Phase-shift analysis of neutron-^{209}Bi scattering and its comparison to neutron-^{208}Pb scattering

Z. P. Chen
Department of Physics, Tsinghua University, Beijing, The People's Republic of China ,
Department of Physics, Duke University, Durham, North Carolina 27708 ,
and Triangle Universities Nuclear Laboratory, Duke Station, Durham, North Carolina 27708

W. Tornow and R. L. Walter
Department of Physics, Duke University, Durham, North Carolina 27708
and Triangle Universities Nuclear Laboratory, Duke Station, Durham, North Carolina 27708
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Published n-^{209}Bi elastic differential cross-section, analyzing power, and total cross-section data in the energy range from 1.5 to 14 MeV were analyzed via a phase-shift analysis in order to find out whether these data show similar, unexplained resonance structures as observed recently for n-^{208}Pb scattering. Although the n-^{209}Bi and n-^{208}Pb data are very similar, some of the phase shifts are quite different for the two systems. Only one resonancelike structure was observed for n-^{209}Bi scattering in the excitation energy range from 9 to 18 MeV compared to eleven in the n-^{208}Pb system, implying that n-^{209}Bi data are probably more suitable than the classical n-^{208}Pb system for detailed mean-field analyses approached through dispersion-relation optical models.

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I. INTRODUCTION

A phase-shift analysis was performed by Chen *et al.* [1] in an attempt to find reasons why sophisticated optical-model analyses employing the dispersion relation do not provide a better fit to n-^{208}Pb scattering data. In their study they found that the n-^{208}Pb scattering system is characterized by broad and overlapping resonancelike structures. To be specific, in the incident neutron energy range from 4 to 14 MeV, corresponding to an excitation energy range in ^{209}Pb from 8 to 18 MeV, spin, parity, excitation energy, total and partial width of 13 resonances were identified. It was speculated in Ref. [1] that the low-lying resonances in ^{209}Pb might be caused by cusp effects related to the opening of inelastic channels and that other resonancelike structures might be caused by many-body effects specific to the doubly closed shell nature of the ^{208}Pb core. In order to check on this interpretation we performed a phase-shift analysis of the n-^{209}Bi scattering system in the incident neutron energy range from 1.5 to 14 MeV. Except for the $(n,2n)$ channel, the threshold energies for the neutron induced reactions of interest are quite different for ^{209}Bi and ^{208}Pb. Therefore, we expect to observe structures in some phase shifts that differ from those found in the n-^{208}Pb analysis. Furthermore, the additional proton in ^{209}Bi is expected to generate a larger number of configurations than are available in the n-^{208}Pb system; this aspect reduces the possibility for observing distinct resonancelike structures in the n-^{209}Bi system because of the relatively poor resolution of the experimental systems used to obtain n-^{209}Bi scattering data.

Although many phase-shift analyses of nucleon-nucleus scattering have been performed for light nuclei in the energy range of 5 to 10 MeV, to our knowledge nobody has published such analyses of differential cross section and analyzing power data for medium weight or heavy nuclei in this energy range. One reason for this is that the number of partial waves is fewer for light nuclei, and another is that insufficient analyzing power information exists for neutron-nucleus scattering in this energy range. It was only with the availability of the recent analyzing power measurements of Roberts *et al.* [2] for ^{208}Pb that it became feasible to conduct the phase-shift analysis [1] for a heavy nucleus. (Coulomb scattering complicates the analysis of proton-nucleus scattering data in this energy range because of its dominance.) Building on the results of Ref. [1], it was possible to extend the analysis to the $n+^{209}$Bi system.

II. PHASE-SHIFT ANALYSIS FOR n-^{209}Bi

Differential cross section $\sigma(\theta)$ data from seven sources and the analyzing power $A_y(\theta)$ for n-^{209}Bi elastic scattering at 6 and 9 MeV have been published in the energy range from 1.5 to 14 MeV. Figure 1 illustrates the strong similarity between the data for n-^{209}Bi at 6 and 9 MeV to the phase-shift fits for n-^{208}Pb which were obtained in a previous work [1] by our group. In Fig. 1 the symbols with error bars represent the $\sigma(\theta)$ data of Refs. [3,4] and the $A_y(\theta)$ data of Ref. [5] for n-^{209}Bi, and the dotted curves are the phase-shift fits to the n-^{208}Pb data. (At lower energies the differences between n-^{209}Bi and n-^{208}Pb are larger in the diffraction minima due to larger differences in the magnitude of compound-elastic contributions to the scattering observables.) The similarity between the two systems is further documented by the close agreement (3%) between the total cross-section σ_{tot} data in the energy range of interest. Figure 1 clearly demonstrates that the n-^{208}Pb phase shifts of Ref. [1] are logical starting values for conducting a phase-shift search of the n-^{209}Bi data. Accurate $\sigma(\theta)$ data exist in the energy range from 1.5 to 14 MeV at 38 energies. The only high accuracy $A_y(\theta)$ data are those shown in Fig. 1 which are taken from recent work of our group.

As is common in conventional spherical optical-model

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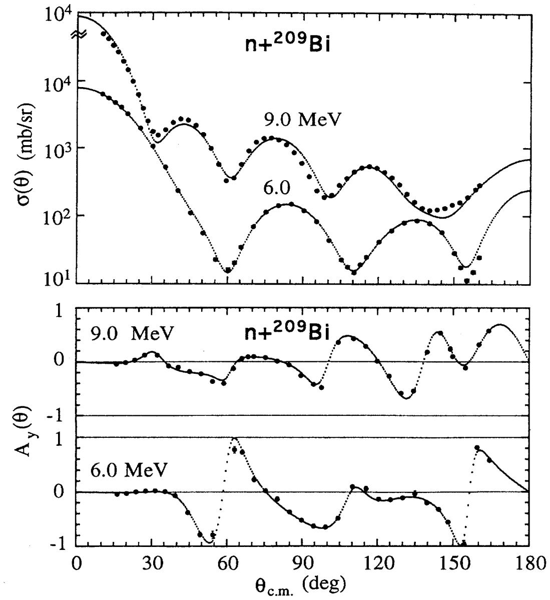

FIG. 1. Differential cross-section data (top panel) from Refs. [3,4] and analyzing power data (bottom panel) from Ref. [5] for n-^{209}Bi at 6 and 9 MeV in comparison to predictions calculated from the recent n-^{208}Pb phase-shift analysis (Ref. [1]).

analyses, we neglected the spin of ^{209}Bi (9/2) and followed closely the phase-shift analysis strategy described in Ref. [1]. We tried several different starting energies in our multi-energy phase-shift analysis search, i.e., 9, 6, 4, and 1.5 MeV and always ended up with the same final phase-shift solution. Samples of the data and phase-shift fits are plotted in Figs. 2 and 3. The $\sigma(\theta)$ fits at other energies and fits to $A_y(\theta)$ were of comparable good quality. Figure 4 (top panel) shows our

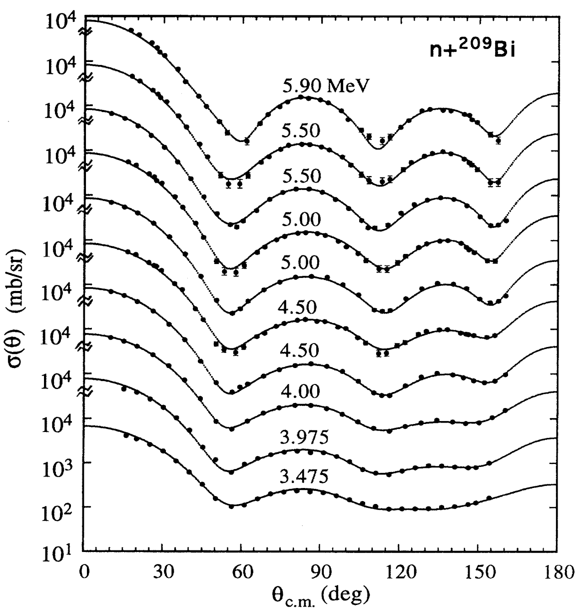

FIG. 2. Comparison of phase-shift analysis results (curves) and $\sigma(\theta)$ data for n-^{209}Bi between 3.475 and 5.90 MeV neutron energy.

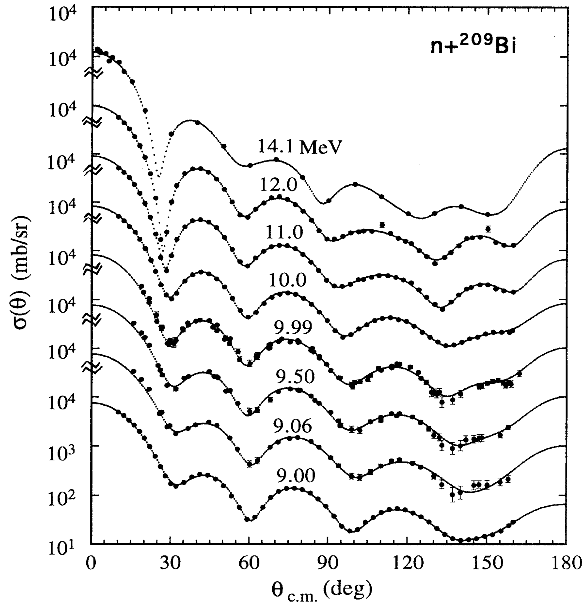

FIG. 3. Same as Fig. 2 for the neutron energy range from 9.0 to 14.1 MeV.

phase-shift fit compared to measured σ_{tot}. The χ^2/N values (chi-squared per number of data points) ranged from 1.2 to 3.9 for the 38 individual sets of data. In general, the real part (δ) of the phase shifts found in the present work exhibit a smooth energy dependence. Similar to our findings in previous n-nucleus phase-shift analyses [1,6], "local" deviations from a smooth energy dependence, i.e., fluctuations from one energy to another, are more likely to show up in the imaginary part (η) of the phase shift rather than in δ. These local deviations are probably due to some irregularities in the data. We tried to smooth these local deviations; however, this was only possible at the expense of considerably deteriorated fits to the data.

Focusing first on the results for the higher partial waves, we note that the δ values for $l=$ 8 and 9 are less than 2° below 7 MeV and have gentle energy dependences out to the highest energy (14 MeV). For $6 \leq l \leq 9$, except where resonant structures were identified in ^{209}Pb, the general behavior of the phase shifts was quite similar for the ^{209}Pb and ^{210}Bi systems. For $I_{13/2}$ there is a strong structure at 9 MeV and the Argand plot was suggestive of a resonance, but not conclusive. A somewhat similar structure was observed for the ^{209}Pb system at a nearby energy, but it was not considered to satisfy the resonance criterion in that analysis. For $l=5$, a dip in η was observed around $E_n=5$ MeV, but the Argand plot did not exhibit resonance behavior.

As for the "gross" structures in δ and η, only in three cases can the structures be considered as resonances based on the criterion that they present a reasonable Argand plot. These resonances are indicated by solid curves in Fig. 5 for $P_{3/2}$ at 3.10 MeV ($E_x=7.69$ MeV, $\Gamma=0.36$ MeV, $\Gamma_n/\Gamma=0.19$) and in Fig. 6 for $F_{7/2}$ at 2.90 MeV ($E_x=7.49$ MeV, $\Gamma=0.36$ MeV, $\Gamma_n/\Gamma=0.39$) and a less certain one at 4.28 MeV ($E_x=8.86$ MeV, $\Gamma=0.64$ MeV, $\Gamma_n/\Gamma=0.15$). The phase-shift values shown in Figs. 5 and 6 were derived in the

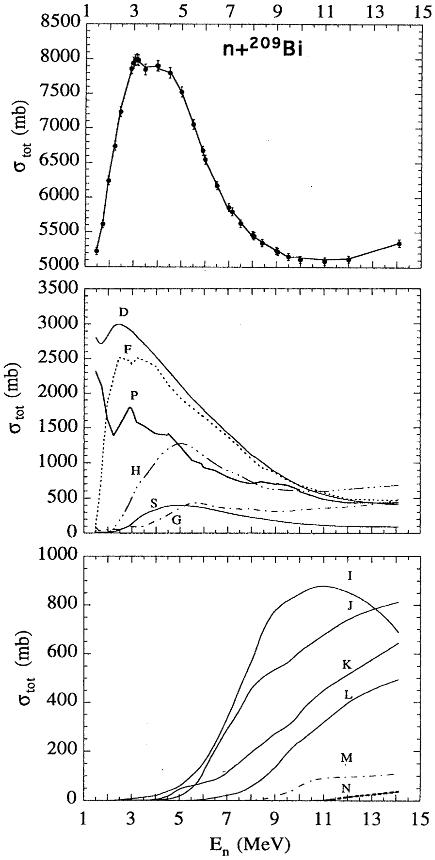

FIG. 4. Top panel: Comparison of phase-shift analysis result (solid curve) and n-^{209}Bi total cross-section σ_{tot} data. Note the suppressed zero on the σ_{tot} scale. Center panel: Individual partial-wave contributions to σ_{tot} from $l=0$ (S waves) to $l=5$ (H waves). Bottom panel: Same as center panel for $l=6$ (I waves) to $l=11$ (N waves). Note the different σ_{tot} scales used in the bottom and center panel.

present work. The uncertainties indicated by the vertical bars were calculated following the procedure in Ref. [1]. The curves shown in the resonance region are fits to the phase shifts using Eq. (2) of Ref. [1]. In Ref.[1] a $P_{3/2}$ resonance was observed in ^{209}Pb at exactly the same excitation energy E_x as in ^{210}Bi; however, its width ($\Gamma=1.1$ MeV) is much larger than found for ^{210}Bi ($\Gamma=0.19$ MeV). The only $F_{7/2}$ resonance reported in Ref. [1] for ^{209}Pb is located at much higher excitation energy ($E_x=11.8$ MeV) than the $F_{7/2}$ resonances found in the present work. In contrast to Ref. [1], where 11 resonances were identified in ^{209}Pb in the excitation energy range from 9 to 18 MeV, only one was found in ^{210}Bi in the corresponding energy range.

It should be noted that the phase shifts displayed pronounced gross structures in regions other than the four resonances noted above. Some of these nonresonancelike structures affect η but not δ. This is the case for $D_{3/2}$ around 4 and 10 MeV (see Fig. 7), for $F_{5/2}$ near 6 and 10 MeV, and for $H_{11/2}$ in the vicinity of 5 MeV. Some structures show up only in δ, especially in $D_{5/2}$ near 3 MeV, in $F_{5/2}$ around 9 MeV, in $G_{7/2}$, $H_{11/2}$, and $H_{9/2}$ in the vicinity of 2 MeV, and in $J_{15/2}$ and $J_{13/2}$ between 3 and 5 MeV. Finally, gross structures are

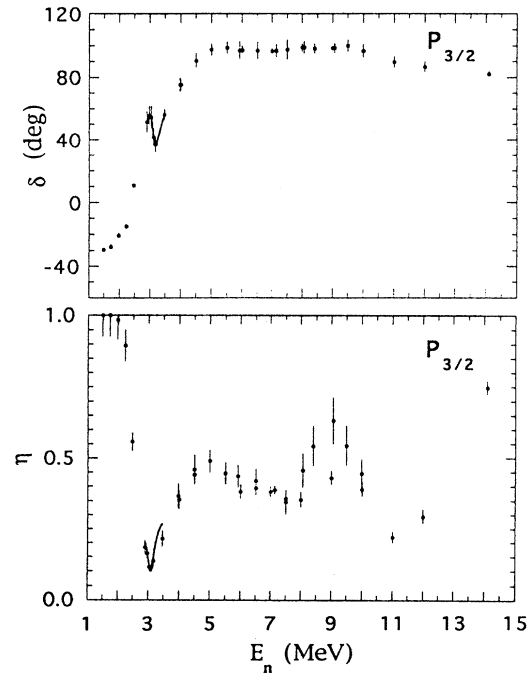

FIG. 5. Energy dependence of n-^{209}Bi phase-shift parameters δ (real part) and η (absorptive part) for $P_{3/2}$ partial wave. The solid curves around 3 MeV represent fits to the $P_{3/2}$ resonance using parameters given in text.

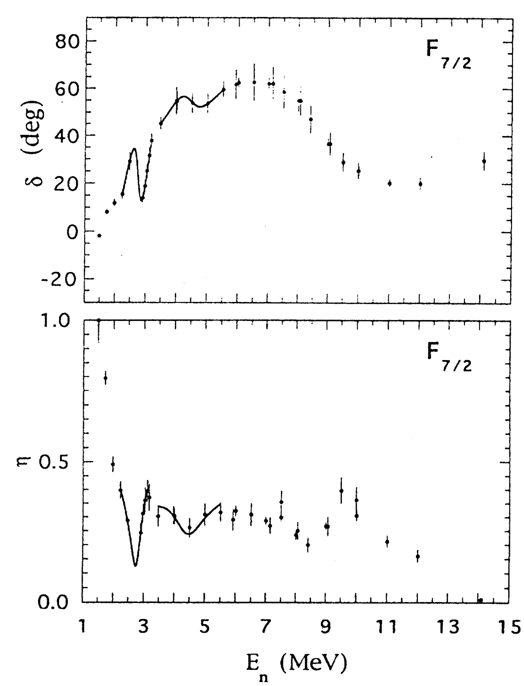

FIG. 6. Same as Fig. 5 for $F_{7/2}$ partial wave. The solid curves between 2 and 6 MeV represent fits to two $F_{7/2}$ resonances using the parameters given in text.

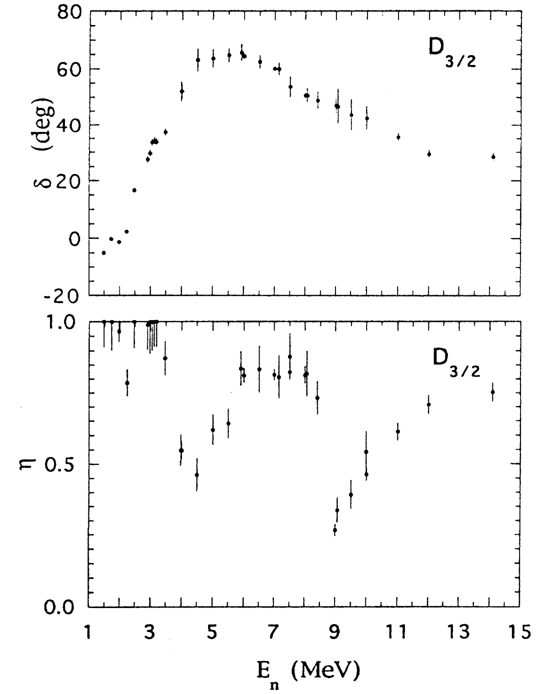

FIG. 7. Same as Fig. 5 for $D_{3/2}$ partial wave.

present both in δ and η in $S_{1/2}$ near 4 MeV, in $P_{1/2}$ centered around 7 MeV, in $H_{9/2}$ in the vicinity of 6 MeV, and in $J_{13/2}$ in the vicinity of 8 MeV. As in the case of the local deviations mentioned above, extensive searches were performed in attempts to remove these gross structures in the phase shifts and simultaneously describe the data accurately; again, this turned out to be impossible.

Partial-wave contributions to σ_{tot} are presented in the center and bottom panels of Fig. 4. As can be seen, they exhibit a fairly smooth energy dependence, except for $l=1$ (P waves) and $l=3$ (F waves). Clearly, the structure observed in σ_{tot} in the vicinity of $E_n=$ 3 MeV (see top panel of Fig. 4) is caused by an F- and P-wave resonance ($F_{7/2}$ at $E_{nR}=2.9$ MeV and $P_{3/2}$ at $E_{nR}=3.1$ MeV). The small bump in σ_{tot} near 4 MeV is due to the second $F_{7/2}$ resonance ($E_{nR}=4.28$ MeV) found in the present work; the F partial-wave contribution nicely accounts for this structure.

III. DISCUSSION AND CONCLUSION

Comparing the present n-^{209}Bi phase-shift analysis results to the n-^{208}Pb results of Ref. [1], one immediately notices the absence of resonancelike structures in the n-^{209}Bi system in the excitation energy range from 9 to 18 MeV. For the n-^{208}Pb system 11 resonancelike structures were reported in this energy range. For the n-^{209}Bi system only one fairly broad resonancelike structure ($I_{13/2}$ near 9 MeV) was positively identified. The structure observed in η for the $G_{9/2}$ and $H_{11/2}$ phase shifts in the vicinity of $E_n=5.5$ MeV is not accompanied by the required behavior in δ to form a reasonable Argand plot. However, the uncertainty associated with the δ and η values in this energy region does not completely rule out the possible existence of a resonancelike structure in the $G_{9/2}$ and/or $H_{11/2}$ phase shift.

In contrast to the n-^{208}Pb system, the n-^{209}Bi system is governed by gross structures that do not have resonance character. The physical origin of these structures is unclear. However, all the gross structures are starting to develop at either 3 MeV ($S_{1/2}$, $P_{1/2}$, $D_{3/2}$, $D_{5/2}$, $H_{9/2}$, $J_{15/2}$, and $J_{13/2}$), 4 MeV ($F_{5/2}$ and $H_{11/2}$), or 8 MeV ($F_{5/2}$ and $F_{7/2}$), in close correlation with the ^{209}Bi(n,t) threshold at 2.7 MeV, the (n,np) and $(n,^3$He) thresholds near 4 MeV, and the $(n,2n)$ threshold at 7.5 MeV. Unless this correlation is accidental, the most likely explanation for these gross structures is the action of cusp effects related to the opening of inelastic reaction channels. Such a correlation between nonresonancelike structures and threshold energies could not be established for the n-^{208}Pb system since the associated energy region is dominated by resonancelike structures.

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[1] Z.P. Chen, W. Tornow, and R.L. Walter, Phys. Rev. C **46**, 1019 (1992).
[2] M.L. Roberts, P.D. Felsher, G.J. Weisel, Z.M. Chen, C.R. Howell, W. Tornow, R.L. Walter, and D.J. Horen, Phys. Rev. C **44**, 2006 (1991).
[3] R.D. Lawson, P.T. Guenther, and A.B. Smith, Phys. Rev. C **36**, 1298 (1987).
[4] R.K. Das and R.W. Finlay, Phys. Rev. C **42**, 1013 (1990).
[5] G.J. Weisel, Ph.D. dissertation, Duke University, 1992.
[6] W. Tornow, E. Woye, and R.L. Walter, J. Phys. G: Nucl. Phys. **13**, 177 (1987), and references therein.