ-rays had to be performed with the use of strong sources. The active natural Xe embedded in Al foil was used for this purpose. The small activities due to other xenon isotopes did not affect the results.

The measurements were done for three angles 90°, 135° and 180°. Corrections for the position of the source and for the decay were checked by the isotropic angular distribution of γ-rays in coincidence with the 243.4 keV transition (the spin of the 243.4 keV level is $\frac{1}{2}^+$).

The spectra coincident with the 188.4 keV peak measured at 90° and 180° are shown in Fig. 3. The dashed curve with the solid circle is the appropriately normalized 243.4 keV γ coincidence spectrum and presents the contribution to the 188.4 keV γ coincidence spectrum arising from the cross feeding by the 55 keV transition. A weak contribution due to the Compton scattering of 243.4 keV quanta was also accounted for. The subtraction of these components and random coincidences from the spectrum coincident with the 188.4 keV γ transition yields the net coincidence with the 188.4 keV transition (solid line with open circle in Fig. 3).

The contribution of the 243.4 keV γ coincidence spectrum was calculated from the experimentally determined relative attenuations of the 188.4 and 243.4 keV γ-rays in the filter, and the mean total intensity of the 55 and 243.4 keV transitions taken from Refs [1, 2]. The background coincidences were calculated from the count rates and resolving time, $\tau = 24$ ns.

The determine the area under the particular peaks adequately, the spectrum of net coincidence with the 188.4 keV γ transition was resolved to components by fitting standard lines. The correlation coefficients were obtained by the least-squares method and fitted to the correlation function $W(Q) = A_0 + A_2 P_2 (\cos Q)$ ($A_4 \equiv 0$, considering intermediate state spin is $\frac{3}{2}$, Fig. 6). Finally, after introducing appropriate corrections, the correlation coefficients for the 1193 keV — 188.4 keV, 902 keV — 188.4 keV and 992 keV — 188.4 keV $\gamma-\gamma$ cascades are given in Table I.

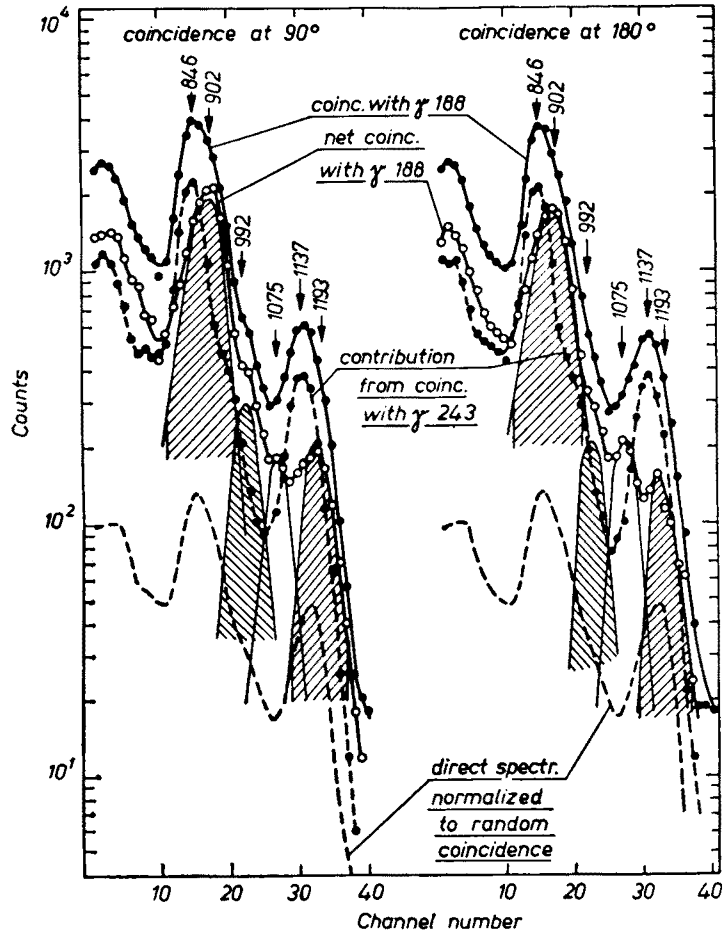

Fig. 3. Spectra coincident with the 188.4 keV transition

TABLE I

The results of the γ—γ directional correlation in ^{125}I

Cascade	The anisotropy (A) or the A_2 coefficients
55 — 75 keV	$A = -0.27 \pm 0.14$
75 — 113.6 keV	$A = -0.22 \pm 0.04$
636 — 372 keV	$A = -0.28 \pm 0.06$
636 — 454 keV	$A = 0.57 \pm 0.06$
726 — 454 keV	$A = 0.07 \pm 0.06$
1069 — 372 keV	$A = 0.17 \pm 0.07$
902 — 188.4 keV	$A_2 = -0.114 \pm 0.013$, $A_0 = 1$
992 — 188.4 keV	$A_2 = -0.250 \pm 0.090$, $A_0 = 1$
1193 — 188.4 keV	$A_2 = -0.250 \pm 0.032$, $A_0 = 1$

Fig. 4 shows the spectra coincident with the 636 and 726 keV transitions at 90° and 180°. The random coincidences under the 372 and 453.8 keV peaks were obtained by normalization of the background coincidences with the 846 keV γ-line. The calculation of the background coincidences in this way provided a partial explanation of the very weak coincidence

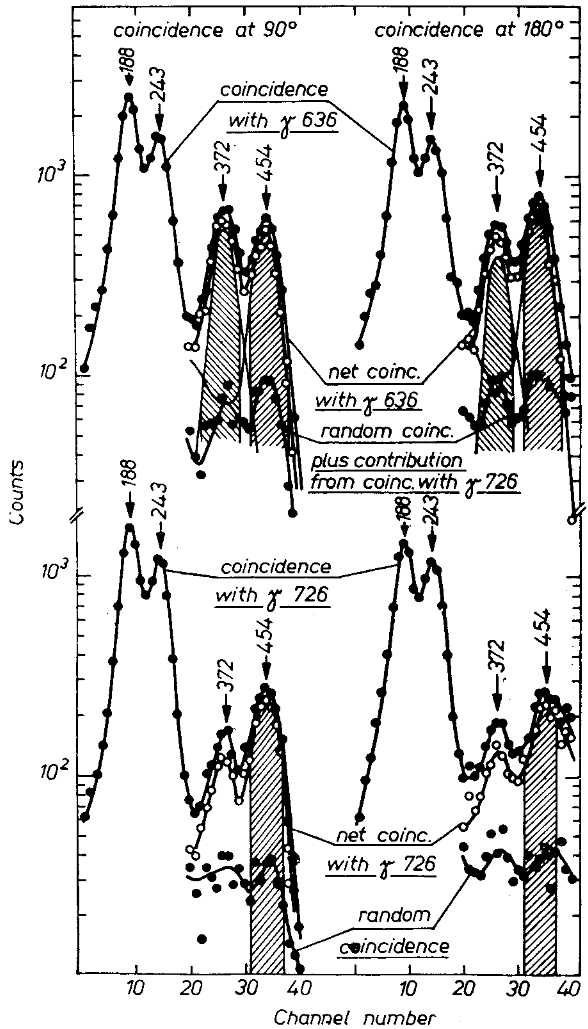

Fig. 4. Spectra coincident with the 636 and 726 keV transitions

with the Compton scattered γ-rays of energies higher than 726 keV being in cascades with the 373 and 453.8 keV transitions (Fig. 5).

The 453.8 keV peak seen in the spectrum coincident with the 726 keV transition at 180° (Fig. 4) is wider than that at 90°. This is due to the annihilation quanta from the weak position radiation feeding the 243.4 keV level. The 726 keV peak is covered in part by the sum of energies 243.4 and 511 keV, and this explains why the annihilation peak appeared in the coincidence spectrum.

For the correlations with the 372 and 453.8 keV γ-rays we calculated only the anisotropy because the statistics at 135° was poor. After introducing corrections for the position of the source, background coincidence and the solid-angle effect, and after accounting for the

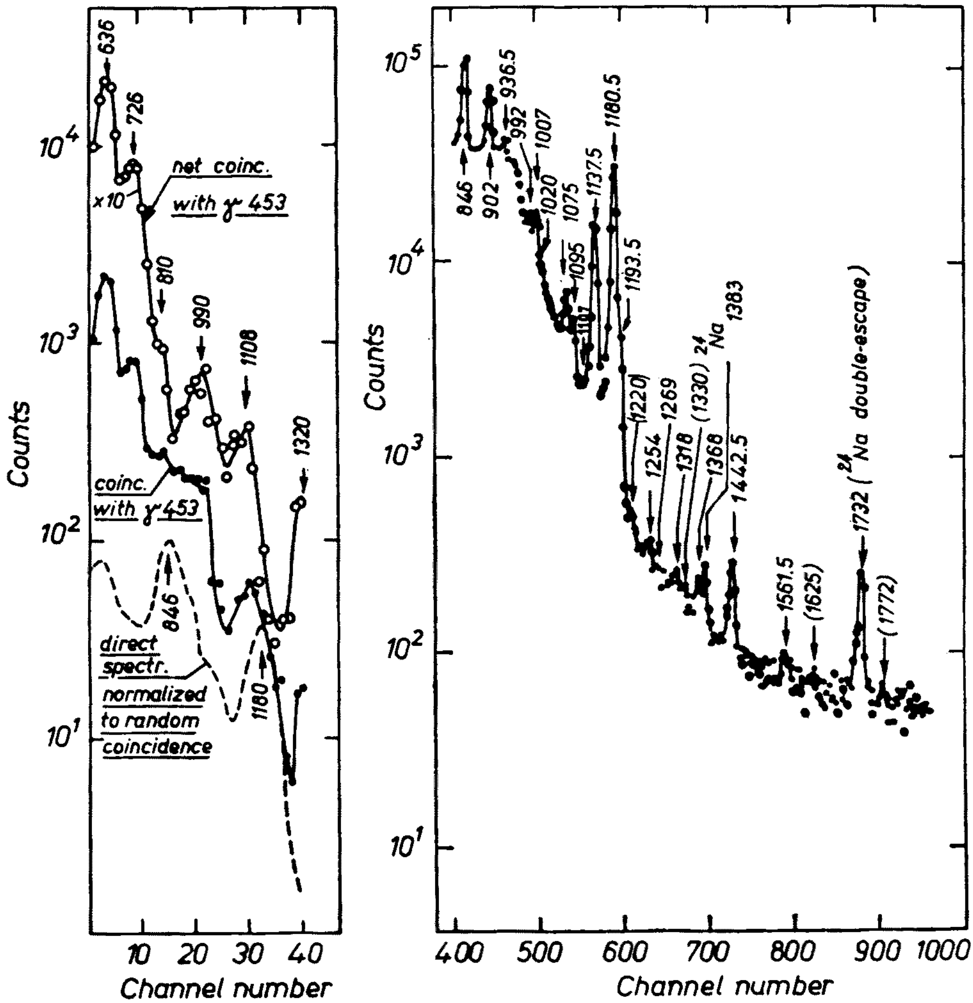

Fig. 5. Spectrum coincident with the 453.8 keV transition, and the high-energy part of the ^{125}Xe γ-ray spectrum from a natural gaseous source measured with a Ge(Li) detector

contribution of other transitions due to the Compton scattered γ-rays, the values of the anisotropy for the 636 keV — 454 keV, 636 keV — 372 keV, 726 keV — 453 keV and 1069 keV — 372 keV γ—γ cascades listed in Table I were obtained.

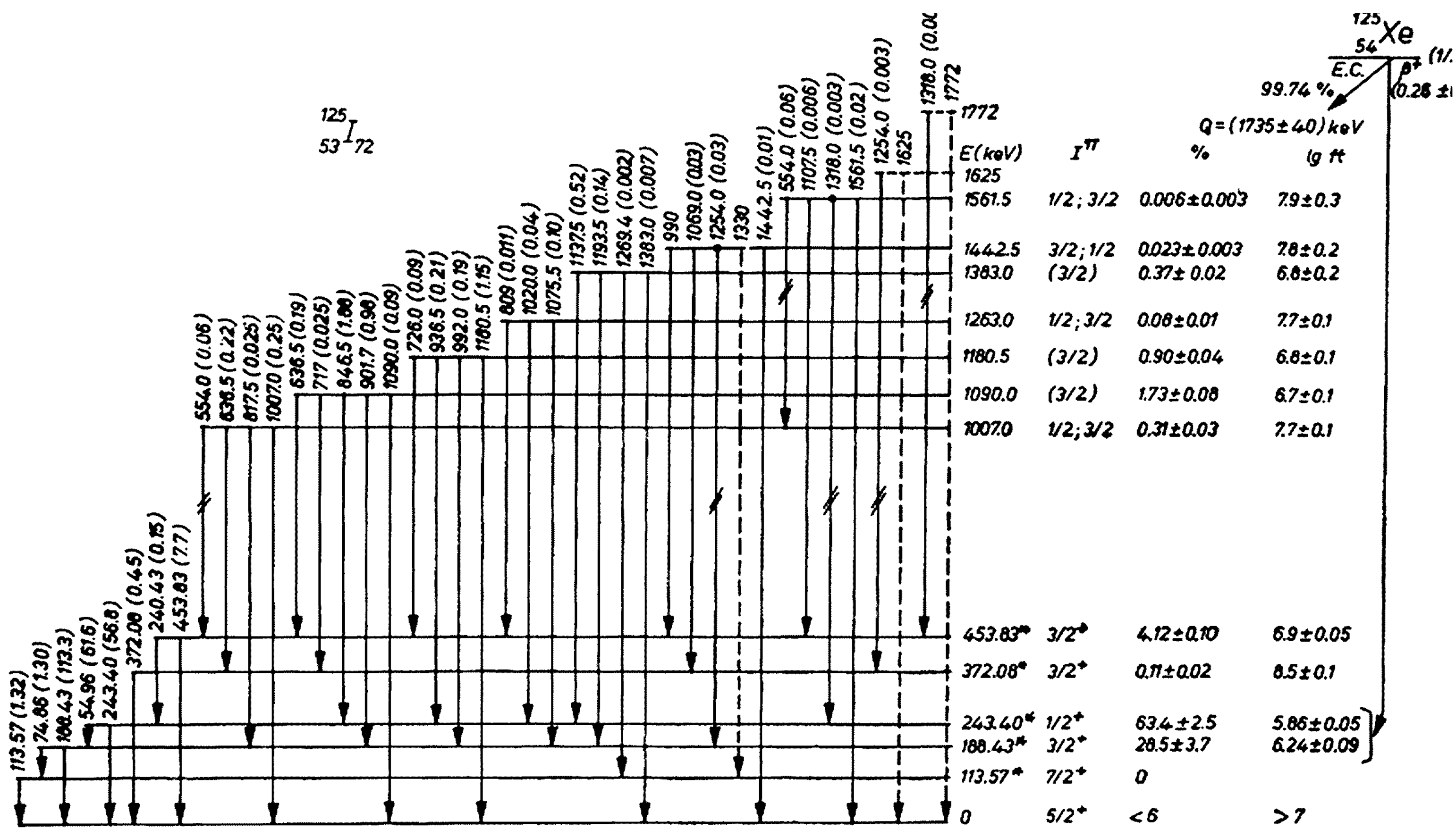

Fig. 6. Decay scheme of ^{125}Xe according to Ref. [2], the results obtained in the present work having been included. The energy values and the relative intensities (in paranthe given. The energies obtained with a β-spectrometer [1] are marked with an asterisk. Dubious transitions and levels are marked with dashed lines. Double hatches mark a tr which is in two positions; the intensity of such a transition is assigned to one level only marked with a full circle. According to the K.S. model prediction [11] the pa high-energy levels should be positive

3.3. Coincidence with the 453.8 keV transition

In this measurement we concentrated mainly on the very weak γ-transitions. The result is presented in the left-hand part of Fig. 5. Besides the 636 and 726 keV peaks already known [1, 2], new peaks appear at energies of 810, 990, 1108 and over 1320 keV. From this spectrum it follows that the 809.4 keV transition observed by Geiger [1] in the singles Ge(Li) γ spectrum does not feed the 372 keV level, as was expected from the sum energy coincidence, but feeds the 453.8 keV level. Besides the known 992 keV γ-transition from the 1180.5 keV level to the 188.4 keV one, a transition of a slightly different energy occurs between the 1442.5 and 453.8 keV levels. The intensity of this transition is close to that of 1107.5 keV.

The introduction of the new levels at 1625 and 1772 keV Fig. 6 is based on the coincidence experiment and the singles Ge(Li) γ-spectrum shown in Fig. 5. However, the very weak transitions suggested as depopulating these levels may be due to some impurities, as only the natural Xe source were used here.

In the spectrum coincident with the 726 keV γ transition, the 372 keV line is more intense than would follow from coincidence with the Compton scattered 1069 keV γ-rays (Fig. 4). It is more likely therefore, that it results from the 717 keV — 372 keV $\gamma-\gamma$ coincidence. Hence, we assumed that the 717 keV transition observed in the singles Ge(Li) γ-spectrum [1] feeds the 372 keV level.

The results described in this section are included in the decay scheme shown in Fig. 6.

4. *Assignment of spins and parities*

The spins and parities of the ground state, and of the second and third excited states of ^{125}I are $\frac{5}{2}^+$, $\frac{3}{2}^+$ and $\frac{1}{2}^+$, respectively [3, 9]. The electron capture E.C. feeding of the ground state [2] ($<6\%$), the shell — model considerations and the level systematics in this mass region [10] support the $\frac{1}{2}^+$ spin and the parity assignments for the ^{125}Xe ground state.

The possible spin and parity assignments for the levels populated by the E.C. decay of the $\frac{1}{2}^+$ state are $\frac{1}{2}^\pm$, $\frac{3}{2}^\pm$ and $\frac{5}{2}^\pm$. However, the possibility of negative parity for the low-energy levels of ^{125}I may be eliminated in view of the model considerations. The lowest negative-parity state predicted by the shell model is $h_{11/2}$, and it is expected to lie about 2 MeV above the ground state [11]. Furthermore, the E.C. from the $\frac{1}{2}^+$ to the $h_{11/2}$ state or any other level created by photon coupling with this state are highly forbidden. The negative-parity states arising from coupling of 3^- octupole states with positive-parity single-quasi-particle states should also lie at high energies, as is the case with the neighbouring doubly even nuclei, where they lie above 2 MeV [12–14]. Thus, the permissible assignments for the low-lying excited states of ^{125}I populated by ^{125}Xe decay are $\frac{1}{2}^+$, $\frac{3}{2}^+$ and $\frac{5}{2}^+$.

No E.C. transition takes place to the 113.6 keV level [2]. The multipolarity of the 113.6 keV transition is of the M1 type with a $(1.4\pm0.4)\%$ E2 admixture [1, 3], and the 74.9 keV one is of E2 type with less than 15% M1 admixture. These data and the spins of the ground and the second excited states restrict the number of possible spins for the 113.6 keV level to $\frac{7}{2}^+$ and $\frac{5}{2}^+$. The measured anisotropies A (75 keV — 113.6 keV) $= -0.22\pm0.04$ and A (55 keV — 75 keV) $= -0.27\pm0.14$ assign uniquely the spin $\frac{7}{2}^+$ to the 113.6 keV level, and determine the phase $\delta_{113.6} < 0$. The second possibility $\frac{5}{2}^{+}$ yields the 55 keV — 75 keV $\gamma-\gamma$ cascade anisotropy with a positive sign and, hence, it was rejected.

In view of the anisotropies found for the 636 keV — 372 keV, 1069 keV — 372 keV and 636 keV — 453 keV $\gamma-\gamma$ cascades, the spins $\frac{1}{2}$ of the 372 and 453.8 keV levels were excluded. The internal-conversion coefficients α_K of the 372 and 453,8 keV transitions point to an M1+E2 character of these transitions and, hence, to a positive parity for the 372 and 453.8 keV levels [1]. Since the log ft value calculated for the E.C. transition to the 453.8 keV state does not correspond to the second forbidden transition, the spin $\frac{5}{2}^{+}$ is rejected. Hence, only the spin and parity $\frac{3}{2}^{+}$ are possible for the 453.8 keV level. As no other data are available,

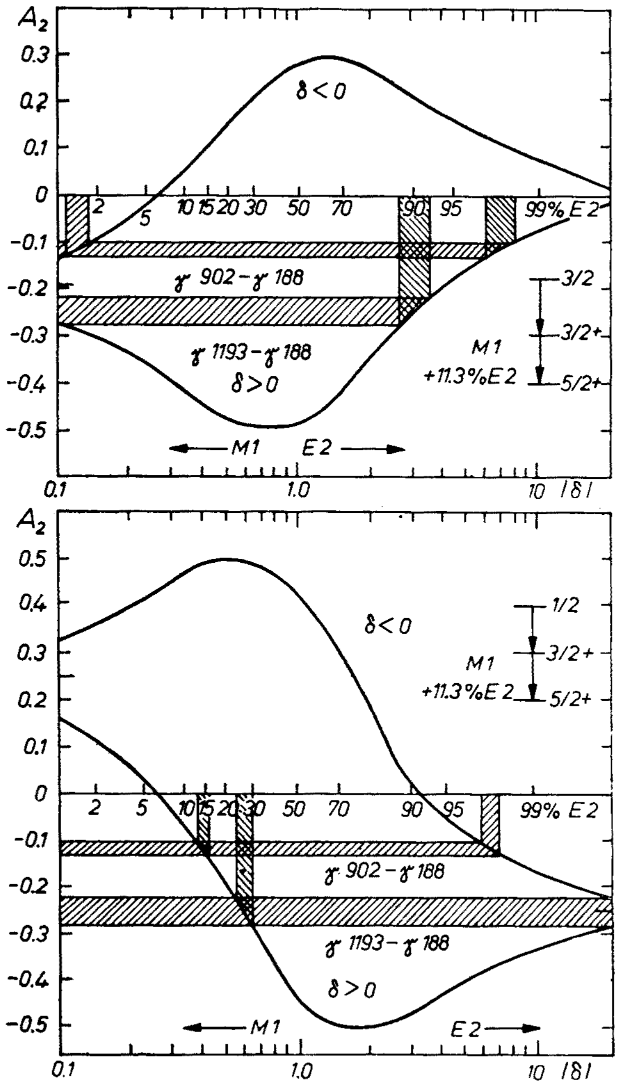

Fig. 7. The $\gamma-\gamma$ directional correlation analysis the 902—188.4 and 1193—188.4 keV cascades for spin sequences as given in the figure

except for the conversion coefficients, it is not possible to assign unambiguously the multipolarity mixing ratios to the γ-rays of interest.

The log ft value >9 for the E.C. transition to the 372 keV level indicates a second-forbidden transition and, hence, $\frac{5}{2}$ spin and positive parity for this level. However, many examples are known in this mass region of allowed transitions having extremely high log ft values [18–21]. It is therefore difficult to exclude the $\frac{3}{2}^+$ spin and parity of the 372 keV level. A possible explanation for the abnormally slow beta transitions is the strong phonon mixing in the initial and final state wave functions. However, systematic trends of low-lying levels of odd-mass iodine isotopes ^{125}I through ^{131}I support the $\frac{5}{2}^+$ spin and parity assignments for the 372 keV state [21]. This level corresponds to the 418 and 487 keV ones in ^{127}I and ^{129}I, respectively.

The E2/M1 mixing ratio for the 188.4 keV transition is known to be $+0.357 \pm 0.009$ [1]. The logft values restrict the possible spins of the 1090, 1180.5 and 1383 keV levels to $\frac{1}{2}$ and $\frac{3}{2}$. The analysis of the 902 keV — 188.4 keV and 1193 keV — 188.4 keV $\gamma-\gamma$ correlation (Fig. 7) shows that in the case of $\frac{1}{2}$ spin of the 1090 and 1383 keV levels, the 902 and 1193 keV transitions are M1 with an E2 admixture either about 15 and 25%, respectively, or more than 97% E2. Also the 992 keV transition should contain about 20% E2 admixture, ($A_2 = -0.25 \pm 0.09$ for the 992 — 188.4 keV cascade). The "pairing-plus-quadrupole-force" model predicts for the M1 transition between the $\frac{1}{2}$ and $\frac{3}{2}$ states (particularly for the l-forbidden M1 transition) a very low E2 admixture [22]. In fact, this is observed experimentally for iodine isotopes [4, 5] and for some other isotopes from this mass region [23], at least for the low-energy states. In this situation we assumed the $\frac{3}{2}$ spin of the 1090, 1180.5 and 1383 keV levels as more probable.

The 1269.4 keV transition to the 113.6 keV ($\frac{7}{2}^+$) level confirms the $\frac{3}{2}$ spin of the 1383 keV level, and the 1330 keV transition suggests the $\frac{3}{2}$ spin of the 1442.5 keV level. Both transitions are very weak and are placed in the decay scheme on the basis of the energy sum alone. The assignment should thus be considered as tentative.

The spins of other levels were derived from logft values.

The decay scheme of ^{125}Xe ^{125}I with the spins of levels as inferred here and in the previous assignments [3, 9] is shown in Fig. 6.

5. *Influence of eventual perturbation of angular correlations on spin assignments*

Since the 74.9 keV transition is a pure E2 transition, this suffices for calculating the anisotropy values for the $\gamma-\gamma$ cascades of interest. The following values were obtained:

$$A\,(75\text{ keV} - 113.6\text{ keV}) = -0.338 \pm 0.020 \quad \text{for } \delta_{113.6} < 0;$$
$$A\,(75\text{ keV} - 113.6\text{ keV}) = -0.068 \pm 0.020 \quad \text{for } \delta_{113.6} > 0;$$
$$A\,(55\text{ keV} - 75\text{ keV}) = -0.296 \pm 0.012 \quad \text{for } \delta_{55} > 0.$$

Comparing the experimental value of anisotropy with the one calculated from the complementary data (for $\delta_{113.6} < 0$) we find that the 75 — 113.6 keV correlation is attenuated with an attenuation factor of roughly 0.8. This attenuation may be caused by the Compton scattering of the cross-over γ-ray of 188.4 keV in the 180° position, not accounted for sufficiently in our experiment, and/or by the perturbation due to a randomly oriented static quadrupole interaction. For ^{127}I, Leisi [17] found the attenuation of the correlation for a similar cascade caused by quadrupole interaction.

Although the perturbation on this case has not been well established, it enabled us to draw some conclusion regarding the 55 keV — 188.4 keV $\gamma-\gamma$ correlation measured by Geiger and Brown [1, 3]. If we tentatively assume that a quadrupole interaction is responsible for this perturbation ($G_2 \approx 0.8$) we can calculate the perturbation of the 55 keV — 188.4 keV $\gamma-\gamma$ correlation and foresee its effect on the spin assignments. Using the perturbation factor calculated by Alder *et al.* [15] in the approximation of an axially symmetric field gradient, and finding a quadrupole coupling constant $eQV_{zz}/h \approx 280$ MHz, we obtained the attenuation factor $G_2 \approx 0.72$ for the 55 keV — 188.4 keV $\gamma-\gamma$ correlation. This value of perturbation can be explained by the change of sign of δ_{55} from positive to negative [1], what corresponds to a 0.75 attenuation. Therefore, a possible perturbation of the 55 keV — 188.4 keV $\gamma-\gamma$ correlation does not affect the assignment of the spins of the 188.4 and 243.4 keV levels.

In the above calculation we assumed the quadrupole moments of the same order in the ground state, 113.6 and 188.4 keV levels [16], and used $\tau_{188.4} = 0.47$ ns and $\tau_{113.6} = 0.88$ ns from Ref. [4].

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