Aust. J. Phys., 1978, **31**, 47–54

Neutron Resonance Spectroscopy on ^{209}Bi

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Abstract

The neutron transmission through ^{209}Bi was measured with high resolution at both the 80 and 200 m stations of the Oak Ridge Electron Linear Accelerator. Resonance parameters for s-wave levels below 270 keV and for p-wave levels below 100 keV bombarding energy were obtained. Approximately 25% of the expected neutron strength of a particle–vibrator doorway was identified in the energy range analysed for s-wave resonances. The average s-wave level spacing is $\langle D \rangle_s = 4 \cdot 5 \pm 0 \cdot 6$ keV after correcting for missed levels. The s- and p-wave neutron strength functions are respectively: $10^4 S_0 = 0 \cdot 65 \pm 0 \cdot 15\,(E < 170\text{ keV})$; $10^4 S_1 = 0 \cdot 25 \pm 0 \cdot 07\,(E < 60\text{ keV})$. Both strength functions show evidence of energy-dependent structure.

Introduction

In recent years the low energy neutron resonance parameters of ^{209}Bi have been studied by a number of groups. High resolution time-of-flight techniques were employed both by Morgenstern *et al.* (1969) and by, more recently, Singh *et al.* (1976) to provide resonance neutron width information up to 70 keV bombarding energy. For the larger s-wave resonances, there is good agreement between these two data sets, although the reported p-wave neutron strength functions differ by a factor of two. In addition to these, several earlier measurements obtained with poorer instrumental resolution have been evaluated by Mughabghab and Garber (1973).

The neutron capture cross section of ^{209}Bi has also been recently investigated (Macklin and Halperin 1976) using the capture facility at the 40 m station of the Oak Ridge Electron Linear Accelerator (ORELA). The quantity $g\Gamma_n \Gamma_\gamma / \Gamma$ was obtained for resonances below 70 keV including several resonances previously undetected. The average s-wave radiative width was found to be a factor of five greater than the p-wave radiative width, which appears to be quite inexplicable in terms of current ideas on the radiative capture mechanism.

Most of the interest in this nucleus stems from the proximity of the proton and neutron closed shell configurations in ^{208}Pb. Because of the magic number effect, the reaction cross section for s-wave neutrons incident on ^{208}Pb displays particularly simple structure. Only one s-wave resonance, at 500 keV with neutron width 58 keV, has been observed below 1·7 MeV bombarding energy (Farrell *et al.* 1965). Originally, this resonance was interpreted qualitatively as a two particle–one hole doorway state. However, there are no $2p$–$1h$ states in ^{209}Pb with unperturbed energies below 1 MeV, and Beres and Divadeenam (1970) have argued persuasively that the actual doorway configuration involves a neutron in the $g_{9/2}$ orbit, which occurs near the ground state of ^{209}Pb, coupled to the 4^+ collective state of the ^{208}Pb core which is found at 4·31 MeV. The calculated width and energy of this state are in substantial agreement with the measured values.

The same underlying doorway mechanism is expected to influence the s-wave cross section of other nuclei close to ^{208}Pb. In both ^{206}Pb (Farrell *et al.* 1965) and ^{207}Pb (Newson 1972; Divadeenam *et al.* 1973) the total integrated neutron strength below 1 MeV was found to be nearly equal to that found in the single doorway state in ^{208}Pb+n. The plots of cumulative neutron strength versus neutron energy showed typical 'integral'-shaped behaviour, which indicated a considerable increase in the spreading width of the doorway state the further one moved away from the closed shell configuration. A preliminary analysis of poorly resolved data (obtained by F. T. Seibert and others), extending to $\sim$600 keV bombarding energy in ^{209}Bi+n, has never been published, although a plot of the cumulative neutron strength versus neutron energy based on these data was presented by Divadeenam *et al.* (1973). This plot indicated that about 65% of the doorway state neutron strength lies below 600 keV. The spreading width of the doorway appeared to be in the range 300–400 keV; so none of the previously published analyses covered a sufficiently large range of neutron energy to detect any intermediate structure in the neutron widths.

The object of the present experiment was to obtain the total cross section of ^{209}Bi with the high resolution facility at the 200 m station of ORELA and to seek intermediate structure in the analysed s-wave neutron widths. The resolution achieved ($\Delta E/E \approx$ 0·05%–0·1% FWHM) was considerably better than previously obtained for this nucleus and allowed the extraction of resonance parameters for resolved resonances below 270 keV bombarding energy. Above this energy the resonances were too poorly defined to allow any worthwhile analysis to be made.

Experiment and Data Analysis

The transmission data were obtained at the 200 m station of ORELA with 4 ns bursts using an NE110 proton recoil counter (Hill *et al.* 1971). The target was metallic bismuth of thickness 0·0565 at. b^{-1} and useful data down to about 25 keV were produced. In a subsequent experiment, using a ^{6}Li glass detector at the 80 m station of ORELA, data were also obtained covering the lower energy range below 25 keV. For this run the machine operated with 7·5 ns bursts on another target (0·0719 at. b^{-1}) achieving energy resolution of $\sim$0·1%.

Beam filters of 0·45 g cm^{-2} of ^{10}B eliminated overlap neutrons from the beam. The time-of-flight-dependent backgrounds were determined using blacked-out resonances in Cu and Fe. The detectors were shielded from the low energy γ-rays from the γ-ray flash using $\sim$6 mm thicknesses of Pb and U for the experiments at the 80 and 200 m stations respectively.

The raw data were reduced to transmission form with appropriate background corrections, dead time corrections and error calculations using a standard Oak Ridge code (see e.g. Larson *et al.* 1976). The area and the shape of the transmission dip were then analysed using a nonlinear least squares fitting routine written at the Australian Atomic Energy Commission Research Establishment, which uses Doppler-broadened Breit–Wigner single-level resonance theory. Fig. 1 gives four examples of fits to regions of the transmission data.

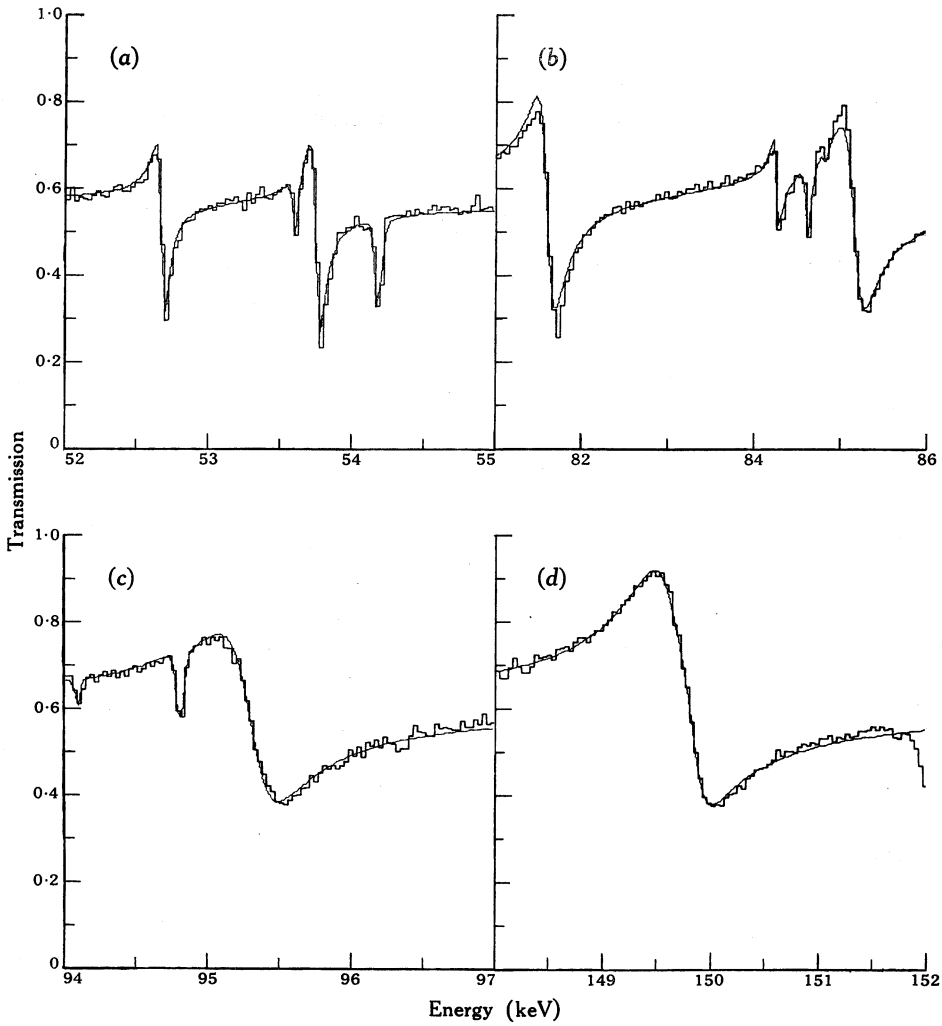

Fig. 1. Calculated fits to portions of the neutron transmission data for ^{209}Bi.

Results

Table 1 lists the resonances observed in the present data to 100 keV and compares the values for $2g\Gamma_n$ with the earlier results of Morgenstern *et al.* (1969) and Singh *et al.* (1976). The s-wave levels were identified by the characteristic interference with the potential scattering cross section. All symmetric resonances were assumed to be p-wave for our analysis, but were subsequently analysed as s-wave to test whether the asymmetry induced would have been detectable in the present data. The stronger symmetric resonances were unambiguously assigned as p-wave by this test. Since ^{209}Bi has spin and parity $J^{\pi} = 9/2^{-}$, s-wave neutrons form resonance sequences with spins 4^{-} and 5^{-}. While there is a slight shape difference between the transmission profiles for s-wave levels of the two spin states, it is insufficient to determine the resonance J values decisively. The J values listed in parentheses in

Table 1. ^{209}Bi resonance parameters below 100 keV*

E (keV)	Γ_n (eV)	l	J	$2g\Gamma_n$ (eV) obtained from: Present	SRLH[A]	MAJS[B]
0·800	4·655±0·050	0	(5)	5·120	5·1	4·74
2·312	18·1±0·3	0	(4)	16·3	17·6	16·20
3·347		1		0·094±0·010	0·16	
4·453		1		0·169±0·018	0·24	0·208
5·108	5·74±0·14	0	(5)	6·31	5·9	6·66
6·282				0·10±0·02		0·11
6·519		1		0·64±0·08	0·56	0·74
9·008		1		0·53±0·10	0·32	0·52
9·150		1		0·28±0·07	0·24	0·40
9·708				0·085±0·020		0·10
9·756		1		0·59±0·08	0·22	0·74
12·123	259±6	0	(4)	233	243	240
15·548	129±2	0	(4)	116	106	106
17·419		1		1·99±0·70	1·00	2·2
17·821				0·51±0·20		
20·84				1·05±0·25		
21·04		1		6·95±1·00	5·0	7·6
22·25				0·20±0·10		
23·12				0·27±0·20		
23·94				0·11±0·08		
25·26		1		25·3±2·0	19·0	28·0
27·04	24·1±2·0	0	(4)	21·7	22	22
28·76				1·4±0·3		0·8
29·00				2·2±0·4		2·2
29·19		1		4·0±0·6	6·0	4·6
29·50		1		3·6±0·5		3·6
32·72		1		2·6±0·5		2·4
32·88				1·0±0·3		1·4
33·33	273±7	0	(4)	246	216	250
34·66				2·8±0·5		2·2
37·24		1		12·7±1·0	12·6	17·4
39·13				2·2±0·4	3·4	2·6
42·36		1		22·0±1·0	14	20
45·53	152±4	0	(5)	167	176	173
45·88		1		6·4±0·8		
46·64		1		7·6±0·8		10
48·41				2·8±0·6		
49·67				2·2±0·5		
49·84		0		8·6±0·8		9·4
50·99		1		11·1±0·9		10·0
52·68		0		24·7±1·0	24	25·2
53·61				5·1±0·6		8·0
53·76		0		36·6±1·0	64	41·4
54·18		1		15·1±0·9		16·4
55·40		1		10·3±0·9		4·8
56·85				4·8±0·6		
58·27		1		8·1±1·0		12·0

* For notes, see end of table.

Table 1 (*Continued*)

E (keV)	Γ_n (eV)	l	J	$2g\Gamma_n$ (eV) obtained from: Present	SRLH[A]	MAJS[B]
60·58		1		3·4±0·8		5·8
61·63	93±4	0	(4)	84	80	88
62·99		1		7·4±1·0		8·2
63·72				3·8±0·5		5·6
67·16		1		14±1	13	15
68·39		1		7±1		
68·58		1		4·6±1·0		
69·14	470±10	0	(5)	517	572	552
70·67		1		21±1		21
72·61	21·5±1·5	0	(4)	19±4	24	
71·68		1		7·9±1·0		
73·07				5±1		
79·70		1		14±1		
81·63	172±5	0	(5)	189		
84·26		0		20·6±0·5		
84·62		1		18·4±0·3		
84·84				2·5±1·0		
85·19		0		238±3		
89·51		1		10·7±2·0		
91·07		1		9·2±1·7		
91·49		1		13·4±2·0		
92·94		1		11·0±1·5		
94·09				3·3±0·8		
94·81		1		15·4±1·8		
95·35	400±13	0	(4)	360		
99·45				5·6±0·7		

[A] SRLH, Data from Singh *et al.* 1976.
[B] MAJS, Data from Morgenstern *et al.* 1969.

the table produce slightly better fits to the data in each case, and are consistent with the previous assignments. Where no preferred J value was obtained, only the quantity $2g\Gamma_n$ is listed. The analysis in these cases proceeded assuming $g = 0\cdot5$ and an average radiative width $\Gamma_\gamma = 0\cdot04$ eV.

Above 100 keV only the s-wave levels were analysed, and above $\sim$270 keV individual resonances became too indistinct to warrant further analysis. Reduced l-wave neutron widths were obtained from

$$\Gamma_n^l = \Gamma_n / P_l E_0^{\frac{1}{2}},$$

where the l-wave neutron penetrability is given by

$$P_0 = 1, \qquad P_1 = (kR)^2/\{1+(kR)^2\}, \qquad P_2 = (kR)^4/\{9+3(kR)^2+(kR)^4\},$$

where k denotes the neutron wave number and R the penetrability radius. In the present calculations we used $R = 9\cdot0$ fm. Table 2 lists the s-wave resonance parameters obtained above 100 keV.

Fig. 2*a* shows a staircase plot of the cumulative count for s-wave levels below energy E. A test of the observed s-wave reduced neutron widths against the expected Porter–Thomas distribution (assuming the neutron strength function is equal for both spin states) indicates that about nine resonances, with reduced neutron widths $g\Gamma_n^0 < 0\cdot05$ eV, are missed over the analysed energy range. The average level spacing for the observed levels, derived from the best straight line fit to the data (solid line in Fig. 2*a*), is $\langle D\rangle = 5\cdot3$ keV. After correcting for the missed levels, the average s-wave level spacing becomes

$$\langle D\rangle = 4\cdot5\pm0\cdot6 \quad \text{keV},$$

corresponding to the dashed line in Fig. 2*a*. Thus the addition of the extra proton to the previously discussed ^{209}Pb compound nucleus has quite a dramatic effect on the complexity of the level structure observed. This is the reason that the doorway spreading width increases so rapidly away from the magic number configuration.

Table 2. ^{209}Bi s-wave resonance parameters above 100 keV*

E (keV)	$2g\Gamma_n$ (eV)	E (keV)	$2g\Gamma_n$ (eV)	E (keV)	$2g\Gamma_n$ (eV)
102·49	684±20	164·0	79±6	213·1	520±20
107·33	108±16	168·4	313±26	221·0	46±4
108·73	175±13	174·4	285±18	225·1	320±25
112·66	390±30	177·9	1560±70	233·9	542±30
118·07	350±20	185·7	1795±100	240·0	1526±175
122·70	42±3	189·5	59±20	246·9	940±50
132·33	112±10	193·9	340±40	253·5	310±25
135·75	617±30	202·2	32±2	261·3	315±30
149·7	618±50	204·1	30±2	263·7	1910±100
149·9	250±40	205·3	97±7		
163·3	112±11	210·3	40±8		

* Values of E have uncertainties of $\pm0\cdot15\%$.

A plot of the cumulative reduced neutron strength below energy E is given in Fig. 2*b*. Since the reduced neutron width of the ^{209}Pb doorway state is $\sim$82 eV, we have found only a little more than 25% of the expected neutron strength in the neutron range covered. The curve fitted to the data in Fig. 2*b* represents the integrated Breit–Wigner profile expected for the doorway state centred near 300 keV bombarding energy with spreading width $\Gamma^{\downarrow} = 350$ keV. No attempt was made to optimize the fit; however, the fits for both $\Gamma^{\downarrow} = 300$ keV and 400 keV were somewhat poorer than that shown. Below 170 keV the best straight line fit to the plot of $\Sigma\, g\Gamma_n^0$ indicates a strength function $10^4 S_0 = 0\cdot65\pm0\cdot15$, in excellent agreement with previous values. Above 170 keV the strength function increases to $\sim1\cdot1\times10^{-4}$ as the centroid of the doorway state is approached.

The capture measurement of Macklin and Halperin (1976) has a greater sensitivity to weak resonances than do transmission measurements, and they reported nine extra levels below 30 keV which are undetectable in the present work. They found the average spacing for $l > 0$ levels to be $1\cdot14\pm0\cdot25$ keV. This implies that about half are d wave, assuming that level densities for states of spin J are proportional to $2J+1$ and independent of parity.

The d-wave strength function is expected to be close to a maximum in this mass region, since the 3d shell model state is located near threshold while the p-wave strength function is small. Accordingly, above $\sim$50 keV some of the smaller resonances identified as p wave in the present data could be large d-wave resonances; however, even at 70 keV the ratio of p- to d-wave neutron penetrability is 30:1, which strongly suppresses the d-wave neutron widths.

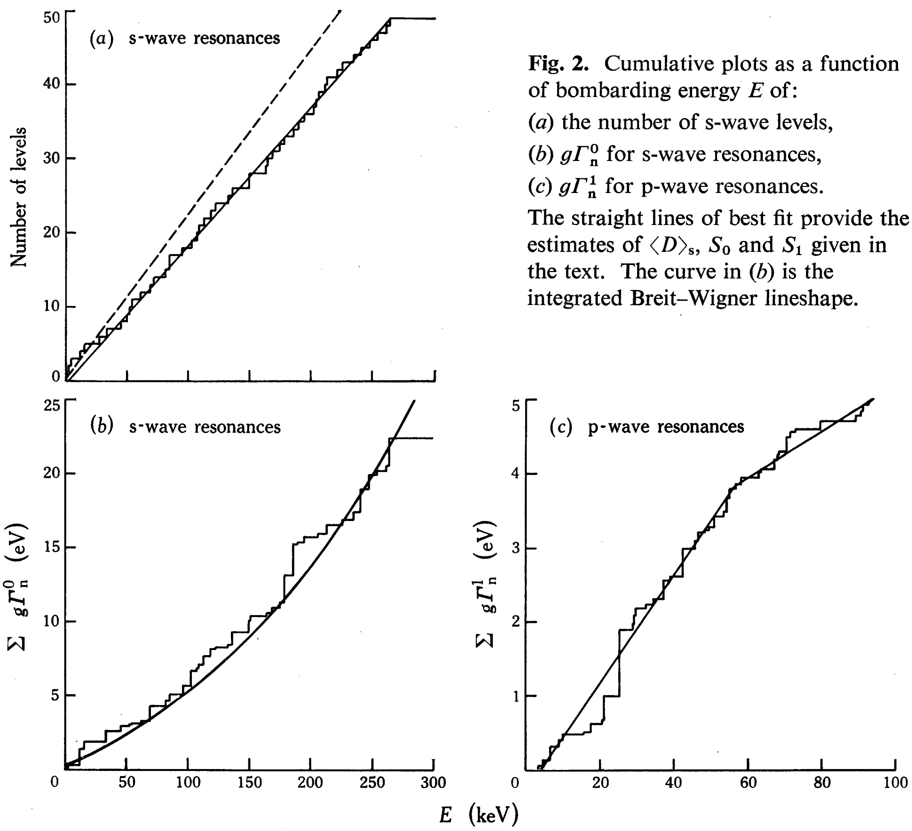

Fig. 2. Cumulative plots as a function of bombarding energy E of:
(*a*) the number of s-wave levels,
(*b*) $g\Gamma_n^0$ for s-wave resonances,
(*c*) $g\Gamma_n^1$ for p-wave resonances.
The straight lines of best fit provide the estimates of $\langle D\rangle_s$, S_0 and S_1 given in the text. The curve in (*b*) is the integrated Breit–Wigner lineshape.

Fig. 2*c* is a cumulative plot of p-wave reduced neutron widths as a function of energy. The best straight line fit below 60 keV indicates that the p-wave strength function is given by $10^4 S_1 = 0{\cdot}25 \pm 0{\cdot}07$. Again there appears to be some evidence for intermediate structure, since the strength function reduces quite significantly above $\sim$60 keV (where it is given by $10^4 S_1 \approx 0{\cdot}10 \pm 0{\cdot}04$). This decrease is not caused by missed levels since the probability of missing p-wave resonances is approximately independent of energy. Our value for S_1 favours the value reported by Morgenstern *et al.* (1969) ($S_1 = 0{\cdot}25 \times 10^{-4}$) and is considerably higher than the value ($S_1 = 0{\cdot}13 \times 10^{-4}$) reported by Singh *et al.* (1976).

It is interesting to note that the 13 s-wave levels below 70 keV have an average radiative width which is a factor of five greater than that for the p-wave levels (Macklin and Halperin 1976). In addition, there exists a high degree of correlation between Γ_n^0 and Γ_γ ($\rho \approx 0{\cdot}6 \pm 0{\cdot}3$) even though valence neutron transitions, which can normally account for the presence of such correlations, are expected to be extremely weak for this nucleus (Allen and Musgrove 1978). Furthermore, a calculation of the radiative capture cross section of ^{206}Pb due to the proposed particle–vibrating-core doorway, revealed a cross section smaller by a factor of 1000 than that measured (Lev and Beres 1976). Therefore it appears unlikely that the correlations between Γ_n^0 and Γ_γ in ^{209}Bi could be a result of a common doorway in both neutron and photon channels.

However, there is evidence to suggest that the prompt background correction applied to the Macklin and Halperin (1976) data could have been underestimated, leading to the observed occurrence of large radiative widths for the largest scattering resonances (Allen *et al.* 1978).

Conclusions

The high-resolution measurement of neutron widths in ^{209}Bi below 270 keV identified approximately 25% of the expected neutron strength of the particle–vibrator doorway state which has been identified in the cross section of ^{208}Pb. The spreading width for the doorway state appears to be in the vicinity of 350 ± 50 keV. The $g_{9/2} \otimes 4^+$ doorway state carries negligible intrinsic radiative strength; so the high correlation occurring between s-wave radiative widths and neutron widths could be a result of prompt neutrons scattering in the γ-ray detector.

Acknowledgments

The authors acknowledge the assistance of W. Wilson of Argonne National Laboratory, who collaborated in obtaining these data. This research is sponsored in part by ERDA under contract to Union Carbide Corp.

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Manuscript received 5 September 1977