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GAMMA-GAMMA ANGULAR CORRELATION IN THE DECAY OF ^{76}As *

Cibele Bugno Zamboni and Rajendra Narain Saxena

ABSTRACT

The directional correlations of coincident gamma transitions have been measured in ^{76}Se following the β^- decay of ^{76}As ($t_{1/2}$ = 26.4h)using a spectrometer consisting of two large volume hyperpure Ge detectors.The measurements were carried out for 24 gamma cascades,17 of these for the first time. A spin assignment of 3^+ for the 2363 keV level is suggested and many previous spin assignments were confirmed. The multipole mixing ratios,δ,for 16 transitions were extracted from the present results.

CORRELAÇÃO ANGULAR GAMA-GAMA NO DECAIMENTO DO ^{76}As

RESUMO

A correlação angular direcional das transições gamas no núcleo do ^{76}Se foram medidas a partir do decaimento β^- do ^{76}As ($t_{1/2}$ = 26.4h) utilizando-se um espectrometro gama constituído por dois detectores de germânio hiperpuro. As medidas foram realizadas para 24 cascatas gama, 17 das quais pela primeira vez. Um valor de spin 3^+ foi sugerido para o nível a 2363 keV e foram confirmados valores de spins para outros níveis medidos anteriormente. As misturas multipolares δ para 16 transições gama foram extraídas dos presentes resultados.

INTRODUCTION

The even-even isotopes of selenium (Z=34, N=38-48) are situated rather far away from both the proton and neutron closed shells of 28 and 50, respectively and it has been difficult to describe their low lying level structure in terms of simple models. Traditionally these isotopes have been treated as nearly spherical and attempts made to describe them by vibrational model. Qualitatively this seems reasonable as all of them show a 0^+, 2^+, 4^+ triplet at nearly twice the energy of the first excited state 2^+. In every one of these isotopes a 3^- state has also beem identified. However several recent investigations[1,3] have revealed that many

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of the individual properties deviate considerably from the pure vibrational picture and their structure is much more complex.

A large number of investigations have been made in the past to determine the level structure of ^{76}Se through β^- decay of ^{76}As and β^+/Ec decay of ^{76}Br. These are summarised in nuclear data sheets[4]. The earlier studies were made with the use of NaI(Tl) detectors while the more recent investigations utilized the Ge(Li) detectors for singles and a combination of NaI(Tl) and Ge(Li) detectors for gamma-gamma coincidence measurements. Included among these studies are the low temperature nuclear orientation[5,6] and angular correlation work[7-9]. All of these studies have contributed to establish reasonably well the level scheme of ^{76}Se with spin and parity assignments made to many of the levels.

Recently several nuclear reaction studies have also been carried out in order to obtain additional information regarding the collective properties of the levels of ^{76}Se. These include ^{76}Se (n,n')[10], ^{76}Se (p,p')[11], ^{74}Ge (α,2nγ)[3] and $^{71}Ga(^{7}Li,2n\gamma)$[12] among the more recent studies.

In the previous gamma-gamma angular correlation studies by Kaur et al[9] seven relatively strong gamma cascades were measured and the multipole mixing ratios of five transitions determined. The present study was undertaken with a view to measure the angular correlations of a large number of additional gamma cascades in ^{76}Se including transitions of intermediate intensities using a spectrometer consisting of two germanium detectors in order to better define the spins of some of the levels and to determine the multipole mixing ratios for as many gamma transitions as possible to further elucidate the level structure of ^{76}Se. The levels and transitions in ^{76}Se were studied by measuring a total of 24 gamma cascades populated through the β^- decay of ^{76}As.

Results of a recent nuclear orientation study[6] of ^{76}As decay were published during the course of our work and although the mixing ratios for a large number γ-transitions in ^{76}Se were determined, they were derived from the A_2 distribution coefficients which in many cased suffered from large statistical errors. Nevertheless these results are quite helpful for the purpose of comparison.

Experimental

The radioactive sources of ^{76}As were prepared by neutron irradiation of 99.99% pure arsenic metal in the IEA-R1 reactor at São Paulo . Approximately 10 mg of arsenic metal were irradiated in a flux of 2 x 10^{13} n/cm^2 s for 3 hours. The resulting source of ^{76}As was dissolved in ~ 0.5 mL of 6N HNO_3. A couple of drops of this solution (~ 20 μCi) were transferred to a lucite container which was then mounted at the centre of the gamma-spectrometer for measurements. The source dimension was 2.5 mm ϕ x 5 mm.

The γ-γ spectrometer consisted of two hyperpure germanium detectors. The fixed and the movable detectors had volumes of 115 cm^3 and 89 cm^3 respectively. The γ-γ coincidences were recorded using a standard low noise fast coincidence system and a pulse height analyser. The measurements were carried out at angles of 90°, 120°, 150° and 180°. Angular position of the movable detector was changed every four hours and the coincidence spectrum observed through the 115 cm^3 germanium detector was stored in a 2048 channel subgroup of the analyser memory for each angle. Counting from a single source was for a period of 16 hours after which a new source with approximately same initial activity was used. A total of 60 sources were used for the entire experiment.

The single channel analyser (SCA) windows were set to accept photopeaks (559 + 563) and (1212 + 1216 + 1228) keV as seen in the 89 cm^3 germanium detector. The intensities of the coincident gamma rays were measured from the 115 cm^3 detector spectra recorded at various angles and corrected for the source decay during the measurement and for chance coincidences. The chance coincidences were determined separately for each gate setting by introducing a delay of 1 μs in the pulses from one of the detectors before reaching the coincidence unit and recording the coincidence spectrum. The effects of Compton scattered radiation of higher energy gamma rays included in the window setting were also determined for both gates by setting windows at slightly higher energies and recording the coincidence spectra. These corrections were applied in all cases before calculating the A_{kk} coefficients. The angular correlation coefficients A_{kk} were determined by the least square fitting procedure in the usual manner.

Results

The γ-ray spectrum in the decay of ^{76}As obtained with the 115 cm^3 germanium detector is shown in Fig. 1(a). The γ-γ coincidence spectra obtained with the (559 + 563) keV and (1212 + 1216 + 1228) keV gate settings are shown in figures 1(b) and 1(c) respectively. These spectra represent only partial measurements and have not been corrected for the Compton contribution and accidental coincidences. The directional correlation coefficients A_{kk} corrected for the finite solid angle effects are given in Table I. The solid angle corrections were determined by numerical calculations using a computer code[13]. The A_{kk} values for the gamma cascades measured by Kaur et al[9] and Nagahara[8] are included in this table for comparison.

The multipole mixing ratios for the γ-transition together with the spin sequences consistent with the observed angular correlation data, decay properties and the results of other studies are presented in Table II. The mixing ratios were determined by the usual X^2 analysis as a function of δ for the mixed transition. The convention of Becker and Steffen[14] has been adopted for the definition of mixing ratio. The results of mixing ratios obtained in this study are compared with the previous angular correlation results of Kaur et al[9] and with the results of nuclear orientation studies of Barclay et al[5] and Subber et al[6]. A partial level scheme of ^{76}Se taken from the work of Kaur et al[9] is shown in figure 2. Only γ-transitions of interest in this study are shown. The spin and parity assignments in this figure are consistent with the present results and other available data.

The ground state spin of ^{76}As is established as 2^- from the atomic beam measurements[15]. The spin and parity assignments to the levels in ^{76}Se and the results of present angular correlation measurements are discussed below.

The 1122 keV level: Previous angular correlation results[8,9] of the 563-559 keV cascade originating from this level established the 0^+-2^+-0^+ sequence. Support for the 0^+ assignment for this level was subsequently provided by the nuclear orientation study[5] which indicated a vanishing anisotropy for the 563 keV γ-ray as expected for a transition from a 0^+ state. The present angular correlation results for the 563-559 keV cascade are in agreement with the previous measurements of Kaur et al[9] and Nagahara[8].

The 1216 keV level: 2^+ assignment for this level is well known from Coulomb excitation[16]. The directional correlation of the 657-559 keV cascade[8,9] also supports this assignment. The present result for this cascade gives $\delta(657) = 5.26 \pm 0.50$ in good agreement with most of the earlier reported values. The value obtained by Subber et al[6] is some what smaller; $\delta = 4.15 \pm 0.2$.

The 1330 keV level: Decay studies limited the spin and parity of this level to 0^+, 3^+ and 4^+. The 4^+ assignment was established from the Coulomb excitation[1] and $(\alpha,2n\gamma)$ reaction studies[3]. The angular correlation of the 772-559 keV cascade measured for the first time in the present study is consistent with the 4^+-2^+-0^+ sequence.

The 1689 keV level: This level was tentatively assigned 3^+ from the beta decay and reaction studies[8,9,3]. The angular correlation of the 1130-559 keV cascade measured by Kaur et al[9] was unable to distinguish between 2^+ and 3^+. A recent nuclear orientation study by Subber et al however shows that the A_2 coefficient for the 740 keV transition feeding this level is only consistent with the 3^+ assignment. The present result for the 1130-559 keV cascade shows a clear indication of the 3-2-0 sequence thus firming the assignment made by Subber et al. The present $\delta(1130)=1.08 \pm 0.10$ is in agreement with the values obtained by Subber et al, $0.57 < \delta < 3.55$, and Kaur et al, $0.5 < \delta < 1.8$

The 1787 keV level: A spin and parity of 2^+ for this level was established from the angular correlation result of the 1228-559 keV cascade[8]. Angular correlations of three cascades 1228-559 keV,571-1216 keV and 665.(563)-559 keV were measured in the present work, the last two for the first time. The mixing ratios of the 1228 keV and 571 keV transitions are given in Table 2 and they agree well with the values obtained by Subber et al[6] and Barclay et al[5].

The 1881 keV level: The level was proposed from the observed coincidences between the 665 keV (weaker component of a doublet at 665 keV[8]) and the 1216 keV gamma rays and later confirmed by Kaur et al[9] from their observation of a weak 1881 keV transition from this level to the ground state. These studies limit the spin and parity of this level to 1^+ or 2^+. The present angular correlation result of the 665-1216 keV cascade is consistent with these assignments but is unable to eliminate either possibility. The mixing ratio $\delta(665)$ for either choice of the spins are given in Table 2.

The 2363 keV level: Decay studies[8] limited the spin and parity of this level to 2^+, 3^+ or 4^+. The nuclear orientation results of Subber et al[6] are inconsistent with the 4^+ assignment leaving the possible values as 2^+ or 3^+. The present angular correlation results of the 575-1228 keV cascade were analysed for both spin values and using the already determined $\delta(1228) = -0.73$. A much better fit was obtained with the 3-2-2 sequence. We therefore suggest a 3^+ spin for this level. Our value for the mixing ratio $\delta(575) = -1.18 \pm 0.33$ does not agree with the value obtained by Subber et al $\delta(575) = -13.8 < \delta < -3.7$.

The 2429 keV level: This level is known to have a spin and parity of 3^- [17]. Five gamma cascades 1870-559 keV, 1212-1216 keV, 1212-657 keV, 1212-(657)-559 keV and 740-(1130)-559 keV originating from this level were measured in the present study all of them for the first time. The observed predominantly dipole character of the 740 keV, 1212 keV and 1870 keV transitions from this level to known positive parity states below 3^+, 2^+ and 2^+ respectively is consistent with the 3^- assignment for the 2429 keV level. The results of mixing ratios are given in Table II.

The 2655 keV level: Previous decay studies[8], the angular correlation measurements[9] and the nuclear orientation studies[5,6] are consistent with the 1^- assignment for this level. Out of five gamma cascades 2096-559 keV, 1439-1216 keV, 867-1228 keV, 1439-(657)-559 keV and 867-(1228)-559 keV measured in the present work only the first two were measured previously by Kaur et al. The mixing ratios for the 867 keV, 1439 keV and 2096 keV transitions given in Table II agree with the values of previous angular correlation[9] and nuclear orientation work[5,6].

The 2670 keV level: The spin and parity of this level as 2^- is established from the decay studies[8], angular correlation measurements[9] and nuclear orientation studies[5-6]. Three direct and two 1-3 correlations were measured in the present work involving transitions which de-excite this level i.e. 2111-559 keV, 1453-1216 keV, 882-1228 keV, 1453-(657)-559 keV and 882-(657)-559 keV cascades. All three transitions 2111 keV, 1453 keV and 882 keV are predominantly dipole in character. This is in agreement with the previous results[5,6,9].

Discussion

Strongly deformed structures are not expected in the A=70-80 region because, when both N and Z are less than 50, N and Z are never very far from a magic number (Z=28, N=50 especially if N=40 is also considered magic). It is therefore quite reasonable to ascribe collective features to ^{76}Se and assume that the excited states arise as a result of surface vibrations. In fact some of the basic features of the low lying levels of ^{76}Se seem to conform to the predictions which follow from the theoretical considerations of vibrational model. The 559 keV level would correspond to one-phonon state and levels at 1122 keV, 1216 keV and 1331 keV may be interpreted as the members of two-phonon triplet $(0^+, 2^+, 4^+)$. The average energy of the two-phonon state gives a ratio of 2.2 with the energy of one-phonon state, comparing not too badly with the predicted value of 2.0. The gamma transition from the 2_2^+ state at 1216 keV to the first excited 2_1^+ state is predominantly E2 in character and B(E2) ratio[6] of the cascade to crossover transition from this level is 36.7 in agreement with the general predictions of the harmonic vibration model. A possible three-phonon character of the 3^+, 2^+ and 4^+ levels at 1689, 1787 and 2026 keV was earlier ponited out by Nagahara[8], however in the Coulomb excitation studies Barrett et al[1] found no evidence for the population of 1689 keV level and found very weak population for the 1787 and 2026 keV levels indicating that these states are probably not collective. The spin and parity of 3^- for the 2429 keV level is well established and its collective nature is reflected by the B(E3) value of 16.6 Wu[1] for the ground state transition. This state therefore might be the one--octupole-phonon state.

On the other hand despite the fact that a 0^+, 2^+, 4^+ triplet of states has been identified in ^{76}Se their charactersties certainly do not agree whith the vibrational model since the transition rates to the first 2^+ state are much smaller than predicted. A similar situation is found in other even-selenium nuclei with A=72-82. The only exceptions are the 0^+ and 4^+ states in ^{74}Se. Moreover the measured large and negative static quadrupole moments of the first 2^+ excited states in $^{76-82}$Se isotopes[2] clearly indicate a prolate deformation for these nuclei. A possible oblate to prolate shape transition at N=40,42 was suggested earlier by Ardouin et al[18], this was however not confirmed[2]. In a study of (α,2nγ) reaction Matsuzaki and Taketani[3] have identified the existence of band structure in ^{76,78}Se. Four well defined bands were observed by these authors, the ground state band a positive parity γ-band based on the second 2^+ state, a negative parity octupole band bult on a 3^- state and a band buit on high lying J=4 state. While Delaroche et al suggested a significant triaxial deformation for the ^{76,78,80}Se isotopes from their (p,p') reaction studies[11], Hamilton[20] proposed from the experimental data that ^{72,74}Se isotopes have a nearly spherical ground state and a low-lying well deformed band built on the second excited 0^+ level indicating a shape coexistance in these nuclei.

Many theoretical calculations have been carried out in the past to account for the observed proporties of even-selenium isotopes, however no single model is able to describe simultaneously all the data. The observed crosssover transition rates and non-zero values of the quadrupole moment of the first 2^+ state have been considered to result from anharmonic vibrations[19]. The rotation-vibration model and asymmetric rotation model has been used by Delaroche et al[11] to describe the properties of $^{76-82}$Se nuclei. These authors found that the structure of ^{82}Se is quite different from that of the lighter isotopes and that the 3^- levels of ^{76,78,80}Se do not behave as simple vibrational octupole states. Matsuzaki and Taketani[3] carried out calculations using the proton-neutron interacting boson model (IBM-2) and found reasonable agreement with the level energies and B(E2) ratios for some intraband transitions between γ- and ground state bands for ^{76,78}Se. The IBM-1 has been applied to ^{74,76}Se[20], however the very low energy of the second 0^+ state and E2 strengths of the transitions from the second 2^+ state to the ground state band are difficult to explain.

Recently Subber et al have calculated the level energies and transition rates to describe the collective level structure of the selenium isotopes with A=72-82 using the dynamic deformation model (DDM) and interacting boson model (IBM-1 and IBM-2). The results were compared with the available experimental results. A general satisfactory agreement with the experimental data was obtained in all three models, in particular the idea of shape coexistence in this region is supported by DDM. The model predicts however that ^{78}Se is more γ-soft and more deformed than ^{76}Se in disagreement with the observed $B(E2, 2_1^+ \longrightarrow 0^+)$ values and $Q(2_1^+)$ values in these isotopes. Moreover, DDM does not reproduce the signs of $Q(2_1^+)$. These authors have also calculated the multipole mixing ratios $\delta(E2/M1)$ for some of the γ-transitions in $^{72-80}Se$.Agreement with the experimental results is marginal. Especially in the case of $^{76,78}Se$ where more data are available in general the observed transitions are predominanlly M1, (with the exception of $2_2^+ \longrightarrow 2_1^+$ transition)while the calculated values show predominance of E2-

In the present work angular correlations of 24 gamma cascades were measured, 17 of them for the first time. Multipole mixing ratios of 16 transitions were determined. Results are generally in good agreement with the values obtained in the recent nuclear orientation work[6]. In several cases where only upper and lower limits were given for the δ values by Subber et al, the present results were able to define these values. A spin assignment of 3^+ for the 2363 keV level was made and many previous spin assignments were confirmed.

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TABLE I - Results of Directional Correlation Measurements of Transitions in ^{76}Se

Energy Level (keV)	Gamma-cascade (keV)	Gating Transition (keV)	A_{22}	A_{44}
1122	563-559	559	0.234 ± 0.056	1.108 ± 0.095
			0.257 ± 0.092	1.148 ± 0.145*
			0.25 ± 0.05	1.09 ± 0.09**
1216	657-559	559	-0.225 ± 0.015	0.309 ± 0.030
			-0.220 ± 0.007	0.275 ± 0.010*
			-0.185 ± 0.012	0.305 ± 0.02**
1330	772-559	559	0.105 ± 0.019	-0.014 ± 0.030
1689	1130-559	559	0.240 ± 0.019	-0.057 ± 0.032
			0.255 ± 0.054	0.036 ± 0.078*
			-0.1 ± 0.1	0.1 ± 0.1**
1787	571-1216	1216	0.145 ± 0.022	0.048 ± 0.035
	665-(563)-559	559	-0.013 ± 0.006	0.046 ± 0.010
	1228-559	559	0.471 ± 0.007	0.097 ± 0.011
			0.463 ± 0.006	0.102 ± 0.009*
			0.462 ± 0.016	0.150 ± 0.029**
1880	665-1216	1216	-0.096 ± 0.042	0.021 ± 0.065
2363	575-1228	1228	0.352 ± 0.031	0.009 ± 0.052
	740-(1130)-559	559	0.143 ± 0.020	-0.033 ± 0.03
	1212-657	1212	-0.011 ± 0.008	0.020 ± 0.013
	1212-(657)-559	559	-0.051 ± 0.008	0.081 ± 0.012
2429	1212-1216	1212	-0.058 ± 0.008	0.013 ± 0.013
	1870-559	559	0.050 ± 0.040	0.008 ± 0.064
	867-1228	1228	0.133 ± 0.023	-0.003 ± 0.038
	867-(1228)-559	559	-0.095 ± 0.018	-0.016 ± 0.027
2655	1439-(657)-559	559	-0.028 ± 0.019	0.010 ± 0.031
	1439-1216	1216	-0.273 ± 0.039	0.012 ± 0.063

(cont.)

TABLE I - (continuation)

Energy Level (keV)	Gamma-cascade (keV)	Gating Transition (keV)	A_{22}	A_{44}
			-0.377 ± 0.075	0.067 ± 0.106*
	2096-559	559	-0.258 ± 0.012	-0.034 ± 0.019
			-0.200 ± 0.009	-0.040 ± 0.013*
	882-1228	1212	0.004 ± 0.034	0.002 ± 0.055
	882-(1228)-599	559	0.010 ± 0.025	-0.080 ± 0.040
2670	1453-(657)-559	559	-0.046 ± 0.035	-0.048 ± 0.053
	1453-1216	1216	0.223 ± 0.041	-0.040 ± 0.067
	2111-559	559	0.320 ± 0.016	-0.047 ± 0.026
			0.259 ± 0.008	0.067 ± 0.013*

* values from ref. 9

** values from ref. 8

TABLE II - Multipole Mixing Ratios of γ-Transitions in ^{76}Se

Level (keV)	Mixed Transition (keV)	$I_i^\pi - I_f^\pi$	Mixing Ratio δ this work	Mixing Ratio δ Previous work
1216	657	$2^+ - 2^+$	5.26 ± 0.50	4.15 ± 0.20 a) 5.2 ± 0.2 b)
1330	772	$4^+ - 2^+$	0.01 ± 0.01	
1689	1130	$3^+ - 2^+$	1.08 ± 0.10	0.57 < δ < 3.55 a) 0.5 < δ < 1.8 c)
1787	571	$2^+ - 2^+$	0.13 ± 0.12	>1.37 or -0.13 ± 0.34 a)
	1228	$2^+ - 2^+$	-0.54 ± 0.10	-0.53 ± 0.08 a) -0.49 ± 0.05 b)
1880	665	$1^+ - 2^+$ $2^+ - 2^+$	-0.13 ± 0.09 0.49 ± 0.06	
2363	575	$3^+ - 2^+$	-1.18 ± 0.35	0.07 ± 0.10 or -13.8<δ<-3.7 a)
2429	740	$3^- - 3^+$	-0.21 ± 0.12	0.08 ± 0.16 a)
	1212	$3^- - 3^+$	0.025 ± 0.02	0.11 ± 0.10 a) -5.7 < δ < 0.12 b)
	1870	$3^- - 2^+$	0.17 ± 0.03	0.002 ± 0.076 a)
2655	867	$1^- - 2^+$	0.08 ± 0.07	$0.38 \pm {}^{0.57}_{0.28}$ a)
	1439	$1^- - 2^+$	0.01 ± 0.03	-0.02 ± 0.10 a) $0.015 \pm {}^{0.02}_{0.015}$ c)
	2096	$1^- - 2^+$	0.02 ± 0.06	0.002 ± 0.081 a)
2670	882	$2^- - 2^+$	0.26 ± 0.15	-0.24 < δ < 5.3 a)
	1453	$2^- - 2^+$	0.05 ± 0.02	-0.11 ± 0.12 a)
	2111	$2^- - 2^+$	-0.09 ± 0.02	-0.02 ± 0.16 a) 0.0025 ± 0.0025 c)

a) values from ref. 6

b) values from ref. 5

c) values from ref. 9

FIGURE 1

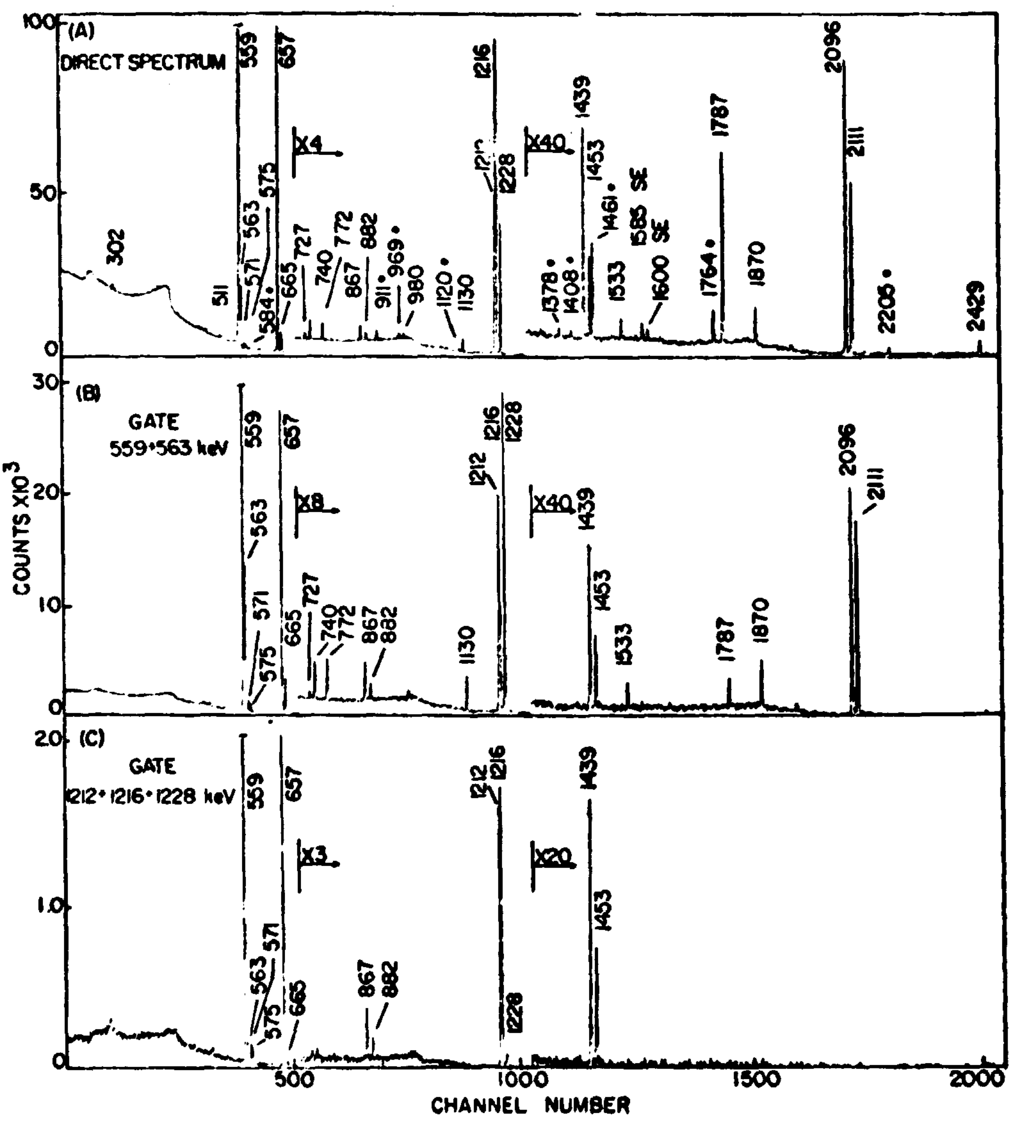
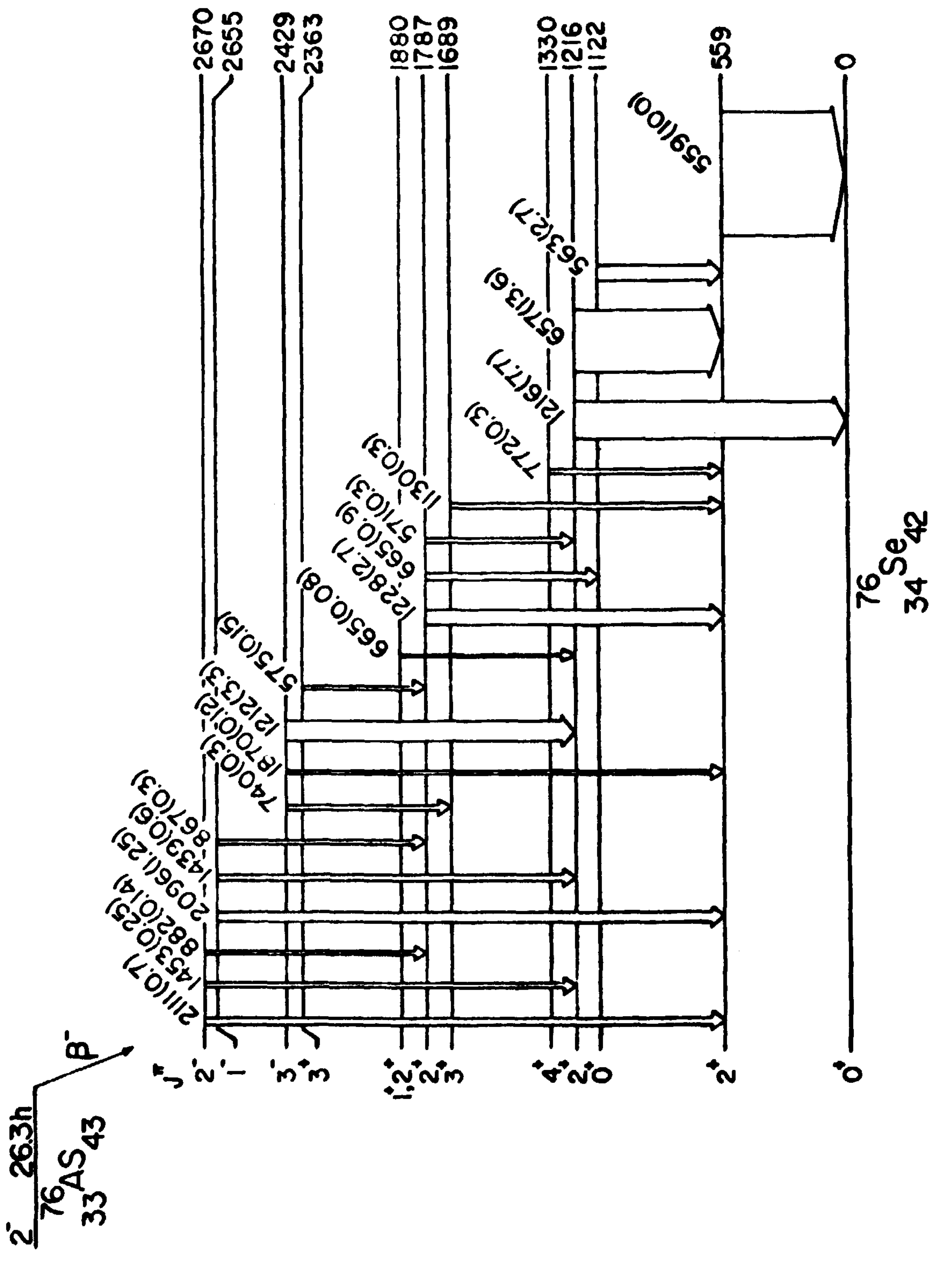

(A)
DIRECT SPECTRUM
(B)
GATE
559+563 keV
(C)
GATE
1212+1216+1228 keV
COUNTS X10^3
CHANNEL NUMBER
X4
X40
X8
X40
X3
X20
SE
SE

FIGURE 2


2⁻ 26.3h
$^{76}_{33}As_{43}$
β⁻
$^{76}_{34}Se_{42}$
J^{π}
2670
2655
2429
2363
1880
1787
1689
1330
1216
1122
559
0
559(100)
563(2.7)
657(13.6)
1216(7.7)
772(0.3)
1130(0.3)
571(0.3)
665(0.9)
1228(2.7)
665(0.08)
575(0.15)
1212(3.3)
1870(0.12)
740(0.3)
867(0.3)
1433(0.6)
2096(1.25)
882(0.4)
1453(0.25)
2111(0.7)