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ENERGY DEPENDENCE OF THE ^{208}Pb(^{16}O,^{15}N)^{209}Bi REACTION[*]

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Abstract:

The elastic scattering and one-proton transfer reaction induced by 312.6 MeV ^{16}O ions on ^{208}Pb are investigated and compared with data at lower incident energies. A conventional DWBA analysis can account for the qualitative features of the energy spectra but overestimates the energy dependence of the observed absolute cross sections by almost an order of magnitude between 104 and 312.6 MeV.

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Studies of heavy-ion induced direct-transfer reactions over a wide range of incident energy can reveal aspects of the reaction mechanism that are obscured at any one energy by uncertainties concerning the internal structure of the nuclear states involved. This letter reports measurements at 312.6 MeV of the differential cross sections for the proton-transfer reaction ^{208}Pb(^{16}O,^{15}N)^{209}Bi populating several known single-particle states in ^{209}Bi. Together with the results of earlier studies[1,2] at 104, 140 and 216.6 MeV, transfer cross sections are now available at incident energies extending from near the Coulomb barrier to more than 200 MeV above, thereby enabling a sensitive study of the reaction mechanism. The nuclei under consideration are near major shell closures, and their microscopic nature is well understood. The ^{208}Pb(^{16}O, ^{15}N)^{209}Bi reaction should thus be well suited for testing the applicability of the DWBA over a wide range of incident energy. It is the purpose of this letter to show that the DWBA fails by nearly one order of magnitude to reproduce the energy dependence of the experimentally observed cross sections even for such a well-understood system as ^{16}O + ^{208}Pb.

The elastic scattering of ^{16}O on ^{208}Pb and the reaction ^{208}Pb(^{16}O, ^{15}N)^{209}Bi were studied at an incident energy of 312.6 MeV using the QSD magnetic spectrometer at the Lawrence Berkeley Laboratory 88-Inch Cyclotron. An energy spectrum for the reaction ^{208}Pb(^{16}O, ^{15}N)^{209}Bi at $\Theta_{lab} = 11.9^{\circ}$ is shown in Fig. 1. A comparison of this spectrum with those previously obtained at lower energies[1-3] shows several qualitative differences: (1.) Whereas spin-flip transitions (e.g., transfer of a proton from a $j = \ell - 1/2$ state in ^{16}O to a $j = \ell + 1/2$ state in ^{209}Bi) are favored at energies close to the Coulomb barrier, the non-spin-flip transitions dominate at 312.6 MeV; (2.) The transitions to the 3p states in ^{209}Bi are much weaker than at lower energies; (3.) Transitions to the $3/2^{-}$ excited state at 6.32 MeV in ^{15}N are strong at 312.6 MeV although they were negligible at 104 MeV. These aspects of the reaction will be discussed in detail in a forthcoming paper[4] where it will be shown that they are rather well accounted for by a DWBA analysis. Here we discuss the failure of the DWBA to reproduce the energy dependence of the cross sections.

Angular distributions have been measured for transitions to each of the single particle states identified in Fig. 1. All of the angular distributions were observed to have nearly identical bell-shaped behavior, centered at 13.5° (c.m.).

Finite-range calculations for the ^{208}Pb(^{16}O,^{15}N)^{209}Bi reaction were made with Ptolemy,[5] a program for heavy-ion direct-reaction calculations. The effective transition operator was chosen to include the Coulomb and core-Coulomb corrections.[6] As was shown in Ref. 6, and verified in the present work, such corrections bring calculations in "post" and "prior" representations of the DWBA to within a few percent of each other.

Several optical model descriptions of the ^{16}O + ^{208}Pb elastic scattering at 312.6 MeV have been investigated. Each optical potential was derived by first extrapolating to 312.6 MeV energy-dependent Woods-Saxon potentials fitted to the lower energy data.[7] The resulting parameters were then used as initial values in a least-squares fit to the elastic data at 312.6 MeV. A final chi-square per point of 0.4 was obtained for 5% error bars. Comparable fits were obtained for several different parametrizations of the energy dependence but, since all these potentials yield similar predictions for the energy dependence of the transfer cross section, only one potential will be considered here. This potential is based on a quadratic energy dependence for the geometrical parameters (r_o, r_{oi}, a, a_i) and energy-independent depths. The potential parameters used for each of the four incident energies are presented to three significant figures in Table I.

The bound-state form-factors used in the present analysis are those employed[8,9] in earlier studies of heavy-ion induced transfer reactions on ^{208}Pb. The radial wave functions for single-proton states in ^{209}Bi and ^{16}O are eigenfunctions of Woods-Saxon potentials with central and spin-orbit components. The real depths of the potentials were adjusted to reproduce the known binding energy of each state. The resulting bound state potentials for ^{15}N + p and ^{208}Pb + p are only slightly state-dependent (maximum variation in depth less than 5%), and have been shown[10] to yield r.m.s. charge radii consistent with those obtained in electron scattering around $A \approx 16$ and $A \approx 208$. These potentials are very similar to the single-proton potentials obtained[11] as the zero-energy limit of proton-nucleus optical potentials. The ^{208}Pb + p potential has been used[12] to extract spectroscopic factors for the single-particle states of ^{209}Bi from measurements of the reactions ^{208}Pb(^{3}He,d)^{209}Bi, and these spectroscopic factors are used in the present study. The spectroscopic factor for ^{15}N was taken to have the full closed-shell value of $S = 2$ for the $1p_{1/2}$ ground state. The bound-state potential parameters are given in Table I.

The angular distribution obtained in the present work for the ^{208}Pb(^{16}O,^{15}N)^{209}Bi (g.s., $h_{9/2}$) reaction is shown in Fig. 2. Also included in the figure are the angular distributions measured[1,2] at the incident energies of 104, 140 and 216.6 MeV. The corresponding DWBA angular distributions (displayed as solid lines in Fig. 2) fail to account for the magnitude of the experimental cross sections, predicting too small cross sections at low energies and too large cross sections at high energies.

That this failure of the DWBA occurs for all single particle states in ^{209}Bi considered here is shown in Fig. 3, where the ratio of the calculated to the experimental total cross section is displayed for each of the five transitions measured in the present work. Between 104 and 312.6 MeV, the DWBA fails to reproduce the energy dependence of the experimental cross sections by almost an order of magnitude.

We believe that the failure of DWBA to account for the energy dependence of the transfer cross sections is of great significance. It can be concealed by treating the reactions at each energy as isolated phenomena. Absolute cross sections in better agreement with experiment could be achieved, energy by energy, by ad-hoc variations in bound state and optical model parameters, and sacrificing, if necessary, both the qualitative relationship of the bound state potentials to the nucleon-nucleus optical model as well as the quality of fits to the elastic scattering data. For example, the absolute cross sections at 312.6 MeV can be reduced by a factor of 2.54 by using the $^{15}N + p$ bound state potential parameters at both vertices.[13] However, this modification has a similar effect at 104 MeV (the factor is 2.86), so that the discrepancy in the energy dependence is not removed. Moreover, such stratagems miss the point of the optical-model DWBA treatment of peripheral reactions, and obviously have no predictive power, which is a most important feature of any theory. If, as shown in the present work, systematic application of the model uncovers major shortcomings, then this result should be taken as an indication that the physical premises of the model have broken down.

An important deficiency of the conventional DWBA-optical model treatment of heavy-ion reactions is the neglect of inelastic core excitations. The usual remedy of including coupled-channel effects is not likely to account for the large discrepancy observed at the higher incident energies if only a few specific channels are coupled. It has been recently suggested that the single particle wave functions might be substantially polarized during the collision process - an extreme limit being adiabatic, two-center shell model wave functions.[14] This effect might substantially change the absolute cross sections, but is most important only at low energies and thus would not be expected to remove the large discrepancy observed above 200 MeV.

An alternative explanation of the failure of the DWBA concerns the basic premise of the model that each transfer process is a minor perturbation on the dominant elastic channel. Since it has recently been shown[15] that the cross section to all quasi-elastic continua increases drastically between 104 MeV and 312.6 MeV (where it amounts to more than 30% of the total reaction cross section), it is conceivable that the large flux going into this peripheral process is related to the failure of the DWBA to reproduce the energy dependence of the transfer cross sections. In general, it is not clear that the large flux going into fast peripheral processes can be successfully described by an optical potential, or that an individual perturbative treatment of each direct reaction channel is still adequate.[16]

FOOTNOTES AND REFERENCES

[*] Work performed under the auspices of the U.S. Energy Research and Development Administration.

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TABLE CAPTIONS

Table I. Optical and bound-state potential parameters.

Table I.

Optical Potentials:

$V = 51.1$ MeV, $W = 51.5$ MeV, $r_{co} = 1.3$ fm

E_{Lab} (MeV)	$r_o = r_{oi}$ (fm)	a (fm)	a_i (fm)
104.0	1.28	.498	.445
140.0	1.21	.681	.631
216.6	1.15	.708	.709
312.6	1.11	.796	.741

Bound-State Potentials:

System	r_o (fm)	a (fm)	V_{so} (MeV)	r_{so} (fm)	a_{so} (fm)	r_{co} (fm)
^{208}Pb+p	1.28	.76	6	1.09	.60	1.3
^{15}N+p	1.20	.65	7	1.20	.65	1.2

FIGURE CAPTIONS

Fig. 1. Energy spectrum obtained at a laboratory angle of 11.9° for the reaction ^{208}Pb(^{16}O, ^{15}N)^{209}Bi. Transitions to known single-particle states in ^{209}Bi are identified.

Fig. 2. Differential cross sections for the reaction ^{208}Pb(^{16}O, ^{15}N)^{209}Bi populating the $h_{9/2}$ ground state at an incident energy of 104, 140, 216.6 and 312.6 MeV, from right to left. The solid lines are DWBA calculations described in the text; the dashed lines are drawn to guide the eye.

Fig. 3. The ratio of the DWBA to the experimental total cross section for the five observed transitions to single-particle states in ^{209}Bi.

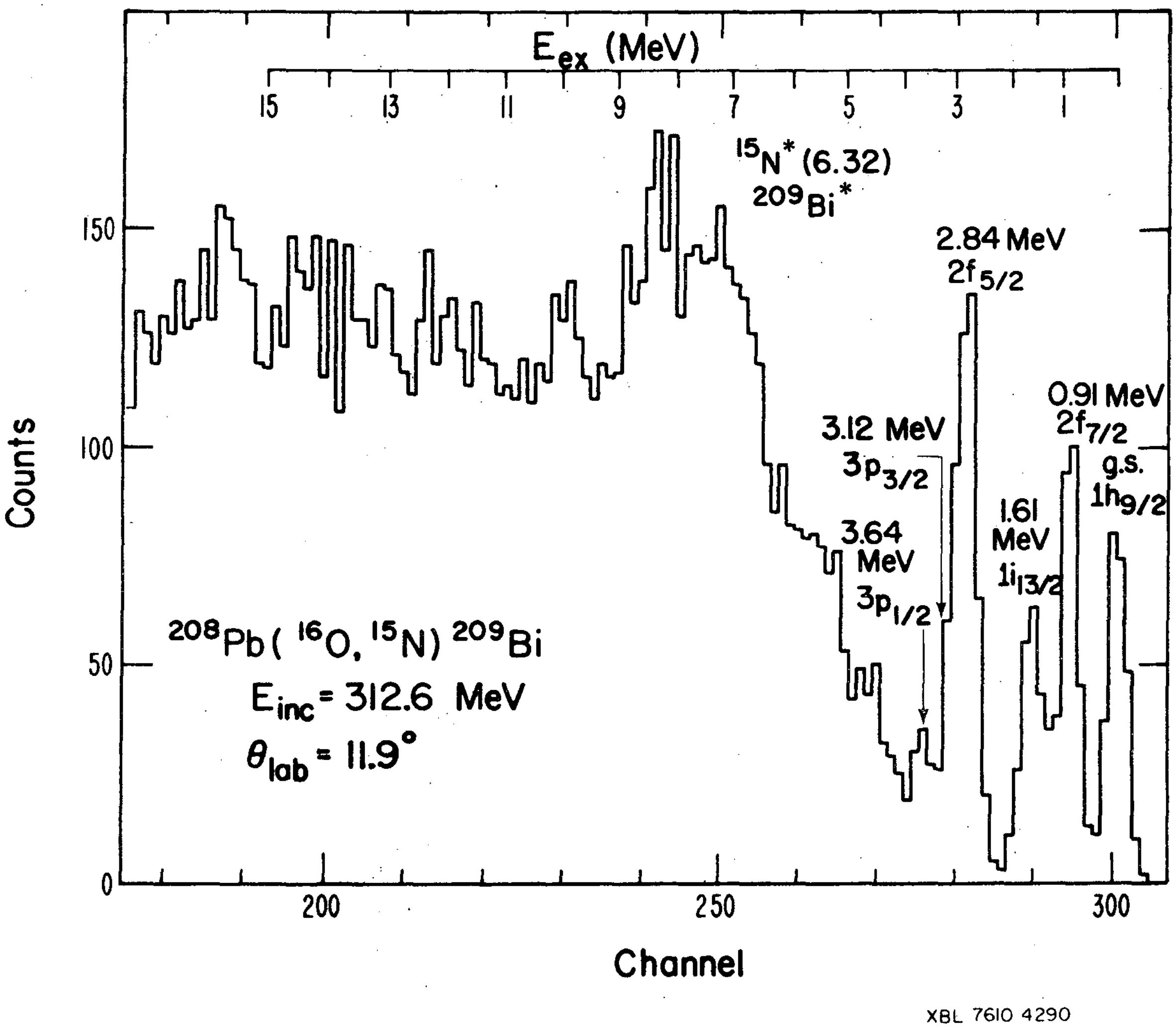

E_ex (MeV)
15
13
11
9
7
5
3
1
¹⁵N* (6.32)
²⁰⁹Bi*
2.84 MeV
2f5/2
3.12 MeV
3p3/2
0.91 MeV
2f7/2
g.s.
1h9/2
3.64
MeV
3p1/2
1.61
MeV
1i13/2
²⁰⁸Pb(¹⁶O, ¹⁵N)²⁰⁹Bi
E_inc = 312.6 MeV
θ_lab = 11.9°
Counts
150
100
50
0
200
250
300
Channel
XBL 7610 4290

Fig. 1

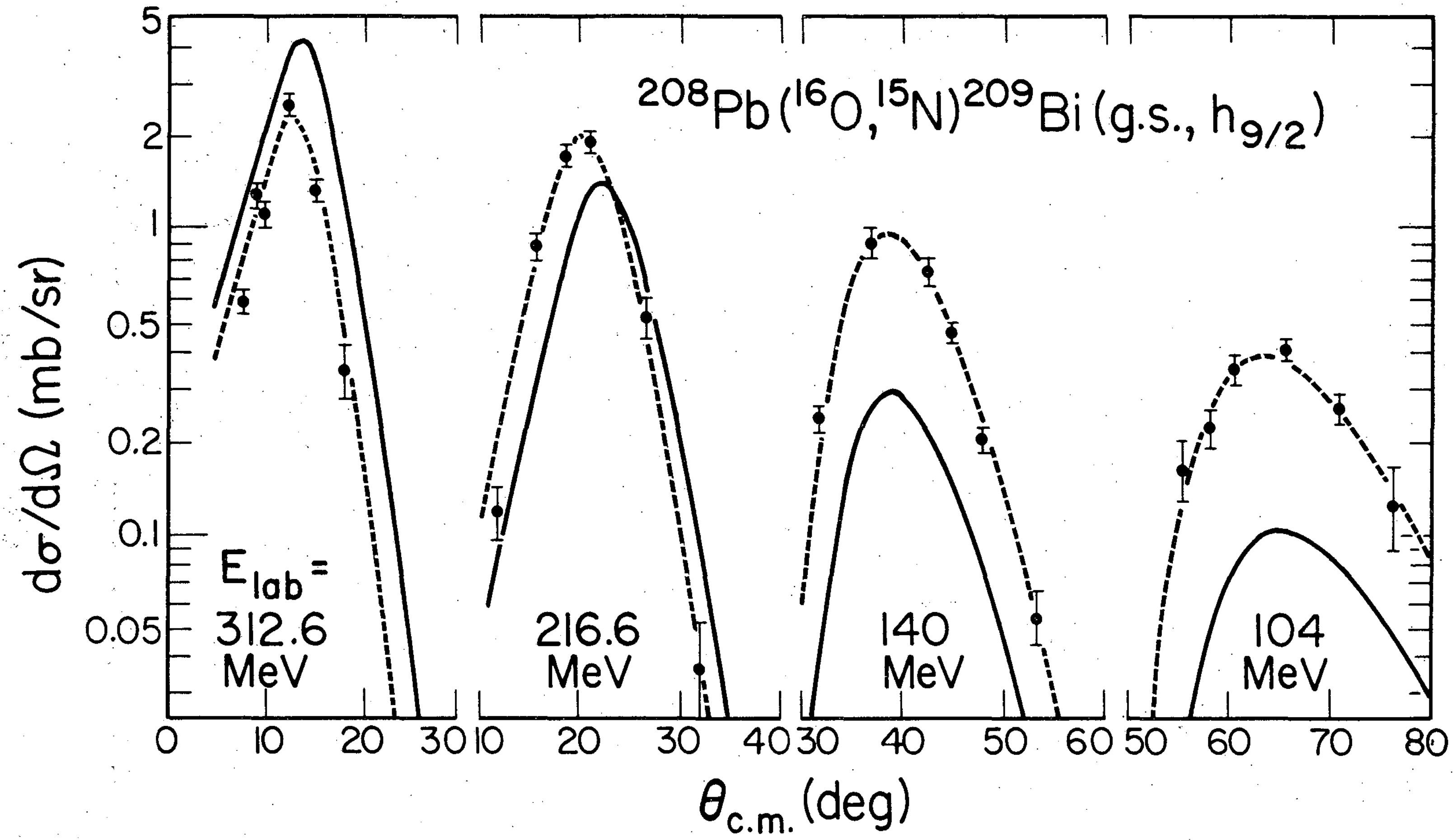
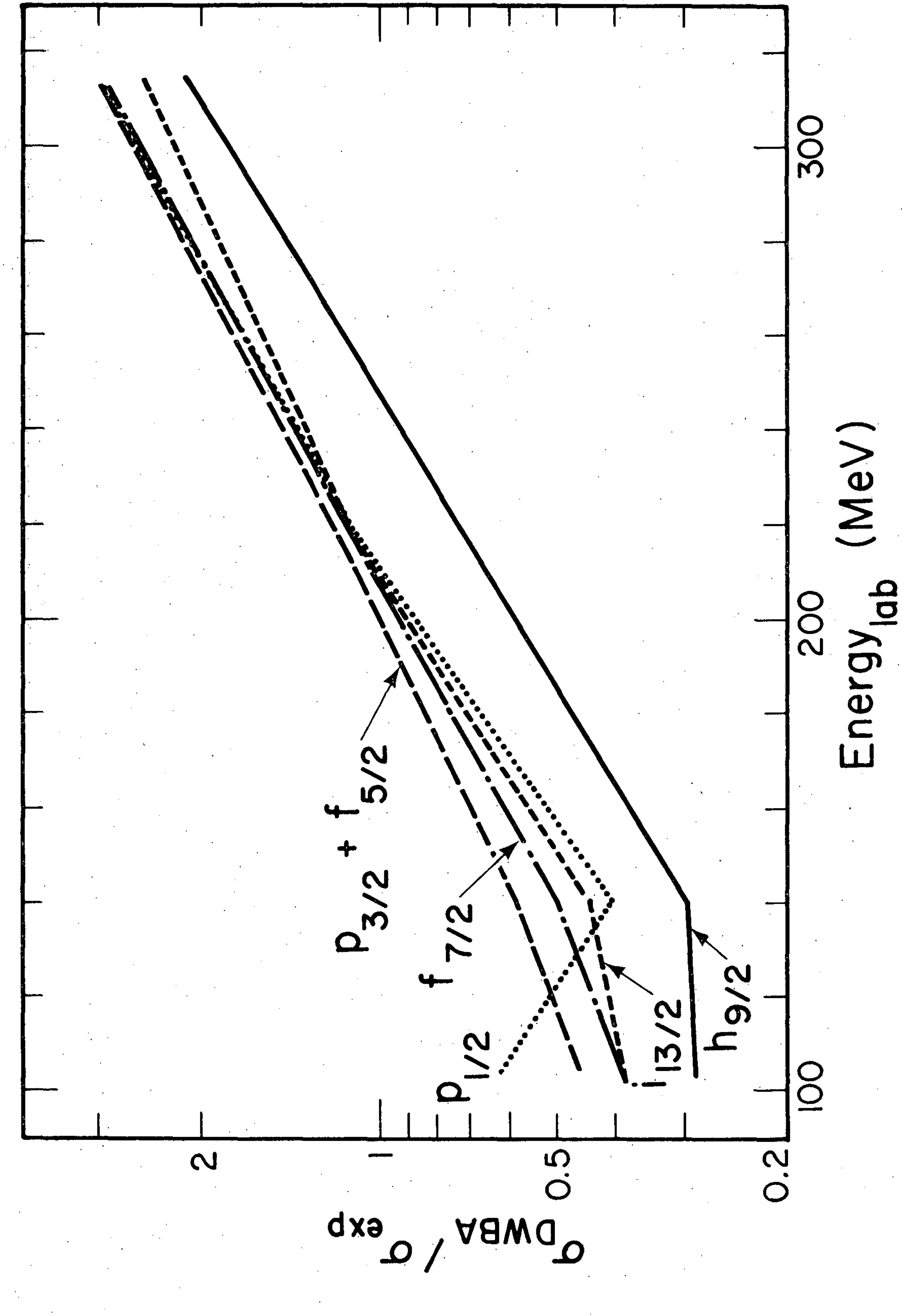


Fig. 2

XBL 7611-4444



XBL 7611-4434

Fig. 3

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