Neutron resonance spectroscopy: ^{209}Bi†

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Neutron total cross section vs energy measurements were made for several thicknesses of bismuth metal. The results of the resonance parameter evaluation for 30 levels (12 s and 18 p) to 75 keV are given. Parameters for the p levels, and for three weak s levels were determined using a transmission area analysis. An R-matrix multilevel shape analysis fitting was used to obtain the final choice resonance parameters for the nine dominant $l=0$ levels. The experimental points and R-matrix fit curve to 75 keV are shown. The (E_0, J, Γ_n) choices for these nine levels are (0.800, 5, 4.6), (2.312, 4, 19.5), (5.112, 5, 5.4), (12.15, 4, 270), (15.54, 4, 118), (27.08, 4, 24), (33.34, 4, 240), (45.58, 5, 160), and (69.18, 5, 520), where E_0 is in keV and Γ_n is in eV. On the basis of these levels, we obtain for the s and p strength functions $10^4 S_0 = (0.62^{+0.36}_{-0.20})$ and $10^4 S_1 = (0.13^{+0.06}_{-0.04})$. A channel radius of 9 fm was used to calculate S_1 and the evaluation ignores the possibility that some p levels were missed below 75 keV.

[NUCLEAR REACTIONS ^{209}Bi, $E = 500$ eV–75 keV, measured $(n,$ total); deduced resonance E_0, l, J, Γ_n or $g\Gamma_n$, S_0, S_1.]

I. INTRODUCTION

This is one of a series of papers[1–21] presenting the results of high resolution neutron time of flight spectroscopy measurements using the Columbia University Nevis synchrocyclotron. We present here the results of our analysis of 200 m transmission data for Bi samples giving R-matrix fit level parameters to 75 keV for the dominant $l=0$ levels. For the p levels, we used our usual transmission dip area analysis.

Natural Bi is 100% ^{209}Bi which has ground state $(I^\pi) = (\frac{9}{2})^-$. Since it is only one proton removed from closed neutron and proton shells ^{208}Pb, its neutron resonance spacing is similar to that for much lighter nuclei rather than for other heavy nuclei such as the odd A isotopes of Ta, W, or Au. The $l=0$ levels can have $J=4$ or $J=5(-)$, while the p levels can have $J=3$, 4, 5, 6(+). The analysis in this paper is mainly based on older data which were analyzed to yield σ vs E from ~500 eV to >100 keV, curves of which have been published in the 1966 edition of BNL-325.[22] This is supplemented by a later measurement, using a single sample which was particularly useful for the p-level evaluation and as a cross check. Preliminary results of the level analysis were presented recently.[23] Subsequent R-matrix fitting has given the somewhat different best $l=0$ level parameters reported here.

The main other high resolution σ_{tot} measurements below ~200 keV are those of Morgenstern *et al.*[24] (Saclay), 4 keV $\leq E \leq$ 70 keV; Nichols *et al.*[25] and Gibbons[25] (Duke), 1 keV $\leq E \leq$ 130 keV; and Firk *et al.*[26] (Harwell), $E \leq 20$ keV. The Saclay resonance parameter results are the most complete below ~70 keV. It is unfortunate that they have not made plots of their experimental σ_t vs E available for the record. Since completion of the work in this paper, we have learned that very high quality, high resolution measurements on Bi have been made using the electron linac at ORNL.[27] When fully analyzed, they should yield greatly improved and extended σ_t vs E and resonance parameter results for Bi to ≫100 keV.

II. EXPERIMENTAL DETAILS

Our earlier more complete measurements used our 200 m flight path, with experimental details as described in a previous paper.[1] A 2000 channel analyzer was used with 100 ns detector channel widths. Metallic samples of Bi were used having $(1/n) = 9.92$, 50.4, and 228 b/atom. These data provide the main σ vs E results.

Later measurements for a single sample, $1/n = 30.31$ b/atom of Bi metal, used a 16 000 channel analyzer with 40 ns channel widths for most of the energy region. The experimental conditions were as described in our paper on Na.[7] The newer data were somewhat incomplete in that, while the count per channel N vs E corresponding to (transmission) $T=0$ could be established with fair accuracy below ~100 keV from the "bottoming resonance" dip count rates, the N vs E corresponding to $T=1$ needed to obtain sample transmission (T)

and σ_{total} vs E could not be established reliably. Our final procedure involved choosing a smooth N vs E for $T=1$ to give general agreement with the older data σ vs E between levels. The newer data were mainly useful as a check on the older data for resonances, and to yield better area analysis results for the p-level parameters.

III. ANALYSIS DETAILS AND RESULTS

The analysis procedures have been described in our previous papers.[2,7,19] The p-level analysis used our standard area analysis programs which include the effects of Doppler broadening and are insensitive to the experimental resolution. We also first used the area programs for the s-level analysis. The $l=0$ area analysis also includes the contributions from interference between potential and resonance scattering. For all levels, a capture width of 0.1 eV was used.

The results were insensitive to the exact choice of Γ_γ for $\Gamma_\gamma \lesssim 0.2$ eV. The area analysis was considered to be satisfactory for evaluating $g\Gamma_n$ values for the p levels (where $g=0.35$, 0.45, 0.55, or 0.65 for $J=3, 4, 5, 6$). The effect of the interference asymmetry between potential and resonance scattering was such that a shape fit procedure was favored for s levels. We used a single level Breit-Wigner analysis including interference and Doppler effects. Each s resonance was considered independently, comparing the measured and calculated σ vs E in the resonance region for a range of Γ_n values for each level J choice (4 or 5) and for a range of choices for the $J=4$ and 5 potential cross sections, including the wing effects of other s levels. This yielded "best choice" resonance J and Γ_n values for the main s levels.

The final fit procedure for the s levels attempted to obtain a best fit of the measured σ vs E below 75 keV, ignoring p levels using a multilevel R-matrix fit. The previous s-level J choices were maintained and Γ_n values near the previous fit

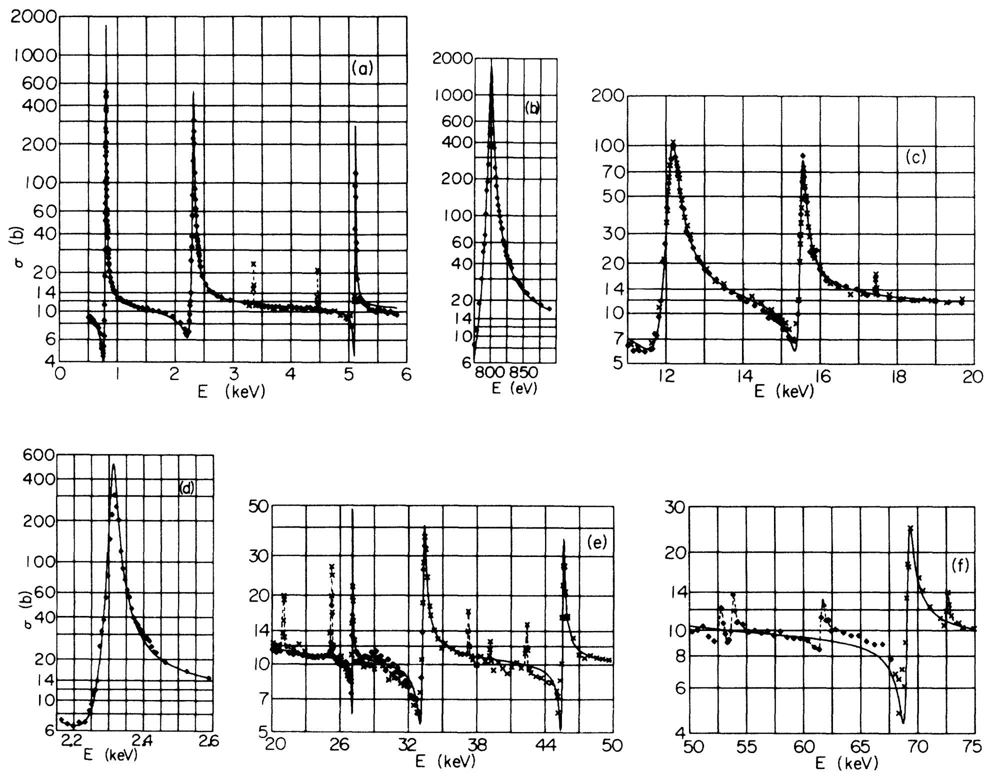

FIG. 1. (a)–(f) The measured neutron total cross section vs energy of ^{209}Bi from 500 eV to 75 keV and a multilevel R-matrix fit to the strongest s levels using the parameters in Table I. To avoid an excess clutter of data points and to reduce statistical fluctuation effects where no true structure is believed to be present, most of the experimental cross sections are averages over 3 to 81 channels. Where abrupt "true" structure is seen, 1 to 3 channel averages are shown. The solid curve is the R-matrix fit which does not include p levels or a few weaker s levels. The dashed curves are included as an aid to the eye in those regions. Points denoted by × are from the newer data and the rest are from the older data.

TABLE I. The R-matrix parameters for nine observed, relatively strong, $l=0$ levels in ^{209}Bi below 75 keV as plotted in Fig. 1. The s-wave potential scattering parameters (Ref. 7) $R_J{}^0 = A_J + B_J(E - E_{1/2})/E_{1/2}$ used $A_4 = -0.03$, $B_4 = 0.04$, $A_5 = -0.03$, $B_5 = 0.04$, with $E_{1/2} = 37$ keV and a channel radius $a = 9$ fm.

E_0 (keV)	J	Γ_n (eV)
0.800	5	4.6 ± 0.4
2.312	4	19.5 ± 1.0
5.112	5	5.4 ± 0.6
12.15	4	270 ± 45
15.54	4	118 ± 20
27.08	4	24 ± 6
33.34	4	240 ± 40
45.58	5	160 ± 30
69.18	5	520 ± 70

TABLE II. The parameters obtained using the transmission area analysis for 18 p levels and 3 weak s levels (denoted ‡) observed in the neutron interaction with ^{209}Bi to 75 keV.

E_0 (keV)	$g\Gamma_n$ (eV)	E_0 (keV)	$g\Gamma_n$ (eV)
3.348	0.08 ± 0.03	39.19	1.7 ± 0.5
4.455	0.12 ± 0.04	42.44	7 ± 2
6.524	0.28 ± 0.08	44.17	1.4 ± 0.4
9.018	0.16 ± 0.05	51.80	3.5 ± 1.0
9.153	0.12 ± 0.04	52.84‡	12 ± 3
9.762	0.11 ± 0.04	53.85‡	32 ± 8
17.45	0.50 ± 0.15	57.60	5.8 ± 1.5
21.05	2.5 ± 0.7	61.80‡	40 ± 8
25.28	9.5 ± 3.0	67.07	6.7 ± 2.0
29.23	3.0 ± 0.8	72.60	12 ± 4
37.25	6.3 ± 2.0		

values were tried for various common choices of $R_J{}^0 = A_J + B_J(E - E_{1/2})E_{1/2}$ (see Refs. 7 and 19). The comparison of the experimental σ vs E and our final choice R-matrix fit is shown in Fig. 1. The s-level parameters are given in Table I for the fit. Table II gives the level energies and $g\Gamma_n$ values for the 18 observed p levels and for 3 weak s levels for which J is not established.

The indicated experimental points are mainly 3 to 81 channel data averages to reduce statistical fluctuations where a careful study of the data did not appear to show unambiguously that true levels rather than just statistical fluctuations were present. This was also necessary to prevent an unreadable overly cluttered figure which would result if too many experimental points were included. At some levels, where relevant, we show selected points having ~1 to 3 channel averaging to demonstrate the presence of the weaker levels, etc. The choice $a = 9.0$ fm for the channel radius, and $A_J = -0.03$, $B_J = 0.04$ for both $l=0$ channels seemed to give a compromise "best fit" with experimental points. The R-matrix curve does not include resolution or Doppler (mainly negligible) contributions. It tends to rise far above the measured $\sigma_{\max}$ for many levels, partly due to not using (thin) samples having high enough $(1/n)$ values. Better fits in local regions could have been obtained using $R_J{}^0$ values which would be worse elsewhere. For example, from 1 to 2 keV, the fit curve is a little below the experimental points. From 6 to 11 keV (not shown), it is ~1 b above the experimental points, with similar effects in other local regions. The shape of our experimental σ vs E should be less uncertain than the absolute σ values. Thus, the fit curve may give a better indication of the true σ vs E behavior, except for weak levels, than the experimental points.

The Saclay group[24] report parameters for 44 levels between 4.4 and 70.3 keV, including many weak levels which we do not. For many of these levels our data show small possible increases in σ at the expected regions, but the effects are too small to unambiguously distinguish from the background fluctuations. Our energies are ~0.6% higher than theirs. For the levels where we both give $g\Gamma_n$ values, there is fair agreement, particularly for the stronger levels.

Using the results in Tables I and II we obtained implied values of s- and p-strength functions as $10^4 S_0 = (0.62^{+0.38}_{-0.20})$ and $10^4 S_1 = (0.13^{+0.06}_{-0.04})$, respectively. Our quoted uncertainties in S_0 and S_1 are based on the 0.841 to 0.159 confidence limits as described in Ref. 28. These values and uncertainties do not include the possibility that weak levels, mainly p levels, were missed according to the Saclay[24] results.

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