PHYSICAL REVIEW C VOLUME 8, NUMBER 4 OCTOBER 1973

High Precision Studies on the Level Scheme of ^{80}Se by the Resonant-Scattering Method

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(Received 5 March 1973)

The energies and reduced strengths of the γ rays following deexcitation of the 7818.9-keV highly excited level in ^{80}Se reached by the (γ,γ') reaction, were measured using a nickel capture γ source. The level scheme deduced for this nucleus is presented. Measurements of the angular distributions of the scattered radiation permitted the assignment of spin values for most of the low-lying levels in this nucleus. Parity determinations were made comparing the reduced strengths with the statistics of known $E1$ and $M1$ transitions.

1. INTRODUCTION

This work is a continuation of several studies, reported by the Nuclear Physics Group[1-4] at the Soreq Center, on the photonuclear excitation of various natural elements using a nickel capture γ source. Preliminary results have already been reported[2] for the 7818.9-keV resonance level in ^{80}Se. The studies mentioned in Ref. 2 were concerned mainly with the statistical behavior of highly energetic states in the neighborhood of the nuclear threshold in even-even nuclei and little attention was paid to the precise determination of the nuclear parameters for the different low-lying levels thus populated. Our measurement of this nucleus is of interest because only a few studies[5-8] containing accurate information about ^{80}Se are known in the literature. The results of our experiments are presented below and compared with the latest published data.

2. EXPERIMENTAL PROCEDURE

The neutron-capture γ-ray scattering facility used has been described.[4] With a 10-kg nickel source at full reactor power, an intensity of about 10^7 photons/cm^2 sec of 8.995-MeV γ rays is obtained at the target position. The spectra of the resonantly scattered γ rays were recorded by a 40-cm^3 Ge(Li) detector, positioned 23 cm from the target, and stored in a 4096-channel analyzer.

In determining the energies and relative intensities of the γ transitions, two independent runs were performed: one comprising the high-energy 3-10-MeV range and the second, the low-energy region of the spectra of the scattered γ rays. In both cases, peak centers and areas were obtained by means of the nonlinear least-squares-fitting method, using a special computer code.

The calibration of the high-energy range spectra was carried out using the reported energies for the Ni(n,γ) spectrum given by Rasmussen *et al.*[9] to determine the energy of the resonant line. The corresponding energy of the remaining lower inelastic transitions was measured using the constant energy difference of 511.006 keV between the peaks created in the Ge diode for each incident high-energy γ ray.

The spectra of the low-energy transitions were calibrated in the usual way, using known standards of ^{22}Na, ^{137}Cs, ^{41}Ar, ^{207}Bi, ^{88}Y, ^{60}Co, and ThC'' sources.

In most cases, the high-energy inelastic deexcitations were interpreted as primary transitions from the resonant state, as expected from the predicted energy dependence of the transition probabilities. The possibility that a particular γ-ray transition could be considered as a secondary deexcitation was discarded if the corresponding complementary primary transition was not present in the spectrum of the scattered γ rays, except where a level having the same approximate energy is known.

For the nucleus under investigation the angular distribution of the elastic component was found compatible only with a pure dipole γ transition. Since ^{80}Se is even-even, the spin of the resonance level can be assigned as a value of 1.

Due to the low γ intensities attainable, the angular distributions of the inelastic transitions were measured at only two angles 90 and 135°, and normalized to the $0\to1\to0$ ground-state transition. Under such conditions, the finite geometry corrections are negligible and it is not essential to monitor the direct beam. The results of these experiments were analyzed by means of pure dipole-type angular distribution of the form $1+A_{22}P_2(\cos\theta)$ where the experimental value of A_{22} should be compared with the theoretical coefficients calculated by Ferentz and Rosenzweig.[10] Though the values of A_{22} are derived here with large errors, for the purpose of the present work, they are sufficiently precise to distinguish, in most cases, between the three possible spin values of 0, 1, or 2.

3. RESULTS

A large resonance giving rise to a complex spectrum of scattered γ rays is obtained from a selen-

TABLE I. Reduced partial radiation widths of the 7818.9-keV resonance level in ^{80}Se.

Energy of transitions (keV)	Energy of final state (keV)	Relative intensity (%)	Reduced widths (eV MeV$^{-4}\times 10^3$)		Most likely character
			k ($E1$)	k ($M1$)	
7818.9	0	100 ± 0.5	6 ± 1	117 ± 22	$E1$
6369.4	1449.5 ± 0.3	8.4 ± 0.2	1.0 ± 0.2	18 ± 4	$E1$ or $M1$
6339.4	1479.5 ± 0.1	9.4 ± 0.2	1.1 ± 0.2	21 ± 4	$E1$ or $M1$
5944.7	1874.2 ± 0.8	1.1 ± 0.2	0.2	3 ± 1	$E1$ or $M1$
5858.4	1960.5 ± 0.2	27.8 ± 0.3	4 ± 1	78 ± 14	$E1$
5507.2	2311.8 ± 0.7	4.2 ± 0.5	0.8 ± 0.2	14 ± 3	$E1$ or $M1$
5304.4	2514.5 ± 0.3	6.4 ± 0.3	1.3 ± 0.2	24 ± 5	$E1$ or $M1$
5191.6	2627.3 ± 0.4	1.0 ± 0.3	0.3 ± 0.1	4 ± 2	$E1$ or $M1$
5004.3	2814.6 ± 0.5	3.5 ± 0.3	0.8 ± 0.2	16 ± 3	$E1$ or $M1$
4991.4	2827.5 ± 0.2	12.4 ± 0.4	3 ± 1	56 ± 10	$E1$
4692.4	3126.5 ± 0.2	12.5 ± 0.3	4 ± 1	68 ± 13	$E1$
4619.1	3199.8 ± 0.3	5.5 ± 0.3	1.6 ± 0.3	30 ± 6	$E1$ or $M1$
4570.1	3248.8 ± 0.5	7.3 ± 0.3	2.2 ± 0.4	43 ± 8	$E1$
4502	3317 ± 1	2.2 ± 0.4	0.7 ± 0.2	14 ± 3	$E1$ or $M1$
4468.2	3350.7 ± 0.2	9.2 ± 0.4	3 ± 1	58 ± 11	$E1$
4427.1	3391.8 ± 0.3	8.5 ± 0.3	3 ± 1	55 ± 10	$E1$
4376.8	3442.1 ± 0.3	5.2 ± 0.4	1.9 ± 0.3	35 ± 7	$E1$ or $M1$
4212.0	3606.9 ± 0.4	3.7 ± 0.3	1.5 ± 0.3	28 ± 6	$E1$ or $M1$
4199.1	3619.8 ± 0.5	2.8 ± 0.3	1.1 ± 0.2	21 ± 5	$E1$ or $M1$
4163	3656 ± 1	1.3 ± 0.3	0.5 ± 0.1	10 ± 3	$E1$ or $M1$
3949.1	3869.8 ± 0.5	3.0 ± 0.4	1.5 ± 0.3	27 ± 6	$E1$ or $M1$
3866.9	3952.0 ± 0.4	3.0 ± 0.5	1.6 ± 0.4	30 ± 7	$E1$ or $M1$
3756.1	4062.8 ± 0.4	4.3 ± 0.4	3 ± 1	50 ± 10	$E1$

TABLE II. Experimental A_{22} coefficients compared with theory, assuming pure dipole.

Energy of transition (keV)	Energy of final state (keV)	Transitions in ^{80}Se Theoretical A_{22} coefficients for various assumed spin sequences		
		0→1→0 0.500	0→1→1 −0.250	0→1→2 0.050
7818.9	0	+0.500		
6369.4	1449.5			+0.15 ± 0.13
6339.4	1479.5	+0.58 ± 0.06		
5944.7	1874.2	+0.62 ± 0.58		+0.62 ± 0.58
5858.4	1960.5			+0.06 ± 0.03
5507.2	2311.8			−0.03 ± 0.17
5304.4	2514.5			+0.17 ± 0.09
5004.3	2814.6	+0.37 ± 0.37		+0.37 ± 0.37 [a]
4991.4	2827.5			+0.13 ± 0.07
4692.4	3126.5			+0.14 ± 0.08
4619.1	3199.8			+0.21 ± 0.10
4570.1	3248.8			+0.01 ± 0.09
4502	3317	+1.2 ± 0.7		
4468.2	3350.7		−0.25 ± 0.08	
4427.1	3391.8			+0.11 ± 0.07
4376.8	3442.1	+0.40 ± 0.18		
4212.0	3606.9			+0.19 ± 0.19
4199.1	3619.8	+0.46 ± 0.28		
3949.1	3869.8		−0.25 ± 0.30	−0.25 ± 0.30
3866.9	3952.0		−0.30 ± 0.38	−0.30 ± 0.38
3756.1	4062.8	+0.39 ± 0.24		

[a] Only spin assignment of 2 is valid for the final state, since the transition to the ground state was observed (see Fig. 1).

ium target using a nickel(n, γ) source. After comparison of the energies of the low-lying levels deduced with the published data[8] the decay scheme thus obtained was attributed to ^{80}Se. A list of the primary inelastic transitions together with the low-energy levels thus populated is shown in Table I. Also shown are the electric and magnetic reduced strengths calculated from the relative intensities corrected for the energy dependence:

$$k_i(E1) = \Gamma_0 \frac{(\Gamma_i/\Gamma_0)}{E_i^3 D A^{2/3}} (\text{eV MeV}^{-4}),$$

$$k_i(M1) = \Gamma_0 \frac{(\Gamma_i/\Gamma_0)}{E_i^3 D} (\text{eV MeV}^{-4}),$$

where the partial width to the ground-state transition Γ_0 and the average level spacing D were taken from Schlesinger *et al.*[2] by analyzing the published statistics of known $E1$ and $M1$ transitions[11] it may be concluded that an observed $M1$ strength greater than abount 50×10^{-3} eV MeV^{-4} can be assumed to be an $E1$ transition. Using this criterion, many of the above transitions are likely to be electric dipoles, as indicated in Table I.

The results of the angular distributions were analyzed assuming a pure dipole-type angular distribution of the form $1 + A_{22}P_2(\cos\theta)$. The derived values of A_{22} for various assumed spin sequences as compared with the theoretical ones[10] are shown

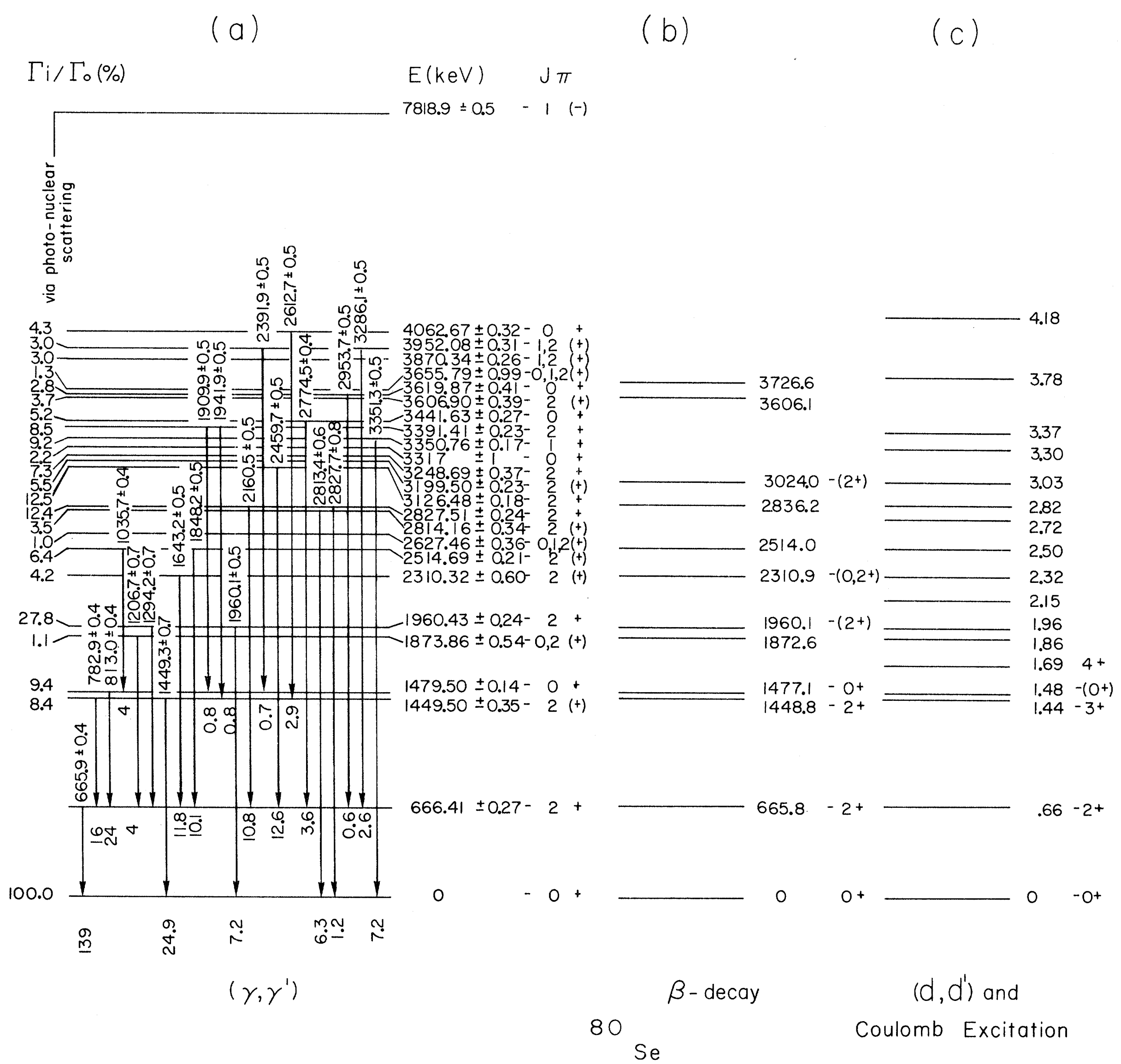

FIG. 1. Level scheme for ^{80}Se: (a) present work; (b) Ref. 5; (c) Ref. 6 (spin assignments from Ref. 7).

in Table II, and conclusions may be drawn concerning the spin values of the different low-lying levels in ^{80}Se.

In addition to the transitions listed in Tables I and II, secondary deexcitation transitions were observed. They are shown explicitly in the level scheme deduced for ^{80}Se shown in Fig. 1, where their intensities, relative to that of the 7818.9-keV transition, are also indicated. These transitions helped us to distinguish between spin assignments 0 and 2 in those cases where the results of the angular distribution measurements were not sufficiently precise.

4. DISCUSSION

The 7152.5-keV transition which populates the first 2^+ 666.41-keV low-lying state in ^{80}Se from the 7818.9-keV resonant level was not observed in the present experiment. This can be explained as due to statistical fluctuations characteristic of deexcitations of highly excited states in nuclei.[2,12] Nevertheless, this level was reached through secondary deexcitations; it is shown in our proposed level scheme for ^{80}Se in Fig. 1 together with more than 22 higher excited states, 12 of which were not previously reported. In the same figure, we also compare our results with those reported by other investigators.[6-8] It should be mentioned that the level energies in the present work are weighted averages of the energy determinations made from the γ-ray spectra in both low- and high-energy regions.

In most cases, the angular distribution measurements were sufficient to make a unique spin assignment for the different levels, as can be seen in Table I. These experiments show that the 2814.16-keV excited level has a spin value of 0 or 2, but since the transition to the ground state from this level was observed, the former was ruled out and a spin assignment of 2^+ was made.

The 1294.2-keV transition that populates the 666.41-keV first phonon state from the 1960.43-keV level is shown in Fig. 1 without intensity determination because the intense background line of 1293.64 keV overlaps the same energy.

A systematic difference of about 1 keV is observed between our proposed energies for the low-lying levels deduced for ^{80}Se and those reported by McMillan and Pate.[5] This may be due to a drift caused by the intensity variation of the activity of the ^{80}As samples used in their work. The spin assignments presented by these authors for the 1449.50-, 1479.50-, 1960.43-, and 2310.32-keV low-lying levels are in agreement with the results of the present work. A comparison with experimental results on ^{80}Se reported before 1971 [6-8] has limited value because of the poor accuracy in the level energies presented by these authors.

From the standpoint of theory the level scheme of the even-even ^{80}Se isotope could be interpreted as being produced by harmonic quadrupole vibrations of the nucleus. Indeed, the triplet, composed of levels at energies of 1.69, 1.4795, and 1.4495 MeV with respective spin values 4^+, 0^+, and 2^+, may be interpreted as being the second phonon state. This interpretation, however, fails for the higher-energy states found experimentally.

Calculations performed using the axially asymmetric rotor model of Davydov and Chaban[13] are mentioned in Ref. 5, but as it is pointed out by these authors, this model cannot yet explain the level structure of ^{80}Se beyond the energy of 2 MeV.

The author wishes to thank Professor G. Ben-David and Dr. B. Arad for valuable discussions and critical reading of the manuscript.

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