PHYSICAL REVIEW C VOLUME 39, NUMBER 6 JUNE 1989

Gamma-gamma angular correlations in the decay of ^{76}As

Cibele B. Zamboni and R. N. Saxena
Instituto de Pesquisas Energéticas e Nucleares, Comissão Nacional de Energia Nuclear, 05499 São Paulo, Brazil
(Received 22 August 1988)

The directional correlations of coincident gamma transitions have been measured in ^{76}Se following the β^- decay of ^{76}As ($t_{1/2}=26.4$ h) 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.

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 the 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 been identified. However several recent investigations[1-3] have revealed that many 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 summarized in Ref. 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 low-temperature nuclear orientation[5,6] and angular correlation work.[7-9] All of these studies have contributed to establishing 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$(\alpha,2n\gamma)$,[3] and ^{71}Ga(^{7}Li,$2n\gamma$) (Ref. 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 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 of γ transitions in ^{76}Se were determined, they were derived from the A_2 distribution coefficients which in many cases 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 2×10^{13} n/cm^2 s for 3 h. The resulting source of ^{76}As was dissolved in $\sim$0.5 ml of 6N HNO_3. A couple of drops of this solution ($\sim$20 μCi) were transferred to a lucite container which was then mounted at the center of the gamma spectrometer for measurements. The source dimension was 2.5×5 mm.

The γ-γ spectrometer consisted of two hyperpure germanium detectors. The fixed and the movable detectors had volumes of 115 and 89 cm^3, respectively. The γ-γ coincidences were recorded using a standard low-noise fast-coincidence system and a pulse-height analyzer. The measurements were carried out at angles of 90°, 120°, 150°, and 180°. The angular position of the movable detector was changed every 4 h and the coincidence spectrum observed through the 115-cm^3 germanium detector was stored in a 2048 channel subgroup of the analyzer memory for each angle. Counting from a single source was for a period of 16 h after which a new source with approximately the same initial activity was used. A total of 60 sources were used for the entire experiment.

The single channel analyzer (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-squares 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 background lines seen in this spectrum are due to natural radioactice sources ^{208}Tl, ^{228}Ac, ^{214}Bi (decay products of ^{238}U and ^{232}Th), and ^{40}K usually present in the environment. The γ-γ coincidence spectra obtained with the (559+563) keV and (1212+1216+1228) keV gate settings are shown in Figs. 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 transitions 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

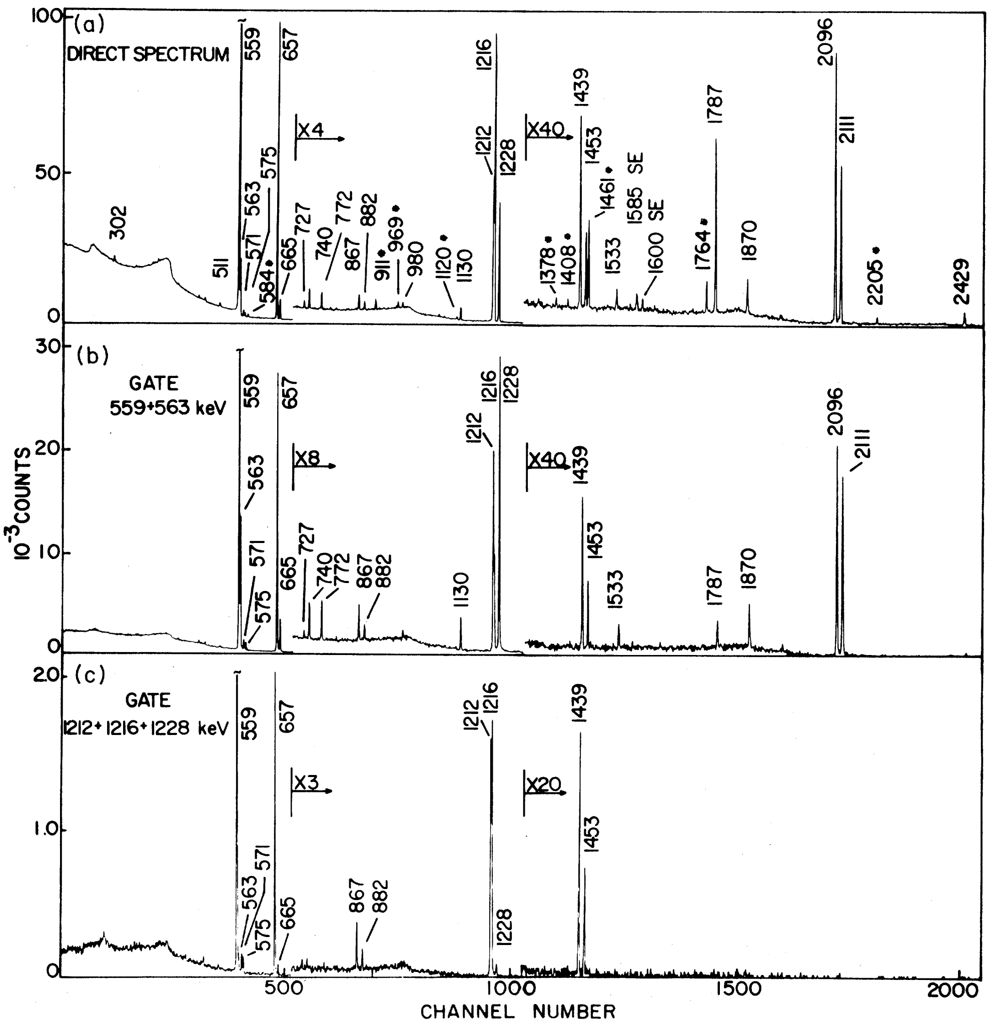

FIG. 1. Direct γ-ray spectrum up to 2.45 MeV in the decay of ^{76}As observed with Ge HP detector (a) and γ-ray spectra in coincidence with photopeaks 559+563 keV (b) and 1212+1216+1228 keV (c). The asterisk and (SE) represent the background peaks and single escape peaks.

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[a]	1.148±0.145[a]
			0.25±0.05[b]	1.09±0.09[b]
1216	657–559	559	−0.225±0.015	0.309±0.030
			−0.220±0.007[a]	0.275±0.010[a]
			−0.185±0.012[b]	0.305±0.02[b]
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[a]	0.036±0.078[a]
			−0.1±0.1[b]	0.1±0.1[b]
1787	571–1216	1216	0.145±0.022	0.048±0.035
	665–(563)–559	559	−0.013±0.006	0.046±0.010
	1228–599	559	0.471±0.007	0.097±0.011
			0.463±0.006[a]	0.102±0.009[a]
			0.462±0.016[b]	0.150±0.029[b]
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
			−0.377±0.075[a]	0.067±0.106[a]
	2096–559	559	−0.258±0.012	−0.034±0.019
			−0.200±0.009[a]	−0.040±0.013[a]
	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[a]	0.067±0.013[a]

[a]Values from Ref. 9.
[b]Values from Ref. 8.

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 Fig. 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 $\delta(657)=5.26\pm0.50$ in good agreement with most of the earlier reported values. The value obtained by Subber *et al.*[6] is somewhat smaller, $\delta=4.15\pm0.2$.

The 1330-keV level. Decay studies limited the spin and

TABLE II. Multipole mixing ratios of γ-transitions in ^{76}Se.

Level (keV)	Mixed Transition (keV)	I_i^π-I_f^π	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	$0.57<\delta<3.55$[a]
				$0.5<\delta<1.8$[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^+	−0.13±0.09	
		2^+-2^+	0.49±0.06	
		3^+-2^+	−0.03±0.10	
2363	575	3^+-2^+	−1.18±0.35	0.07±0.10 or $-13.8<\delta<-3.7$[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]
				$-5.7<\delta<0.12$[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	$-0.24<\delta<5.3$[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.

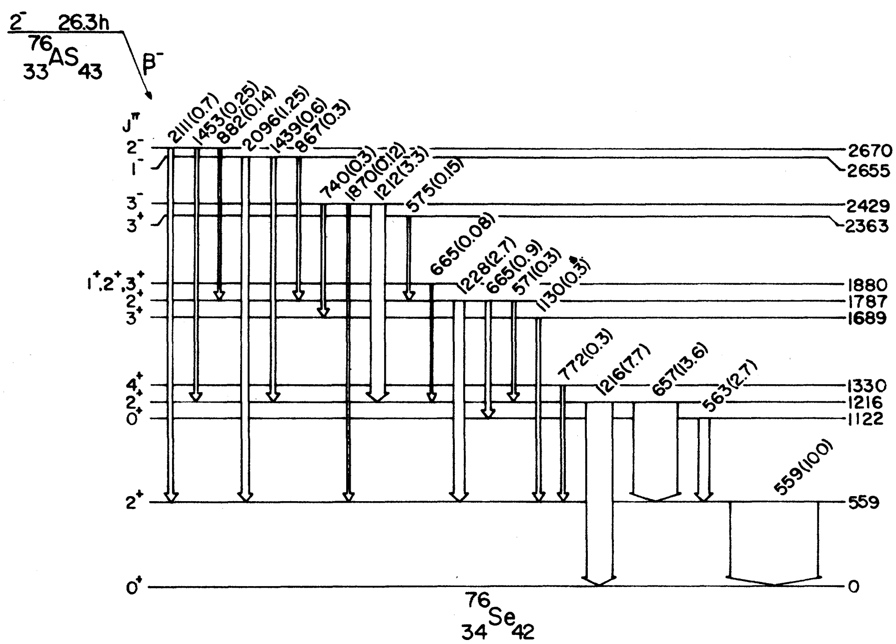

FIG. 2. A partial decay scheme of ^{76}As to the levels in ^{76}Se.

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.*,[6] 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 confirming the assignment made by Subber *et al.*[6] The present $\delta(1130)=1.08\pm0.10$ 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- and 571-keV transitions are given in Table II 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 by Nagahara[8] from the observed coincidences between the 665 keV (the weaker component of a doublet at 665 keV) and the 1216-keV gamma ray. A weak gamma ray at 1881 keV was later observed by Kaur *et al.*[9] and placed in the decay scheme as a ground-state transition from the 1881-keV level. The level is not observed in any of the reaction studies. In the present experiment the 1881-keV gamma ray was not detected in the direct spectrum, however the coincidences between 665- and 1216-keV gamma rays were clearly seen. The present angular correlation result of the 665–1216-keV cascade is consistent with 1, 2, or 3 spin assignment for the 1881-keV level. The parity of the level is most probably positive considering a $\log ft=9.8$ (Ref. 4) for the β^- decay from 2^- ground state of ^{76}As.

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 575–228-keV cascade were analyzed for both spin values using the already determined $\delta(1228)=-0.54$. 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 $(575)=-1.18\pm0.35$ does not agree with the value obtained by Subber *et al.*, $(575)=-13.8<\delta<-3.7$.

The 2429-keV level. A spin and parity of 3^- was established for this level from the ^{76}Se(d,d') reaction study by Lin.[17] A recent angular distribution measurement for this level populated in the ^{76}Se(p,p') (Ref. 11) reaction is in agreement with this assignment. Previous decay studies and several other reaction studies also agree with the value of 3^- for this level.[4] 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-, 1212-, and 1870-keV transitions from this level to known positive parity states below, of 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.*[9] The mixing ratios for the 867-, 1439-, 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 skip cascades were measured in the present work involving transitions which deexcite 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, 1453, and 882 keV, are predominantly dipole in character. This is in agreement with the previous results.[5,6,9]

DISCUSSION

The even-A selenium isotopes had traditionally been regarded as reasonably good vibrational nuclei. However from detailed study of Coulomb excitation[1,2] and $(\alpha,2n\gamma)$ reactions,[3] it has been shown that selenium nuclei with $A=72-82$ all show a very significant deviation from the vibrational picture and are soft with respect to deformation. While a (p,p') reaction study[11] suggested triaxial deformation for the ^{76,78,80}Se isotopes it has been proposed[18] from 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 the shape coexistence in these nuclei.

Several theoretical calculations have been carried out in the past to account for the observed properties of even-A selenium isotopes[3,11,19,20] however no single model is able to describe simultaneously all the data.

Recently Subber *et al.*[6] have calculated the level energies and transition rates to describe the collective level structure of selenium isotopes with $A=72-82$ using the dynamic deformation model (DDM) and interacting boson model. A generally satisfactory agreement with experimental data was obtained, in particular the idea of shape coexistence in this region is supported by DDM. These authors also calculated the multipole mixing ratios $\delta(E2/M1)$ for several γ transitions in $^{72-80}$Se isotopes. Agreement with the experimental results is marginal and both sign and magnitude are wrongly predicted in several cases. Particularly in the case of ^{76}Se where only a few mixing ratios were calculated, observed values are much smaller in magnitude (with the exception of the 657-keV $2_2^+ \rightarrow 2_1^+$ transition) as compared to the predicted ones. The present results show that several transitions in ^{76}Se have quite large $M1$ admixtures, and these are difficult to explain in terms of simple collective models. More refined calculations may be necessary for such a detailed comparison. We hope that the present results will be useful for some future calculations.

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.*,[6] 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.

The authors would like to thank the staff of the IEA-R1 reactor for their efficient help in the irradiation of samples and André Luis Lapolli for his participation in the experiment.

[1]J. Barrette, M. Barrete, G. Lamoureux, S. Monaro, and S. Markiza, Nucl. Phys. **A235**, 154 (1974).

[2]R. Lecomte, P. Paradis, J. Barrete, M. Barrete, G. Lamoureux, and S. Monaro, Nucl. Phys. **A284**, 123 (1977).

[3]T. Matsuzaki and H. Takitani, Nucl. Phys. **A390**, 413 (1982).

[4]B. Singh and D. A. Viggars, Nucl. Data Sheets **42**, 297 (1984).

[5]J. A. Barclay, S. S. Rosenblum, W. A. Steyert, and K. S. Krane, Phys. Rev. **13**, 1991 (1976).

[6]A. R. H. Subber, S. J. Robinson, P. Hungerford, W. D. Hamilton, P. Van Isaker, K. Kumar, P. Park, K. Schreckenbach, and G. Golvin, J. Phys. G **13**, 807 (1987).

[7]Z. Grabowski, S. Gustafsson, and I. Marklund, Ark. Fys. **17**, 411 (1960).

[8]T. Nagahara, J. Phys. Soc. Jpn. **34**, 579 (1973).

[9]R. Kaur, A. K. Sharma, S. S. Sooch, H. R. Verma, and P. N. Trehan, J. Phys. Soc. Jpn. **49**, 1214 (1980).

[10]R. G. Kurup, R. W. Finlay, J. Raport, and J. P. Delaroche, Nucl. Phys. **A420**, 237 (1984).

[11]J. P. Delaroche, R. L. Varner, T. B. Clegg, R. E. Anderson, B. L. Burks, E. J. Ludwig, and J. F. Wilkerson, Nucl. Phys. **A414**, 113 (1984).

[12]J. C. Wells, R. L. Robinson, H. J. Kim, R. O. Sayer, R. B. Piercey, A. V. Ramayya, H. J. Hamilton, and C. F. Maguire, Phys. Rev. C **22**, 1126 (1980).

[13]R. Ribas (private communication).

[14]A. J. Becker and R. M. Steffen, Phys. Rev. **180**, 1043 (1969).

[15]R. L. Christensen, H. G. Bennewitz, D. R. Hamilton, J. B. Reynolds, and H. H. Stroke, Phys. Rev. **107**, 633 (1957).

[16]F. K. McGowan and P. H. Stelson, Phys. Rev. **126**, 257 (1962).

[17]E. K. Lin, Nucl. Phys. **73**, 613 (1965).

[18]J. H. Hamilton, P. G. Hansen, and E. F. Zganjar, Rep. Prog. Phys. **48**, 631 (1985).

[19]S. R. Almoney and G. R. Brose, Nucl. Phys. **A171**, 660 (1971).

[20]K. P. Lieb and J. J. Kolata, Phys. Rev. C **15**, 939 (1977).