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Analyzing Power in Proton-Nucleus Elastic Scattering at 0.8 GeV

G. W. Hoffman
University of Texas, Austin, Texas 78712, and Los Alamos Scientific Laboratory, Los Alamos, New Mexico 87545

and

G. S. Blanpied,[a] W. R. Coker, and R. P. Liljestrand
University of Texas, Austin, Texas 78712

and

N. M. Hintz and M. A. Oothoudt[b]
University of Minnesota, Minneapolis, Minnesota 55455

and

T. S. Bauer, G. Igo, G. Pauletta, J. Soukup, and C. A. Whitten, Jr.
University of California, Los Angeles, California 90024

and

D. Madland, J. C. Pratt, L. Ray, J. E. Spencer, and H. A. Thiessen
Los Alamos Scientic Laboratory, Los Alamos, New Mexico 87545

and

H. Nann and K. K. Seth
Northwestern University, Evanston, Illinois 60201

and

C. Glashausser
Rutgers University, New Brunswick, New Jersey 08903

and

D. K. McDaniels, J. Tinsley, and P. Varghese
University of Oregon, Eugene, Oregon 97403
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The first elastic-scattering analyzing-power (A_y) data at 0.8 GeV are presented and discussed. Angular distributions of A_y over the range 2° to 20° (30° for ^{12}C) have been obtained for ^{12}C, ^{58}Ni, ^{90}Zr, and ^{208}Pb using the high-resolution spectrometer at the Clinton P. Anderson Meson Physics Facility. The analyzing powers oscillate sharply over positive values in qualitiative agreement with expectations.

Medium-energy proton-nucleus elastic-scattering differential cross-section data[1-7] can be analyzed[6-13] with the intention of exploring neutron density distributions, given independent knowledge (generally from electron scattering) of proton density distributions. The results are subject to several uncertainties, the most notable being due to the lack of sufficiently detailed knowledge of spin-dependent effects.[13,14] This unsatisfactory situation could be remedied, at least partially, if the spin dependence of nucleon-nucleon amplitudes were known.[15] Another approach is to determine empirically the spin-dependent amplitudes which give good fits to elastic proton-nucleus analyzing power $[A_y(\theta)]$ data. Unfortunately, while several detailed measurements of medium-energy elastic differential cross sections $[\sigma(\theta)]$ are reported in the literature,[1-7] measurements of $A_y(\theta)$ are almost nonexistent.[16]

In this Letter we report results of the first analyzing-power measurements for the elastic scattering of 0.8-GeV polarized protons from ^{12}C, ^{58}Ni, ^{90}Zr, and ^{208}Pb. The data were obtained using the high-resolution spectrometer (HRS) at the Los Alamos Clinton P. Anderson Meson Physics Facility (LAMPF). The interesting qualitative features of our results are discussed, and the results of a phenomenological analysis are presented. Details of this analysis in terms of the Kerman-McManus-Thaler[17] approach are described by Ray *et al.*[18]

Data were taken over the angular range 2° to 20° (30° for ^{12}C) at 1.5° intervals and divided into bins of ~0.2° width (which is approximately the present angular resolution of HRS). With the ~3° acceptance of the spectrometer this ensured overlap of several bins between successive angles. An energy resolution of 200 to 300 keV was realized. Beam polarization was reversed at the source every three minutes and was typically 87%.

The experimental results for the differential cross sections $d\sigma/d\Omega$ and the analyzing powers $A_y(\theta)$ are shown in Figs. 1 and 2. The errors shown are statistical only; those associated with the differential cross sections are typically 1–3% and ΔA is typically ± 0.01 to ± 0.02 except at the largest angles. Several sources of systematic errors were investigated. Changes in beam phase space with polarization reversal and possible changes in the angle of incidence of the beam on the target were carefully monitored. No such changes were observed. It is estimated that errors in A due to these effects are less than ± 0.01. Since $A_y(\theta)$ often changes very rapidly with angle (e.g., for ^{12}C it changes from $+0.04$ at 13.4° to $+0.73$ at 14.6°), the accuracy of the angle calibration is very important. By setting the HRS at $+12°$ and $-12°$ we were able to determine abso-

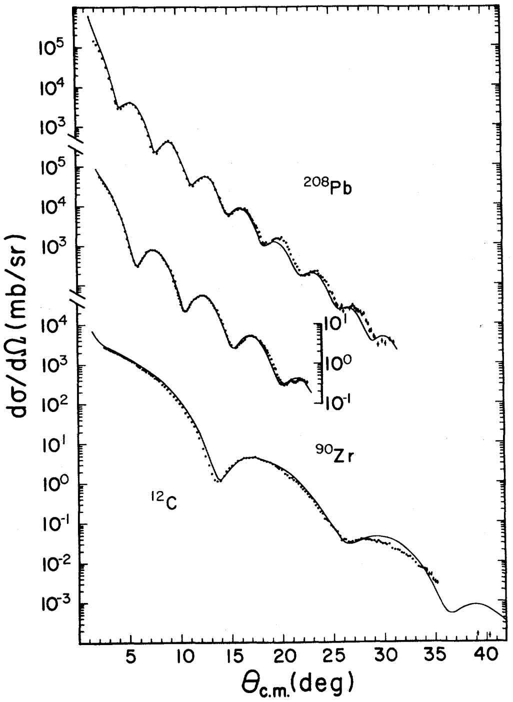

FIG. 1. Elastic angular distribution for 0.8-GeV proton scattering from ^{12}C, ^{90}Zr, and ^{208}Pb. Error bars shown are statistical only, and generally the error bars are much smaller than the data points. The curves are discussed in the text. The ^{58}Ni data and fit are shown in Fig. 1 of Ref. 7. The ^{12}C and ^{208}Pb data shown here are from Ref. 7.

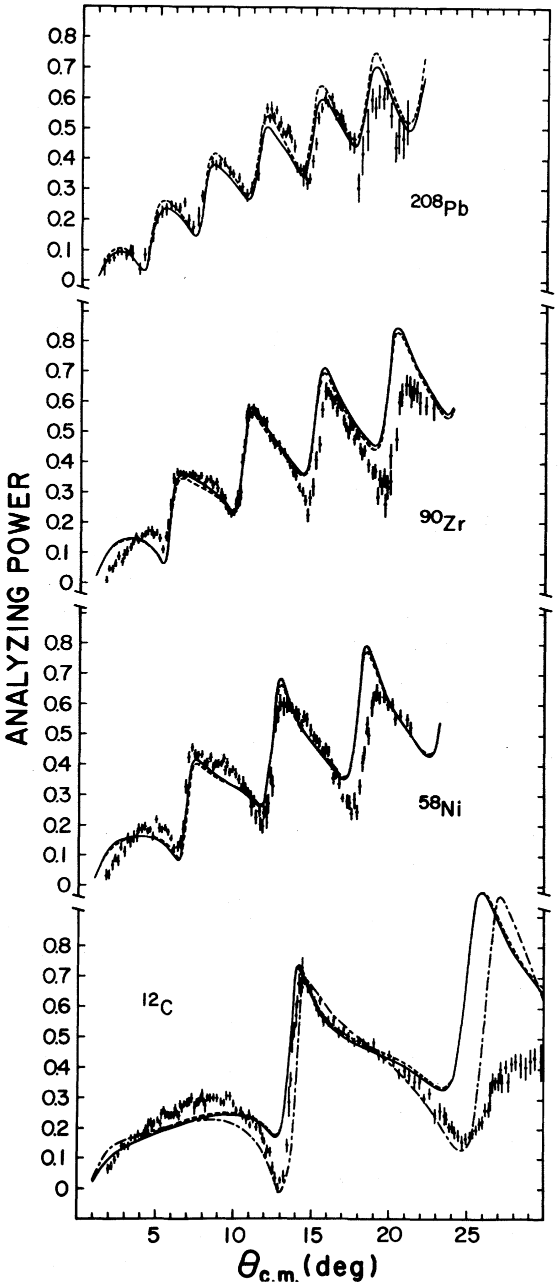

FIG. 2. Elastic analyzing powers for 0.8-GeV polarized proton scattering from ^{12}C, ^{58}Ni, ^{90}Zr, and ^{208}Pb. Errors shown are statistical only. The curves are discussed in the text and in Ref. 18.

lute angle calibration to within ±0.05°.

Interesting features of the data in Fig. 2 include the following: (1) A_y is always positive (same sign as the *pp* analyzing power), (2) the rise in each oscillation of A_y is much steeper than the fall, (3) the minima in $\sigma(\theta)$ are located approximately midway in angle between the minima and subsequent maxima of A_y, and (4) the envelope of A_y monitonically increases with angle (except for ^{12}C near 30°) and is approximately independent of the target nucleus.

Many of these features are qualitatively different from those of data at energies below 100 MeV, where A_y tends to be closely related to the logarithmic derivative of the cross section,[19] and oscillates between positive and negative values. In the earliest polarization studies around 400-MeV incident energy, it was noted that the polarization values are mostly positive[20]; the qualitative reasons were first discussed by Fermi.[21] The gradual change in the shape of A_y as E_p increases from, say, 50 to 800 MeV seems mostly due to the increase in the imaginary central term V_I in the optical potential relative to the real central term V_R. At 800 MeV, for ^{208}Pb, for example, $|V_R|$ is only about 5 MeV compared to a $|V_I|$ of about 50 MeV; the real and imaginary spin-orbit terms are comparable to $|V_R|$. For a spin-up beam, because of the strong absorption, scattering to the left tends to originate from the left-hand side of the nucleus, and since vectors $\vec{l}$ and $\vec{s}$ are antiparallel, is enhanced over scattering to the right which tends to originate from the right-hand side of the nucleus (vectors $\vec{l}$ and $\vec{s}$ parallel). This leads to positive values of A_y and a positive slope of the envelope of A_y as σ decreases. The diffraction oscillations due to interference in the scattering from different regions of the nucleus are now superimposed on this rising average line. The effect is to make the rise of A_y in each oscillation steeper than the fall. A detailed explanation of the A_y data around 200 MeV in terms of the strong absorption diffraction model has been obtained by Frahn and Venter.[22]

We now briefly discuss the curves shown in Figs. 1 and 2. They were generated by solving the Schrödinger equation with relativistic kinematics and a microscopic optical potential derived from nucleon-nucleon scattering amplitudes and nuclear matter densities, as discussed by Ray *et al.*[18] Appropriate nucleon-nucleon polarization data do not yet exist. As a first attempt at understanding spin effects, it is thus reasonable to determine the spin-dependent nucleon-nucleon parameters which give the best fits to the data. In addition, there is no fundamental reason to expect the *pp* and *pn* spin-dependent parameters to be the same. Therefore isospin-averaged spin parameters determined for individual nuclei should be expected to vary from nucleus to nucleus as N/Z varies.

The solid curves shown in Figs. 1 and 2 were obtained[18] for each nucelus by searching on two of the three isospin-averaged spin parameters, and the neutron density parameters, to obtain simultaneous fits to both $\sigma(\theta)$ and $A_y(\theta)$. The numerical values for the various parameters are given by Ray *et al.*[18] The proton densities used for the calculations were taken from electron scattering results. It should be noted that the sign of the ratio of the real to imaginary part of the spin-dependent amplitude is positive. A positive sign reproduces the observed rapid rise from minima to maxima, while a negative sign would result in a sharp drop from maxima to minima. Also shown in Fig. 2 as dashed curves are the results obtained using the same set of spin parameters for each nucleus. This set is an average of the spin parameters for ^{58}Ni, ^{90}Zr, and ^{208}Pb which were used to generate the solid curves. Finally, the dot-dashed curve for ^{12}C was obtained[18] by allowing all three spin parameters to vary freely.

The fits obtained are reasonably good and generally confirm the reliability of the entire analysis. It is interesting that in regions where the solid curves give poor fits, the dashed curves often give good fits. Beginning at about 18° the A_y predictions are systematically higher than the data. This may indicate that the parametrization for the spin-dependent amplitudes is beginning to break down in this region of momentum transfer. More experimental data would help to shed light on this question. The A_y fit is especially bad for ^{12}C near 30°, but strong deformation effects might also be important. It is particularly disturbing that the fits to the very forward angle A_y data (2° to 7°) are poor except for ^{208}Pb. This again may be due to the inadequacy of the parametrization of the spin-dependent amplitude in this very forward-angle region, and the whole question of parametrization is presently under investigation.

Ultimately, intermediate-energy elastic-scattering data are important because of the possible information they contain about neutron density distributions. The importance of simultaneously fitting the analyzing power and differential cross section data in order to explore neutron density distributions systematically is discussed in Ref.

18.

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[a] Present address: New Mexico State University, Las Cruces, N. Mex. 88001.

[b] Present address: Los Alamos Scientific Laboratory, Los Alamos, N. Mex. 87545.

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[16] Besides the results presented here we are aware of only one other set of polarization data [G. D. Alkhazov *et al.*, Phys. Lett. 70B, 20 (1977), and to be published]. These are very recent double-scattering measurements for elastic scattering of 1-GeV unpolarized protons from ^{12}C, ^{40}Ca, and ^{208}Pb in the angular range 2° to 12.5°. These data are more sparse and of a lower quality than the data presented here, and not altogether suitable for the present type of analysis.

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Oscillatory Ion Yields of He^+ Scattered from Atomic and Solid Pb Targets

A. Zartner, E. Taglauer, and W. Heiland
Max-Planck-Institut für Plasmaphysik, EURATOM Association, D-8046 Garching bei München, Germany

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Ion yields of He^+ scattered from atomic and solid Pb in the energy range from 200 to 2000 eV into a large scattering angle are reported. The beam results show an oscillatory structure of the ion yield as function of the energy which is comparable to the same effects observed for a solid target. Thus the atomic nature of the quasiresonant charge exchange is confirmed. The data also give evidence for solid-state effects influencing the oscillations of the ion yield.

Oscillations in the yields of ions scattered from solid targets have been reported first by Erickson and Smith.[1] It has been shown[2] that the effect is most pronounced for nine elements of the third, fourth, and fifth groups of the periodic table, i.e., from Ga to Bi as targets, and He^+ as the scattered particle. The experimental observation is that as a function of primary energy (or velocity) the yield of backscattered ions into a given scattering angle oscillates with intensity ratios up to a factor of 5. Measurements as a function of scattering and impact angle to the surface[3] suggest that the charge-exchange process occurs in a binary collision, i.e., it can be understood as an atom-atom collision. The influence of the solid state seems to be marginal as far as the oscillations are concerned. The overall distribution of backscattered ions is, however, governed by the (elastic) differential scattering cross section and by the possible neutralization processes.[4] The empirical interpretation[1,2] of the oscillations as being due to quasiresonant charge-exchange processes between the He 1*s* level and the *d* levels of the above-mentioned elements has been supported by the first theoretical approaches.[5,6]

In this Letter we report results from the scat-