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Resonance neutron capture by ^{209}Bi†

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Neutron capture measurements were made for bismuth samples up to the inelastic scattering threshold at 901 keV (lab). All resonance peaks ($l = 0, 1$) between 2.6 and 30 keV were fitted to single level parameters by least squares adjustment. From 30 to 70 keV the resonances reported from recent neutron transmission studies were fitted. Average radiative widths found were (164 ± 45) meV for $l = 0$ and (33.7 ± 3) meV for $l \geq 1$. The average spacing of $l > 0$ levels was 1.14 ± 0.25 keV for the energy interval 2.6–30 keV. The astrophysical average capture (10.7 mb at $kT = 30$ keV) is little different from earlier estimates but the rate of change with stellar temperature is slower.

[NUCLEAR REACTIONS ^{209}Bi(n,γ), $E = 2.6$–901 keV; measured $\sigma(E)$; deduced ^{210}Bi level parameters, average radiative widths, p-wave spacing.]

INTRODUCTION

The very small neutron capture probability of $^{209}_{83}$Bi is associated with the 126 neutron and 82 proton closed shell core, leaving only one loosely bound ($Q = -3.3$ MeV) proton with spin $-\frac{9}{2}$. The neutron binding energy is exceptionally low (4.6 MeV to the ground state of ^{210}Bi and 4.33 to the 9^- isomer), making the observation of prompt γ emission more difficult than for typical nuclei where 6–9 MeV are available. About 50 resonances have been seen in neutron transmission[1,2] at energies up to 75 keV above neutron binding. The neutron capture probability for individual resonances does not appear to have been previously reported, only various averages in convenient neutron energy ranges. In the present work resonance capture identification (for $l<2$) appears complete to nearly 30 keV and resonances reported from transmission curve parametrization[1,2] up to 70 keV have also been isolated.

The average cross section at stellar interior temperatures (kT near 30 keV) is of significance in the termination of nucleosynthesis by slow neutron capture[3] (the s process) as natural α decay transmutes the heavier nuclei.

EXPERIMENT

Metallic bismuth (99.9+%, 0.01% Pb found on analysis) was used for two sample thicknesses, $0.002\,04 \times 10^{24}$ atoms cm^{-2} and $0.011\,33 \times 10^{24}$ atoms cm^{-2}, respectively. These samples were observed at 40.123 m from the Oak Ridge electron linear accelerator (ORELA) pulsed neutron source, operating at 800–1000 pulses/s and average 5 ns full width at half maximum (FWHM). For the resonances analyzed in bismuth, the neutron energy resolution, $\Delta E/E$ FWHM, is near $\frac{1}{600}$ and predominantly due to the spatial distribution of final collisions in the moderator.

The prompt capture γ rays were detected by a pair of fluorocarbon liquid scintillators; the incident neutron energy was derived from the time of flight, and the average γ energy release from the pulse height.[4] The experimental equipment and operation including calibration and flux monitoring have been described in earlier papers.[5] The procedure for least squares adjustment of resonance parameters to the peaks seen in the capture cross section has been described recently with examples.[6]

Peaks seen in the capture yield were fitted with resonance parameters as indicated in Table I. The scattered neutron sensitivity correction was largest (~50%) for the 12.1 keV resonance (Fig. 1). Of the 34 peaks seen below 30 keV, 22 have been reported in neutron transmission analysis.[1] Three of these were broad enough peaks in capture for us to determine the total width as well as the resonance energy and capture area. The widths found (in eV) compare as follows with the transmission analyses. At 5113 eV $\Gamma = 6.49 \pm 0.14$, 6.05 ± 0.29,[1] and 5.4 ± 0.6.[2] At 12 100 $\Gamma = 292 \pm 26$, 267 ± 11,[1] and 270 ± 45.[2] At 15 510 $\Gamma = 126 \pm 11$, 118 ± 9,[1] and 118 ± 20.[2] Our error estimates are standard deviations computed from the "goodness of fit" to the data achieved by the least squares fitting code,[6] and indicate consistency with the other experiments. Our energy scale averages slightly (~0.1%) below that of Singh *et al.*,[2] but appreciably (~0.5%) above that of Morgenstern *et al.*[1]

Above 30 keV our data were not adequate to isolate all resonances, particularly those formed with $l \geq 2$ neutrons. As several prominent resonances had been fitted (E_0, $g\Gamma_n$, and J determined) in the transmission work, we elected to fit these in the capture data also (up to 70 keV) and include

TABLE I. Capture parameters for resolved resonances in ^{209}Bi(n,γ). Many resonances above 30 keV were not fitted individually and those analyzed correspond to those reported in neutron transmission measurements (Refs. 1 and 2).

Energy (keV)[a]	$g\Gamma_n\Gamma_\gamma/\Gamma$ (meV)	Energy (keV)[a]	$g\Gamma_n\Gamma_\gamma/\Gamma$ (meV)
0.8000[b]	25.0 ± 3.0[b]	27.45[e]	156.5 ± 21.6
2.310[b]	20.0 ± 10.0[c]	28.79	11.5 ± 2.0
3.351	10.9 ± 0.1[d]	29.01	8.9 ± 1.9
4.458	10.8 ± 0.2	29.20	12.7 ± 2.2
5.113	40.8 ± 0.6	29.52	10.5 ± 2.0
6.289	6.4 ± 0.2	30.48	18.0 ± 4.0
6.527	9.1 ± 0.2	32.73	5.1 ± 2.7
9.018	10.6 ± 0.4	32.90	16.0 ± 6.5
9.159	9.6 ± 0.4	33.31	243.0 ± 18.0
9.375	0.8 ± 0.3	34.68	29.0 ± 4.0
9.718	21.7 ± 0.6	37.25	11.2 ± 3.9
9.766	21.2 ± 0.6	38.10	38.1 ± 3.9
12.09	7.7 ± 0.9	39.17	22.5 ± 4.1
12.10	49.0 ± 7.8	42.40	19.2 ± 4.5
12.24	3.6 ± 0.7	43.60	13.7 ± 4.0
14.88	10.1 ± 0.9	44.09	5.1 ± 3.8
15.51	68.0 ± 9.3	44.60	30.2 ± 4.2
15.65	21.8 ± 1.3	45.18	28.8 ± 5.0
17.44	16.7 ± 1.0	45.56	129.0 ± 12.2
17.83	21.7 ± 1.0	46.49	17.8 ± 5.0
20.86	12.8 ± 0.9	49.85	28.6 ± 5.2
21.06	15.8 ± 1.2	51.74	8.4 ± 5.4
22.27	18.2 ± 1.1	52.77	5.1 ± 5.6
23.13	11.2 ± 1.1	53.70	33.2 ± 7.3
23.85	5.0 ± 1.1	54.22	23.4 ± 5.8
24.20	5.0 ± 1.1	55.42	15.1 ± 5.8
25.27	30.7 ± 2.2	57.76	5.1 ± 5.8
27.05	70.4 ± 3.7	61.57	64.4 ± 9.1
27.29	12.8 ± 2.2	69.14	216.0 ± 25.1

[a] Energies are believed accurate to about 0.1% except for the broad resonances.

[b] From Ref. 10.

[c] Estimated.

[d] Statistical standard deviation combined with uncertainty in scattered neutron sensitivity correction. Additional normalization errors are estimated at ±3%.

[e] Probable multiplet.

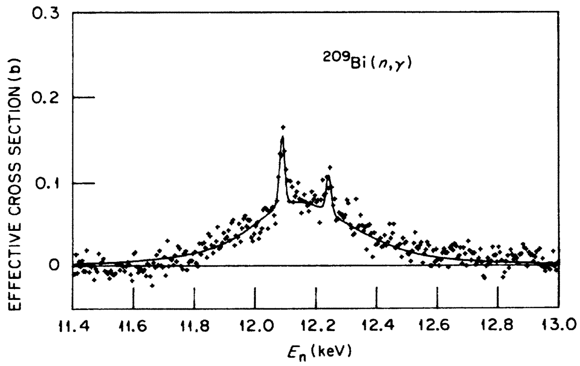

FIG. 1. ^{209}Bi(n,γ) yield for a 0.011 33 atom/b sample. The broad peak has been seen in transmission measurements (Refs. 1 and 2). The curve is a least squares adjusted fit of parameters for three resonances.

the rest as an average capture cross section histogram (see Tables I and II). The cross section histogram was continued (in broadening steps) up to 900 keV, just below the onset of inelastic scattering.

The data have been averaged over a range of Maxwellian temperature distributions appropriate to stellar interiors as shown in Table III. Earlier low resolution Van de Graaff data[7] over a very limited energy range show an exaggerated temperature dependence, though the standard 30 keV values[7,8] are in fair agreement. A recent Hauser-Feshbach calculation[9] is also in reasonable agreement.

The resonance contribution to the resonance capture integral is 200 ± 10 mb and dominates the ~15 mb $1/v$ component.

TABLE II. Residual average ^{209}Bi neutron capture cross sections for unanalyzed resonances up to 900 keV, just below the onset of inelastic scattering.

$\bar{E}$ (keV)	ΔE	$\bar{\sigma}_{n\gamma}$ (^{209}Bi) (mb)
30	10	4.7 ± 3.1 [a]
40	10	18.5 ± 3.1
50	10	10.9 ± 1.7
60	10	9.8 ± 1.7
70	10	9.1 ± 1.7
87.5	25	4.4 ± 1.7
112.5	25	1.0 ± 1.8
137.5	25	3.6 ± 1.8
175	50	4.7 ± 0.9
225	50	3.5 ± 0.9
275	50	2.4 ± 0.9
350	100	3.9 ± 0.6
450	100	4.4 ± 0.6
550	100	2.6 ± 0.6
650	100	2.8 ± 0.6
750	100	2.6 ± 0.4
850	100	2.7 ± 0.4

[a] The indicated error is predominately the 10% uncertainty in the scattered neutron sensitivity correction.

TABLE III. Average ^{209}Bi neutron capture at stellar interior temperatures. The thermal velocity v_T is defined as $(2kT/m)^{1/2}$, with m the reduced mass.

kT (keV)	$\frac{\langle\sigma\cdot v\rangle}{v_T}$	(mb)	$\bar{\sigma}(n,\gamma)$ (mb)
5	16.4	35 [a]	
10	12.4	29 [a]	
20	12.1	17 [a]	
30	10.7	12 ± 4 [a,b]	7.8 ± 2.5 [c]
40	9.3	9 [a]	
50	8.2	7.5 [a]	
60	7.4		
80	6.3		
100	5.7		

[a] Reference 7.

[b] Reference 8 assesses the error.

[c] Reference 9.

DISCUSSION

By combining the neutron widths and parity (and some spin) assignments from the published transmission analyses[1,2] with our capture data we have derived average radiative widths. Four resonances were excluded: the 27.45 keV because it was probably more than one, and those at 9.375, 12.09, and 12.24 keV because the neutron widths were too small or unreported. For 12 s-wave resonances $\bar{\Gamma}_\gamma = 164$ meV with an uncertainty of about 45 meV due to the restricted sample size. The standard deviation was quite large (157 meV), implying 2.2 "degrees of freedom" or very few strong primary γ transitions from these negative parity states in the ^{210}Bi compound nucleus. With such a wide spread in Γ_γ no significant difference was seen between the well-identified $J = 4^-$ and $J = 5^-$ levels (four each).

The 41 $l > 0$ states for which $g\Gamma_\gamma$ could be found gave an average $\bar{\Gamma}_\gamma = 33.7$ meV with an uncertainty of about 3 meV. The standard deviation was 20.3 meV, due in part to lack of knowledge of the individual spin assignments ($J = 3^+, 4^+, 5^+, 6^+$). Calculating the variance contribution for a $2J+1$ level density distribution reduces the standard deviation due to the spread of radiative widths to 19.0 meV implying 6.3 "degrees of freedom" or a significantly greater number of strong primary γ transitions from the $l > 0$ levels than from the s-wave levels discussed despite the much smaller total radiative width.

We find 1.6 and 2.4 times as many weak levels (up to 30 keV) as in transmission.[1,2] The average spacing for $l > 0$ levels we find in the 2.6–30 keV range is 1.14 ± 0.25 keV.

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