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[illegible] (n,n'γ) [illegible]

J. Sigaud, Y. Patin, M.T. McEllistrem*, G. Haouat and J. Lachkar
Service de Physique Nucléaire - Centre d'Etudes de Bruyères-le-Châtel
B.P. n° 61 - 92120 Montrouge, France.

The energy levels and the decay schemes of ^{76}Se, ^{78}Se, ^{80}Se, ^{82}Se and ^{76}Ge have been studied through the measurements of (n,n'γ) differential cross sections. Gamma ray excitation functions have been measured between 2.0 and 4.1 MeV incident neutron energy, and angular distribution have been observed for all of these isotopes.

($^{76,78,80,82}Se$, ^{76}Ge ; (n,n'γ) reaction ; E_n=2.0-4.1 MeV ; $E_γ$; σ($E_γ$,θ) ; level schemes)

Introduction

Besides the applied interest in providing neutron data, there are several reasons for measuring the gamma ray production cross sections for even A Se and Ge isotopes. At first, these isotopes have neutron numbers between 42 and 48, that is just below the closed shell at N=50. Then, the spectroscopy of the low lying states in even A isotopes may give some information about their structures. Secondly, the level schemes of ^{76}Ge, ^{76}Se, ^{78}Se and, in particular, ^{80}Se and ^{82}Se are not well known. The energy levels and their decay schemes have been investigated by coulomb excitation[1] and mainly by means of the β decay from As or Br for the Se isotopes[2-5] and from Ga for Ge isotopes[6]. No previous work on these isotopes using the (n,n'γ) techniques seems to have been reported yet. In the present study, a lot of new information has been obtained from the analysis of the excitation functions of the gamma rays following the inelastic scattering of neutrons between 2.0 and 4.1 MeV. We have completed these results by measuring the angular distributions of the main gamma rays at 3.0 MeV incident neutron energy. More complete level schemes are then proposed for the five isotopes. These measurements supplement the neutron scattering data obtained by direct neutron detection reported elsewhere in this meeting. In this paper we present only our results for ^{76}Se and ^{82}Se.

Experimental procedures and data reduction

The $T(p,n)^3He$ reaction was used to produce the neutron beam in the 2.0- to 4.1- MeV energy range. The incident protons were accelerated by the tandem Van de Graaff accelerator of the Centre d'Etudes de Bruyères-le-Châtel. The beam was pulsed with a burst width of 1 nsec and a repetition rate of 2.5 MHz. The average current was 2μA.

A 3-cm long gas target with two entrance nickel foils (each, 4.4-mg/cm² thick) was used. The description of this tritium gas cell has been presented in detail in a previous report[7].

Each Selenium sample was in a form of metallic powder with an isotopic enrichment greater than 90%. The container for each sample was a polyethylene can of diameter 25 mm and lenght 50 mm.

During a run, the sample was placed at 0° with respect to the incident proton beam and 6.65 cm from the center of the tritium cell.

The apparatus and the experimental techniques have been discussed in detail in previous reports[8,9], and will be described only briefly here.

Photons following the inelastic scattering of neutrons by the sample were detected by an anti-compton spectrometer composed of a central Ge(Li) detector and a Na I (Tl) annulus. A pulsed beam time-of-flight detection mode was used to eliminate background caused by prompt neutrons striking the detector. In the present work a 100-cm³ gamma ray detector was used in the gamma ray spectrometer instead of the 30-cm³ and 67-cm³ detectors used previously. The flight path between the sample and the Ge(Li) detector was 1.7 m. The time resolution of the Ge(Li) detector was 6 nsec for gamma-rays energies greater than 2 MeV. The absolute value of the gamma ray production cross sections has been given by reference to the 846.8-keV gamma ray production cross section of ^{56}Fe, reported by Dickens et al.[10] The overall uncertainties of the measured cross sections vary between 10 to 25 %.

Results and discussion

Neutron induced gamma ray production measurements were undertaken for 11 energies in the range from 2.0 to 4.1 MeV at 55°, in steps of 0.2 MeV, the overall energy spread. These steps were small enough to remove ambiguities in the assignment of energies to the levels found in this work. No other measurements seem to have been reported yet. As an example, the excitation functions for both ^{82}Se and ^{76}Se and the deduced level schemes proposed for these isotopes are given respectively in tables I and II and figures 1 and 2. Detailed discussions of new assignments are beyond the scope of this paper, but new results of this study have been emphasized by an asterisk (*) (figures 1 and 2).

The level schemes proposed for each isotope are a large extension of those deduced from the β decay of As or Br and of Ga. The analysis of the proposed level schemes shows that more levels are excited in the ^{76}Se, ^{78}Se and ^{80}Se than in the ^{82}Se. This is proved by comparing the gamma-ray production cross sections for the first level at 4.1-MeV incident-neutron energy : the values for ^{76}Se, ^{78}Se and ^{80}Se are quite the same : about 135 mb/sr at 55° ; whereas for ^{82}Se the value is 110 mb/sr at 55°.

Angular distributions of the main gamma rays were obtained for each isotope for a neutron energy of 3.0 MeV.

All of these measured cross sections are being compared to predictions of the Hauser-Feshbach formalism with width fluctuation corrections included. New results of this study will be given in subsequent papers.

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*Present address: University of Kentucky, Lexington, Ky.

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^{82}Se		$(d\sigma/d\Omega)_{55°}$ (mb/sr)								
		E_n (MeV)								
Energy	Transition	2.5	2.7	2.9	3.1	3.3	3.5	3.7	3.9	4.1
[illegible]	[illegible]					–	[illegible]	[illegible]	[illegible]	[illegible]
654.8	654.8 → 0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	7.1 ± 0.8	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible] [illegible]	[illegible] [illegible]		0.4 ± 0.1	[illegible]	1.5 ± 0.2	4.9 ± 1.0	4.4 ± 0.9	4.5 ± 0.9	5.4 ± 1.0	4.3 ± 0.9
[illegible] [illegible]	[illegible] [illegible]	22.2 ± 2.4	[illegible]	25.2 ± 2.[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	22.9 ± 2.8
[illegible]	[illegible]				2.5 ± 0.5	4.0 ± 0.9	[illegible]	[illegible]	5.6 ± 0.8	5.1 ± 0.8
[illegible]	[illegible] or [illegible]					1.6 ± 0.4	2.0 ± 0.6	4.2 ± 0.8	4.4 ± 0.9	4.9 ± 1.0
[illegible]	[illegible]						–	[illegible]	[illegible] ± 0.2	–
[illegible]	[illegible]								–	0.8 ± 0.1
[illegible]	[illegible]						–	1.6 ± 0.3	2.3 ± 0.6	2.7 ± 0.3
[illegible]	[illegible]							1.4 ± [illegible]	1.0 ± 0.1	1.6 ± 0.3
1732.1	1732.1 → 0	24.2 ± 2.4	25.6 ± 2.3	25.7 ± 2.[illegible]	20.9 ± 2.3	24.8 ± 2.5	23.3 ± 2.3	21.5 ± 2.2	19.9 ± 2.0	19.3 ± 2.0
1626.6 [illegible]	[illegible] → 1732.1 [illegible] → 1410.5							–	–	2.3 ± 0.8
[illegible]	[illegible] → 654.8		1.4 ± 0.3	2.6 ± 0.5	3.6 ± 0.7	4.2 ± [illegible]	4.2 ± [illegible]	2.5 ± 0.5	2.6 ± 0.5	1.4 ± 0.3
1896.1	2551.0 → 654.8		0.7 ± 0.2	3.2 ± 0.6	3.3 ± 0.7	4.6 ± 1.0	4.5 ± 0.9	5.2 ± 1.0	4.6 ± 0.9	4.5 ± 0.9
[illegible]	[illegible] → [illegible]								–	1.2 ± 0.3
[illegible]	[illegible] → 654.8		0.5 ± 0.2	5.0 ± 1.0	9.2 ± [illegible]	13.1 ± 2.0	13.2 ± 2.0	9.5 ± 1.[illegible]	8.6 ± 1.[illegible]	8.1 ± 1.2
2327.2	[illegible] → 654.8				–	1.8 ± 0.4	2.3 ± 0.5	2.3 ± 0.5	2.1 ± 0.4	2.5 ± 0.5
[illegible]	[illegible] → 654.8				–	3.9 ± 0.8	5.4 ± 1.1	5.1 ± 1.0	5.1 ± 1.0	4.2 ± 0.8
2379.9	3034.7 → 654.8					0.7 ± 0.2	1.9 ± 0.4	1.9 ± 0.4	1.7 ± 0.3	1.9 ± 0.4
2447.0	3101.8 → 654.8						1.5 ± 0.3	1.7 ± 0.3	1.5 ± 0.4	1.4 ± 0.3
2462.7	3117.5 → 654.8						0.7 ± 0.2	1.0 ± 0.3	–	–
[illegible]	[illegible] → 654.8						0.8 ± 0.2	2.2 ± 0.4	3.1 ± 0.6	3.1 ± 0.6
2672.0	[illegible] → 654.8						–	1.0 ± 0.3	2.2 ± 0.6	1.7 ± 0.4
[illegible]	3343.1 → 654.8							0.7 ± 0.2	1.0 ± 0.3	0.8 ± 0.2
[illegible]	3375.8 → 654.8							1.2 ± 0.2	2.2 ± 0.4	3.0 ± 0.6
[illegible]	3398.2 → 654.8							1.1 ± 0.2	1.2 ± 0.2	1.8 ± 0.4
[illegible]	3586.2 → 654.8							–	1.5 ± 0.4	1.3 ± 0.3
[illegible]	[illegible] → 0				–	2.0 ± 0.4	2.4 ± 0.5	2.3 ± 0.5	2.1 ± 0.5	2.6 ± 0.5
3011	3665.3 → 654.8								–	1.8 ± 0.5
3034.4	3034.7 → 0					2.1 ± 0.4	2.4 ± 0.5	3.2 ± 0.6	3.2 ± 0.6	2.4 ± 0.5
[illegible] [illegible]	3101.8 → 0 [illegible] → 0					0.6 ± 0.2	1.7 ± 0.3	2.1 ± 0.4	2.7 ± 0.5	3.3 ± 0.7
[illegible]	3244.8 → 0						1.3 ± 0.3	2.4 ± 0.5	2.5 ± 0.5	2.6 ± 0.5
3342.5	3342.5 → 0						–	1.5 ± 0.3	1.8 ± 0.4	2.1 ± 0.5
3398.2	3398.2 → 0							–	–	1.8 ± 0.3

Table 1

Differential cross section measured at 55 deg for the main gamma transitions from the ^{82}Se (n,n'γ) reaction. (Energies are given in keV).

^{76}Se		$(d\sigma/d\Omega)_{55°}$ (mb/sr)										
		E_n (MeV)										
Level	Transition	2.0	2.2	2.5	2.7	2.9	3.1	3.3	3.5	3.7	3.9	4.1
[illegible]	[illegible]	[illegible]	1.5 ± 0.4	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1.0 ± [illegible]	0.9 ± 0.2	w	
[illegible]	[illegible]			[illegible]	[illegible]	[illegible]	1.4 ± 0.4	[illegible]	1.7 ± 0.4	w	w	w
[illegible]	[illegible]	2.0 ± [illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	4.4 ± 0.9	[illegible]	[illegible]	4.7 ± 0.6	[illegible]
[illegible]	[illegible] - 0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	145.5 ± [illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	21.9 ± 2.2	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	1.5 ± [illegible]	[illegible]	[illegible]	3.2 ± 0.1	[illegible]	[illegible]	[illegible]	[illegible]	4.1 ± 0.8	2.6 ± 0.4	2.1 ± 0.4
[illegible]	[illegible]				1.4 ± 0.2	2.1 ± 0.4	[illegible]	[illegible]	1.2 ± 0.6	[illegible]	[illegible]	2.2 ± 0.3
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	11.2 ± 1.1	10.4 ± 1.4	[illegible]	17.6 ± 1.8	[illegible]	[illegible]	[illegible]	10.2 ± 2.0
[illegible]	[illegible]					w	1.2 ± 0.1	1.1 ± 0.1	1.5 ± 0.3			w
[illegible]	[illegible]		1.1 ± 0.2	1.7 ± 0.3	1.2 ± 0.4	3.5 ± 0.5	3.1 ± 0.6	5.0 ± 0.5	3.0 ± 0.5	3.3 ± 0.5	3.7 ± 0.4	3.6 ± 0.5
[illegible]	[illegible]				w	w	0.5 ± 0.2	0.3 ± 0.1	w	w	w	1.6 ± 0.4
[illegible]	173.2 - 1216.7				0.6 ± 0.2	w	w	w				
[illegible]	[illegible] - 559.5	5.0 ± 0.5	4.6 ± 0.7	[illegible]	9.9 ± 1.0	10.5 ± 1.1	10.1 ± 1.0	11.7 ± 1.1	11.9 ± 1.2	12.6 ± 1.3	11.0 ± 1.1	10.6 ± 1.0
[illegible]	[illegible]				0.5 ± 0.1	1.1 ± 0.2	1.6 ± 0.3	1.6 ± 0.3	1.3 ± 0.3	1.2 ± 0.2	1.0 ± 0.2	
[illegible]	[illegible] - 0	12.2 ± 1.2	15.1 ± 1.5	19.3 ± 2.0	17.3 ± 1.7	19.8 ± 2.0	20.7 ± 2.1	22.0 ± 2.2	22.0 ± 2.2	22.7 ± 2.3	22.2 ± 2.2	21.4 ± 2.2
[illegible]	[illegible]	1.8 ± 0.5	2.2 ± 0.7	[illegible]	10.4 ± 1.0	11.1 ± 1.1	10.3 ± 1.0	6.6 ± 0.9	6.2 ± 0.9	6.7 ± 0.9	7.2 ± 0.7	[illegible]
1770	[illegible]7.4 - 1216.7				w	w	0.7 ± 0.2	w			1.1 ± 0.3	
[illegible]	420 - 1331.6					w	1.2 ± 0.3	w	2.9 ± 0.6	2.5 ± 0.5	3.2 ± 0.6	2.0 ± 0.4
[illegible]	[illegible] - 1216.7					0.4 ± 0.1	0.5 ± 0.2	0.6 ± 0.2	0.4 ± 0.1	w	1.0 ± 0.3	w
[illegible]	[illegible]1.0 - 1216.7					w	1.0 ± 0.3	0.8 ± 0.2	1.1 ± 0.3	0.9 ± 0.2	0.8 ± 0.2	0.9 ± 0.2
[illegible]	[illegible]05 - 1331.6						1.2 ± 0.2	1.7 ± 0.3	1.5 ± 0.3	2.0 ± 0.4	2.3 ± 0.5	1.9 ± 0.4
[illegible]	654 - 1125					w	0.7 ± 0.2	0.6 ± 0.2	0.7 ± 0.2	1.5 ± 0.4	1.1 ± 0.4	1.1 ± 0.3
[illegible]	[illegible]9.1 - 559.5		0.6 ± 0.1	2.7 ± 0.5	4.7 ± 1.2	4.5 ± 1.2	4.3 ± 1.1	3.6 ± 0.9	3.7 ± 0.9	3.3 ± 0.8	2.6 ± 0.7	2.6 ± 0.7
[illegible]	[illegible]05 - 1216.7						w	w	1.6 ± 0.4	1.3 ± 0.3	1.2 ± 0.3	1.1 ± 0.3
[illegible]	611.6 - 1216.7					0.5 ± 0.2	2.3 ± 0.7	4.0 ± 1.2	3.5 ± 1.1	3.1 ± 0.9	2.3 ± 0.7	2.3 ± 0.8
[illegible]	[illegible].2 - 559.5			1.4 ± 0.3	2.5 ± 0.5	2.0 ± 0.6	2.9 ± 0.6	2.5 ± 0.5	2.2 ± 0.4	1.5 ± 0.3	1.1 ± 0.2	0.8 ± 0.2
[illegible]	[illegible]70.2 - 1216.7							1.2 ± 0.5	0.9 ± 0.1	0.7 ± 0.2	w	w
[illegible]	[illegible]8.5 - 0	1.3 ± 0.2	1.8 ± 0.3	1.6 ± 0.3	2.4 ± 0.5	2.1 ± 0.6	2.6 ± 0.5	2.6 ± 0.5	2.0 ± 0.4	2.4 ± 0.5	1.9 ± 0.6	2.4 ± 0.5
[illegible]	515.3 - 559.5				0.9 ± 0.2	1.8 ± 0.4	2.1 ± 0.6	2.3 ± 0.5	2.4 ± 0.5	2.4 ± 0.5	2.3 ± 0.5	2.4 ± 0.5
[illegible]	[illegible]06.1 - 559.5				0.3 ± 0.1	1.2 ± 0.3	1.5 ± 0.4	1.5 ± 0.4	1.0 ± 0.1	1.7 ± 0.4	1.0 ± 0.1	1.5 ± 0.4
[illegible]	[illegible]57.0 - 559.5					1.3 ± 0.3	1.8 ± 0.4	2.2 ± 0.4	1.9 ± 0.4	2.1 ± 0.4	1.7 ± 0.5	1.5 ± 0.3
[illegible]	[illegible]73.0 - 559.5					1.3 ± 0.2	2.4 ± 0.4	2.2 ± 0.3	3.0 ± 0.5	3.3 ± 0.5	1.6 ± 0.5	3.3 ± 0.5
2126.[illegible]	[illegible]125.1 - 0			0.6 ± 0.1	1.9 ± 0.5	0.9 ± 0.2	1.1 ± 0.3	0.6 ± 0.2	0.5 ± 0.1	1.2 ± 0.1	0.9 ± 0.2	0.3 ± 0.2
[illegible]	[illegible]17.0 - 559.5					w	1.0 ± 0.2	1.2 ± 0.7	1.6 ± 0.3	1.8 ± 0.4	1.6 ± 0.3	2.5 ± 0.5
2310.[illegible]	[illegible]70.2 - 559.5						1.0 ± 0.2	1.8 ± 0.4	1.8 ± 0.4	1.6 ± 0.3	1.8 ± 0.4	1.1 ± 0.3
[illegible]	[illegible]51.3 - 559.5					w	0.4 ± 0.1	0.8 ± 0.2	0.9 ± 0.2	1.3 ± 0.3	1.3 ± 0.3	0.9 ± 0.2
2450.[illegible]	[illegible]10.0 - 559.5						w	1.2 ± 0.3	1.9 ± 0.4	1.3 ± 0.3	1.9 ± 0.4	2.1 ± 0.4
[illegible]	[illegible]94.5 - 559.5							1.0 ± 0.2	1.5 ± 0.3	2.0 ± 0.4	2.1 ± 0.4	2.1 ± 0.4
[illegible]	[illegible]06.5 - 559.5							0.5 ± 0.1	0.8 ± 0.2	1.1 ± 0.3	1.0 ± 0.1	1.1 ± 0.3
2654	654 - 0							w	1.6 ± 0.3	3.0 ± 0.6	3.4 ± 0.7	2.8 ± 0.6
2656.8	[illegible]657.0 - 0											
[illegible]	[illegible]7.7 - 559.5									w	1.3 ± 0.4	0.9 ± 0.3
[illegible]	[illegible]354.2 - 559.5									w	1.0 ± 0.3	0.7 ± 0.2
[illegible]	[illegible]65.2 - 559.5									w	1.4 ± 0.3	1.3 ± 0.4
2951.[illegible]	2951.3 - 0						0.4 ± 0.1	0.9 ± 0.3	1.5 ± 0.4	2.0 ± 0.5	1.7 ± 0.4	1.7 ± 0.4
3098.3	[illegible]537.8 - 559.5										w	1.2 ± 0.3
3330.0	3330.0 - 0										w	0.9 ± 0.3

Table II

Differential cross section measured at 55 deg for the main gamma transitions from the ^{76}Se (n,n'γ) reaction. (Energies are given in keV).

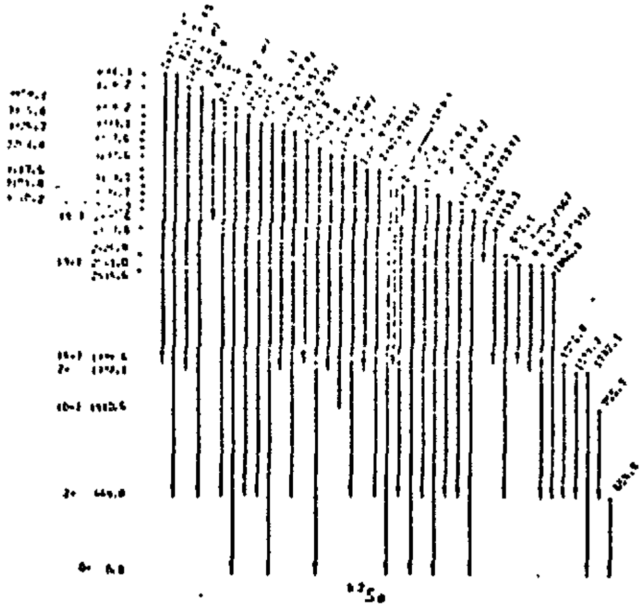

Figure 1. Proposed level scheme of ^{82}Se. The levels noted with an asterisk have least one characteristic determined from these measurements.

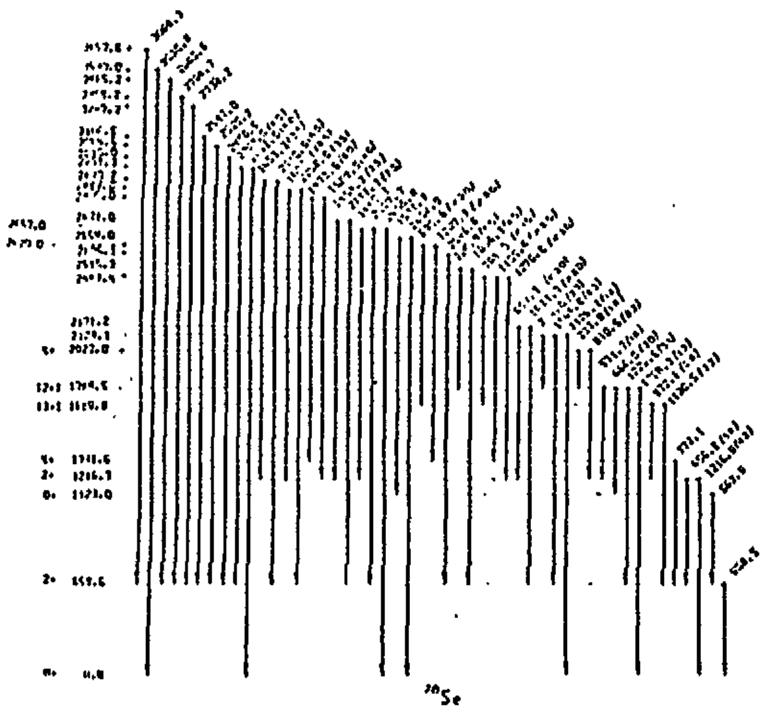

Figure 2. Proposed level scheme of ^{76}Se. The levels noted with an asterisk have at least one characteristic determined from these measurements.