in a distorted-wave Born-approximation description of stripping reactions. For the proton-dominant case a result of $P_d(\theta) = \frac{2}{3}P_p(\theta)$ was found, and for the deuteron-dominant case the result was $P_d(\theta) = P_p(\theta)$. The present work would seem to favor the latter description, provided no radical difference occurs for the predictions with $l > 0$.

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*Present address: Physics Department, McMaster University, Hamilton, Ontario, Canada.

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ELASTIC SCATTERING OF 600-MeV PROTONS BY ^{4}He

E. T. Boschitz, W. K. Roberts, and J. S. Vincent
National Aeronautics and Space Administration, Lewis Research Center, Cleveland, Ohio

and

K. Gotow
Virginia Polytechnic Institute, Blacksburg, Virginia

and

P. C. Gugelot
University of Virginia, Charlottesville, Virginia

and

C. F. Perdrisat and L. W. Swenson
College of William and Mary, Williamsburg, Virginia
(Received 18 March 1968)

The differential cross section for elastic scattering of 600-MeV protons from ^{4}He has been measured for laboratory angles between 4° and 44°. The data are analyzed in terms of the diffraction approximation of Glauber.

When high-energy particles for which the wavelength is considerably less than the internucleon spacings are used in nuclear structure studies, new information may be obtained which is not forthcoming from lower energy data. Recently at Brookhaven[1] the scattering of 1-BeV protons from ^{4}He was measured, and a diffraction pattern was observed with a pronounced minimum at a square of the momentum transfer $\Delta^2 = 0.24$ (BeV/c)^2. Various models were applied to interpret these data. Using the strong-absorption model, the assumption of a sharp surface for the helium nucleus was required.[1] In the optical model a Saxon-Woods potential with a small diffuseness was necessary to fit the data.[2] Both assumptions are at variance with the nearly Gaussian charge distribution for ^{4}He as established from electron scattering.[3,4] Czyż and Leśniak[5] and Bassel and Wilkin[6] have pointed out that a more correct description of the scattering process is the diffraction approximation of Glauber.[7] Using a Gaussian single-particle density distribution in this approximation, the magnitude of the measured cross section as well as its basic features are well reproduced.

In spite of the success of the diffraction approximation, a number of questions remain to be answered, e.g., the importance of spin effects, the necessity of including nucleon-nucleon correlations, and the momentum dependence of the ratio of real to imaginary part in the elastic nucleon-nucleon scattering amplitude. In order to clarify some of these problems, a program has been initiated at the National Aeronautics and Space Administration Space Radiation Effects Laboratory to study cross sections, polarizations, and $(p, 2p)$ reactions for 600-MeV protons interacting with light nuclei. In the present communication, we report the results of elastic scattering of protons from ^{4}He.

Figure 1 shows the experimental arrangement. The external 600-MeV proton beam was brought to a focus on the helium target by the beam transport system (not shown). The intensity of the incident beam was monitored by an argon-filled ion chamber (AIC) and by scattering the particles from aluminum into a pair of range telescopes (M_1 and M_2). The absolute number of incident protons was obtained by CH_2-foil activation using the reaction $^{12}C(p,pn)^{11}C$ ($\sigma = 30.2$ mb).[9] The beam direction was monitored with two split ion chambers (SIC 1 and SIC 2). The helium target was of conventional design and consisted of a 4-in.-diam Mylar cylinder with vertical axis of symmetry. Protons scattered from the helium were detected by two independent multiple-counter range telescopes which were mounted on a precision scattering table. Counters 1 and 2 defined the scattering volume of the helium target and the solid angle subtended by the range telescope. The angular acceptance (full width at half-maximum) was $\Delta\theta = 0.75°$ except for angles greater than $\theta = 32°$, where $\Delta\theta = 2°$. Since the object of this experiment was to study the details of the elastic differential cross section, it was

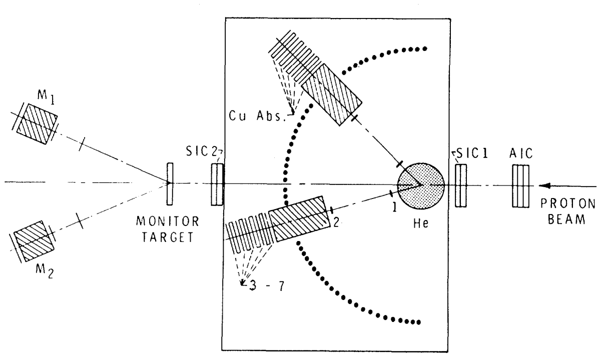

FIG. 1. Schematic diagram of the experimental arrangement.

particularly important to exclude inelastic events. We have therefore used range telescopes consisting of five additional scintillation counters (3-7) placed at the end of the proton ranges in order to monitor continuously the range of the protons as a function of scattering angle. The overall energy resolution was always better than 20 MeV, which is the threshold for the appearance of inelastic protons from the breakup of the alpha particle. The effective proton energy at the target center was measured to be 587.5 MeV. The efficiency of the range telescopes as a function of proton energy was obtained by placing the telescopes at zero degrees and measuring the transmission from zero to total absorption for 570-, 500-, and 430-MeV incident protons. The respective efficiencies were 22, 33, and 46%.

A Monte Carlo calculation for the penetration of protons through a copper slab was performed. Known reaction cross sections in the energy range from 10 to 600 MeV were used. Different reasonable assumptions for the angular distribution and energy spectra of the reaction products were used. The Monte Carlo calculations agreed within 10% with the experimentally observed absorption curves. It was necessary to give considerable attention to the problem of accidental coincidences. Since the duty cycle of the synchrocyclotron is presently about 10^{-3}, it was necessary to limit the number of incident protons to less than 10^7/sec. Accidental coincidences generally amounted to only a few percent but were as large as 20% for scattering angles smaller than 15°. The experimental results are presented in Fig. 2. The errors shown for each data point are the standard deviations of the relative cross section. The error in the absolute cross section due to uncertainties in the efficiency of the telescopes, the $^{12}C(p,pn)^{11}C$ cross section, and the helium target thickness is estimated to be less than ±20%.

We have analyzed the data within the framework of the Glauber approximation in which the incident nucleon is assumed to interact successively with one or more nucleons in the target nucleus, with the same interaction as for free nucleon-nucleon scattering. At small momentum transfers, single scattering dominates the cross section. At larger momentum transfers, a minimum and secondary maximum in the elastic cross section are produced by the destructive interference between the single and double scattering amplitudes. At still higher momentum transfers, minima are produced from inter-

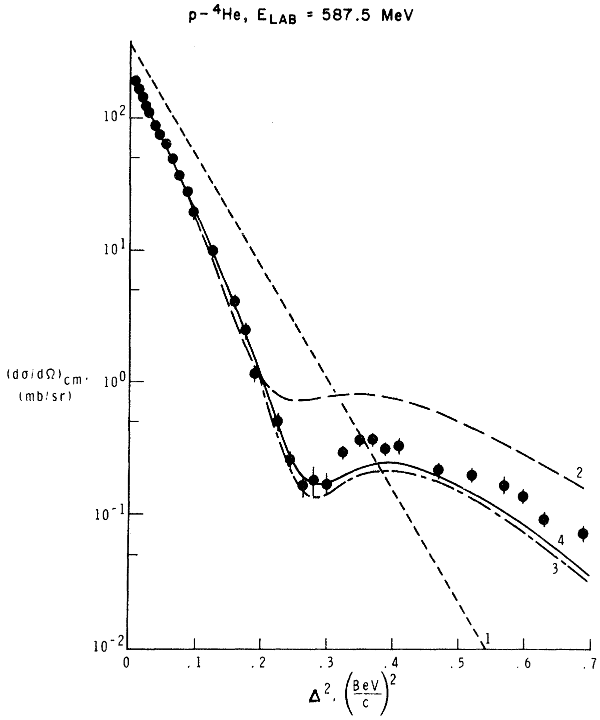

FIG. 2. Comparison of the experimental data with predictions from the Glauber approximation. The curves labeled 1, 2, 3, and 4 are the calculated differential cross sections: if only single scattering (1); single and double (2); single, double, and triple (3); and finally also quadruple scattering (4) is included.

ference of higher order terms in the multiple scattering. The depth of the first minimum is connected with the relative phase between single and double scattering amplitudes and therefore to α, the ratio of real to imaginary part of the nucleon-nucleon scattering amplitude. We have followed Czyż and Leśniak's application[5] of the Glauber approximation, where the p-^{4}He differential cross section is calculated using the Gaussian single-particle density distribution for He^4,

$$|\psi_0|^2 = \prod_{j=1}^{4} \rho_0 \exp(-r_j^2/R^2),$$

and the parametrized form of the nucleon-nucleon scattering amplitude (assumed to be the same for p-p and p-n),

$$f(p,\delta) = [(i+\alpha)/4\pi] p\sigma \exp(-\tfrac{1}{2}a\delta^2).$$

p is the momentum of the incident proton; δ, the momentum transfer; σ, the total nucleon-nucleon cross section; α, the ratio of the real part to imaginary part of the amplitude; and a is the slope of the elastic nucleon-nucleon cross section.

In order to calculate the p-^{4}He cross section, we have used the values $R = 1.25$ fm, $a = 4.3$ $(\mathrm{BeV}/c)^{-2}$, and $\sigma = 3.9$ fm^2 from literature.[9-11] The value a is an average obtained from fitting p-p and p-n data near 600 MeV. The value $|\alpha| = 0.43 \pm 0.05$ was chosen to fit the minimum in the cross section. Bugg et al.[11] recently measured the total cross sections σ_{pp} and σ_{pd} and deduced at our energy $\alpha_{pp} = +0.48$ and $\alpha_{pn} = -0.19$ at zero momentum transfer.

The result of the calculation is shown in Fig. 2. The curves labeled 1, 2, 3, and 4, are the calculated differential cross sections: if only single scattering (1); single and double (2); single, double, and triple (3); and finally also quadruple scattering (4) is included. We find that for small momentum transfers where the theory is most reliable, the agreement with the data is good. The absolute magnitude, the slope, and the location of the minimum of the differential cross sections are well reproduced. Beyond the minimum the calculation overestimates the multiple scattering contributions.

More recently, the effects of nucleon-nucleon repulsion in the ^{4}He nucleus have been investigated within the framework of the Glauber approximation, and it was shown that such effects would change the theoretical cross section at larger momentum transfers in the right direction.[6,11]

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RELATION BETWEEN FINE AND INTERMEDIATE STRUCTURE IN THE SCATTERING OF NEUTRONS BY Fe†

J. E. Monahan and A. J. Elwyn
Argonne National Laboratory, Argonne, Illinois
(Received 11 March 1968)

An investigation of the fine structure in the region of an intermediate resonance observed at $E_n \approx 0.36$ MeV in the scattering of neutrons from Fe reveals properties consistent with the interpretation of this resonance as a doorway state in the compound nucleus.

Phase-shift analyses of differential cross sections and polarization data have shown that definite values of spin and parity can be assigned to the intermediate-width structure observed in various nuclear cross sections.[1,2] Although this is a necessary condition for the identification of these intermediate resonances as doorway states,[3] a more definitive test of the doorway-state model can be obtained by investigating the properties of the fine structure[4,5] of a doorway state that are predicted by the model. Lejeune and Mahaux[6] have shown that the distributions of the fine-structure resonance parameters observed in the total neutron cross section of Pb^{206} are in fairly good agreement with theoretical distributions derived from the doorway-state hypothesis, combined with a "picket-fence" model. The present report describes the results of an investigation of the fine structure in the neighborhood of an intermediate-width peak observed in the scattering of neutrons by Fe. Distributions of the fine-structure resonance parameters are compared with theoretical distributions derived from the doorway hypothesis alone, i.e., without the introduction of additional models or assumptions.

Structure having an intermediate width has been observed[7] in the energy dependence of the differential cross section and polarization of neutrons scattered from Fe at energies between 0.35 and 0.965 MeV. These data, measured with about 20-keV resolution width at five scattering angles, show fluctuations of width 20 keV clearly superimposed on two peaks—each of which has a width of approximately 150 keV. The total scattering cross section obtained from these data is shown in Fig. 1. Also shown in Fig. 1 are values of the total cross section measured with a resolution width of about 1 keV.[8]

Consider first the angular and polarization distributions. To smooth out most of the narrower fluctuations, the measured cross sections and polarizations were averaged numerically over a 75-keV interval and a phase-shift analysis of the en-

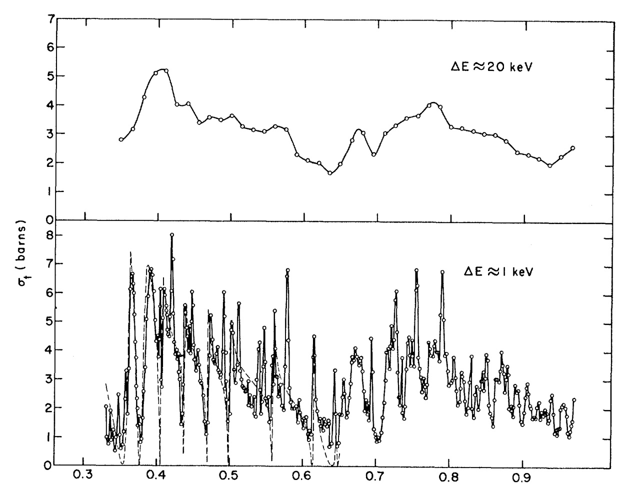

FIG. 1. Total neutron-scattering cross section for Fe. Upper: integrated differential cross sections. Lower: values (points and solid curves) from Smith (Ref. 8) and (dashed) a fit to the total cross section in the region between 0.36 and 0.65 MeV obtained from the reduced K matrix discussed in the text. The dashed curve shows only the s-wave contributions to the total cross section.