Elastic p-^{4}He Scattering near 1 GeV*

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New 1.029-GeV p-^{4}He data and new 1.05-GeV data are in excellent agreement with multiple-diffraction-theory predictions. The theoretical calculations include spin and isospin dependence of the Δ-intermediate-state process and show that it fills the first diffraction minimum. The recently normalized data from Centre d'Etudes Nucléaires de Saclay and the older data from Brookhaven National Laboratory disagree with our calculations and the new data.

The theory of multiple diffraction scattering developed initially by Glauber[1] and extended[2] and modified[3] by others makes an unambiguous prediction for hadron-nucleus multiple scattering *if* one knows in advance the nucleon-nucleon scattering amplitudes and the nuclear wave functions. In this Letter we compare the predictions of multiple diffraction theory including leading eikonal corrections[2] to five sets of p-^{4}He elastic scattering data near 1 GeV (Fig. 1) and show that two new experiments[4,5] are in excellent agreement with the theory when Δ-intermediate-state processes[9,10] are included.

Three experiments[5,7,8] to date have measured 1-GeV proton-helium elastic differential scattering including the small-angle range. In addition, scattering of 1.05-GeV/nucleon helium by hydrogen targets has been measured at intermediate angles in a University of California at Los Angeles–Lawrence Berkeley Laboratory (UCLA-LBL) experiment[4] and at large angles in an experiment at Centre d'Etudes Nucléaires de Saclay.[11] The Brookhaven National Laboratory (BNL) results at 1.0 GeV indicated a diffraction minimum at $-t = 0.24$ (GeV/c)^2 which was given a natural theoretical explanation[12] in Glauber's multiple diffraction theory using a simple Gaussian density for ^{4}He, and simple Gaussian approximations for nucleon-nucleon scattering amplitudes. The BNL data were also explained by optical model analyses.[13] However, the Saclay data[7] at 1.05 GeV (referred to as Saclay-A) differed substantially in its t dependence, particularly in the region of the first diffraction minimum and beyond. The Saclay-A data were reported with an arbitrary normalization and hence it was not clear whether the disagreement with the BNL data was at small or large t. The filling of the first diffraction minimum characteristic of multiple diffraction scattering was anticipated in a paper by Ikeda[10] who showed that production of Δ intermediate states could fill in the ^{4}He minimum. In this

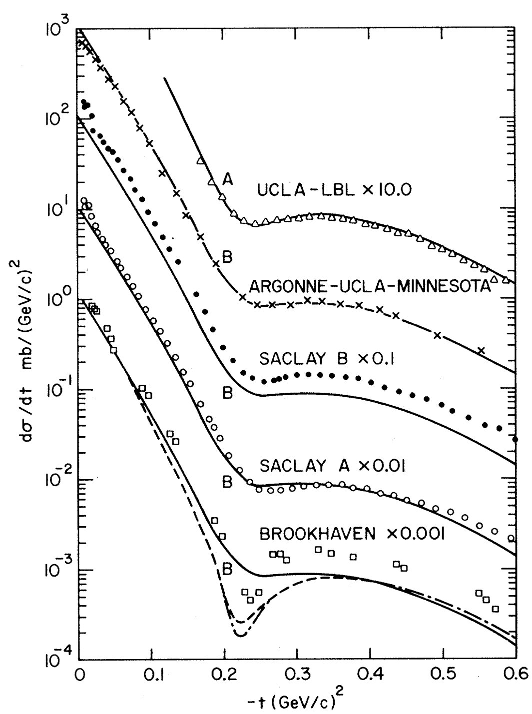

FIG. 1. Comparison of theoretical 1.05-GeV p-^{4}He elastic differential cross section calculations (solid lines) with five sets of experimental data: UCLA-LBL 1.05-GeV data (Ref. 4), Argonne-UCLA-Minnesota 1.029-GeV data (Ref. 5), Saclay-B 1.05-GeV data (Ref. 6), Saclay-A 1.05-GeV data (Ref. 7), and Brookhaven 1.0-GeV data (Ref. 8). In each case, the solid line shows $|F_0+F_1+F_\Delta|^2+|G_0|^2$. F_0 and G_0 are scalar and spin-flip amplitudes, respectively, based on Glauber theory with kinematic modifications of the single-scattering terms. F_1 is the leading order correction to Glauber theory due to noneikonal, Fermi-motion, and kinematic effects as developed in Ref. 2. F_Δ is the contribution due to the spin- and isospin-dependent Δ-intermediate-state process. A strength corresponding to $\sigma(pp\to N\Delta)=17$ mb is used for the solid line marked A and $\sigma(pp\to N\Delta)=21$ mb is used for solid lines marked B. The dashed curve shows $|F_0+F_1|^2+|G_0|^2$ which omits the Δ processes and the dash-dotted curve shows the Glauber result $|F_0|^2+|G_0|^2$ with neither Δ processes or $1/k$ corrections.

process, the fast nucleon becomes a Δ in one collision, the Δ coherently propagates through the nucleus, and it returns to a nucleon state in a later collision thereby re-entering the elastic channel. The Ikeda calculation was not compelling[14,15] because it ignored the strong spin and isospin dependence of the Δ production amplitude which suppresses the effect in nuclear elastic scattering. However, the Saclay-A data obtained later were in quite good agreement with the Ikeda prediction.

While theoretical explanations[15,16] of the Saclay-A data were advanced (which did not include the Δ intermediate states), normalized versions of the data also began to appear[17,18] which cast considerable doubt on both the original data and theoretical fits to it. Recently, final normalized data at 1.05 GeV, herein referred to as Saclay-B, were communicated in tabular form.[6] The Saclay-B data are quite similar to the earlier BNL data except in the region of the first minimum[17]; however, they are at variance with the calculations mentioned above.

This puzzling situation is not rectified by a number of improvements in the theoretical calculations. A high-energy expansion method[2] for nuclear multiple scattering was developed which showed that the leading corrections to Glauber's multiple diffraction theory in a k^{-1} expansion were indeed small (typically less than 15%) and that their inclusion should in principle lead to an accuracy of about 5% in the range $\theta_{\text{c.m.}} = 0$ to 60°. A comparison[19] of the multiple-scattering approaches[1-3] with exact results in a model calculation verifies these estimates. In realistic calculations, additional uncertainties enter because of imprecise knowledge of the nucleon-nucleon amplitudes and the Δ production amplitudes.

Using the formalism of Glauber theory plus leading corrections,[2] we have performed p-^{4}He elastic scattering calculations based on the existing phase shifts for the p-p amplitudes at 0.97 and 1.40 GeV[20] and simple assumptions for the p-n amplitudes. Our calculations include a kinematic transformation of single-scattering amplitudes similar to that developed in Ref. 3 and shown to be partly responsible for filling of the second diffraction dip [at $-t \simeq 1.0$ (GeV/c)^2]. In the small-t region considered here the kinematic transformation has little effect. The full spin and isospin dependence of the N-N amplitudes has been included but we find that only the scalar (A) and spin-flip (C) amplitudes play significant roles. Coulomb effects are also included. The helium wave function used is based on products of sums of Gaussian terms with the center-of-mass constraint. An accurate fit to the measured ^{4}He form factor is obtained while maintaining positivity of the coordinate space density. For the case of single scattering the p-p amplitudes are based directly on the phase shifts,[20] while the p-n amplitudes involve the following parametrization consistent with p-n differential cross section and polarization measurements[21]:

$$A_{pn}(t) = k(\sigma_{pn}/4\pi)(i + \rho_{pn}) \times [(81e^{8.52t} + 20e^{2.61t})/101]^{1/2}, \quad (1)$$

$$C_{pn}(t) = C_0 \exp(C_1 t) e^{i\varphi}\sqrt{-t}, \quad -t \lesssim 0.15\ (\text{GeV}/c)^2, \quad (2)$$

with $\rho_{pn} = -0.35$, $\sigma_{pn} = 39.8$ mb. The p-n spin-flip amplitude parameters C_0, C_1, and φ given in the caption of Fig. 2 are determined by fitting to the new p-^{4}He polarization measurements[5] at 1.029 GeV. The resultant C_{pn} amplitude is smaller in magnitude than the C_{pn} used in Ref. 12 but is rather similar to the C_{pn} used in Ref. 14. We do not employ t-dependent phases for A_{pn} or C_{pn}. Double, triple, etc., scattering terms of the multiple-scattering expansion are based on Gaussian approximations to the N-N amplitudes valid in the small-t range relevant for multiple scattering.

Finally, the amplitude for Δ intermediate states between two scatterings has been evaluated in a spin- and isospin-dependent model. When appropriately averaged over the ^{4}He spin-isospin wave function, the Δ-intermediate-state amplitude is found to be reduced by a factor $\frac{1}{4}$ compared to a scalar calculation. Analysis further reveals that

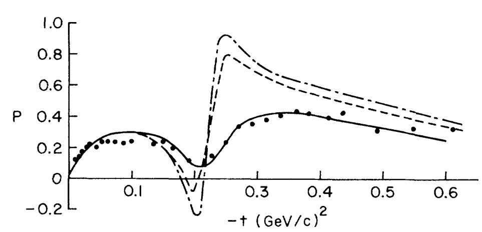

FIG. 2. Comparison of 1.05-GeV p-^{4}He polarization calcuations with data from the 1.029-GeV Argonne-UCLA-Minnesota collaboration (Ref. 5). The solid curve is the result including the intermediate Δ production and $1/k$ correction. The values of the parameters used for $C_{pn}(t)$ [Eq. (2)] are $\varphi = 1.67$ rad, $C_0 = 4.80$ (GeV/c)$^{-2}$, and $C_1 = 8.24$ (Gev/c)$^{-2}$. The dashed curve includes only the $1/k$ corrections to Glauber theory, and the dash-dotted curve is the Glauber-theory result.

the Ikeda calculation contained an incorrect factor of $\frac{1}{2}$ and a factor-of-$2^{-1/2}$ suppression due to spin dependence. As a result the net suppression of the new spin- and isospin-dependent Δ amplitude relative to the Ikeda estimate is just $2^{-1/2}$. We find that on the basis of a strength corresponding $\sigma(pp\rightarrow N\Delta) = 15$ to 20 mb, the spin- and isospin-dependent Δ-intermediate-state processes have essentially the same crucial role in filling the first p-^{4}He diffraction minimum as in the earlier estimates.[10,22] The cross section assumed for coherent Δ production represents 70 to 90% of the observed $\sigma(pp\rightarrow NN\pi)$ at 1 GeV.[21] We note that in nuclei with more rapidly falling form factors, the Δ processes are considerably reduced compared to the ^{4}He case because of the minimum momentum transfer required to produce a Δ. Details of our results will be given in another paper.

All of the refinements lead to a theoretical *prediction* in substantial disagreement with the Saclay-B data *and* the BNL data but in quite good agreement with the Saclay-A results. This situation was initially reported[22] by Wallace and has not changed significantly as refinements have been made to the theoretical calculations. Our theoretical prediction was recently reported by Igo[23] based on somewhat different nucleon-nucleon spin-dependent amplitudes and a scalar estimate of Δ-intermediate-state effects.

A UCLA-LBL collaboration[4] has measured the absolute differential cross section at 1.05 GeV for $-t \geq 0.17$ (GeV/c)^2. Independently an Argonne National Laboratory–UCLA–University of Minnesota experiment[5] at 1.029 GeV has measured p-^{4}He polarization and differential scattering. Figure 1 summarizes the correspondence of our theoretical differential cross sections (solid lines) with five existing data sets. The curve labeled A is in excellent agreement with the UCLA-LBL data,[4] and corresponds to $\sigma(pp\rightarrow N\Delta) = 17$ mb. By taking $\sigma(pp\rightarrow N\Delta) = 21$ mb, with only minor chances in C_0, C_1, and φ, we obtain curve B, in equally good agreement with the Argonne-UCLA-Minnesota results.[5] Curve B is essentially the same as reported in Ref. 23. The two theoretical curves, A and B, differ principally in the region where the Δ process dominates. When the Δ-intermediate-state amplitude is absent, the predicted differential cross section has a deep minimum as shown by the dash-dotted line. This minimum is not appreciably filled by $1/k$ corrections to Glauber theory (as shown by comparing the dashed and dash-dotted lines) or Coulomb effects, but its depth does depend on the phases of p-p and p-n amplitudes.

As already mentioned our differential cross sections are based on p-n amplitudes which provide a reasonable fit to the new polarization data as shown in Fig. 2. The sets of parameters that yield curves A and B for the differential cross section in Fig. 1 produce essentially the same polarization. Again the Δ-intermediate-state amplitude is seen to play a very important role.

The p-^{4}He differential cross section prediction is rather insensitive to the Δ-intermediate-state process at very small t and near $-t \simeq 0.4$ (GeV/c)^2. Reasonable variations of the p-n parameters do not fit the Saclay-B data near these points. The effect of short-range correlations in ^{4}He has also been calculated and is found to be small in the t range of Fig. 1. Hence our result strongly supports (i) the normalization of the new experiments and (ii) the role of the Δ-intermediate-state process in filling the first diffraction minimum at 1 GeV.

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Polarization in p-^{4}He Elastic Scattering at 0.56, 0.80, 1.03, 1.27, and 1.73 GeV*

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The polarization in p-^{4}He elastic scattering has been measured between 0.56 and 1.73 GeV in a range of the square of the four-momentum transfer between 0.006 and 1.2 (GeV/$c)^2$. The data are characterized by positive polarization maxima at $-t$ near 0.08 and 0.36 (GeV/$c)^2$. At 0.56 GeV, a sharp peak of large negative polarization at 0.23 (GeV/$c)^2$ is observed. This structure persists at higher bombarding energies, but is no longer negative and becomes increasingly shallower as the bombarding energy increases to 1 GeV and then is relatively unchanging.

Stimulated by the 1.0-GeV differential cross-section data on p-^{4}He elastic scattering reported by Palevsky *et al.*,[1] a number of theoretical investigations of p-^{4}He elastic scattering have been made. Some of these also predict the induced polarization in elastic scattering.[2-8] To date there have been two polarization measurements at intermediate energies, at 0.72 GeV $[0.01 \leq -t \leq 0.17$ (GeV/$c)^2]$[9] and at 0.54 GeV $[0.006 \leq -t \leq 0.52$ (GeV/$c)^2]$.[10] Both measurements employed polarized beams produced by scattering. In the present experiment, an increase in the range of t investigated and in the statistical accuracy has been made possible by using polarized beams available at the zero-gradient synchrotron at Argonne National Laboratory.

We have recently completed such a measurement using incident proton kinetic energies T_p of 0.56, 0.80, 1.03, 1.27, and 1.73 GeV. We have actually measured the left-right scattering asymmetry (analyzing power), but the analyzing power must equal the polarization in the case of elastic scattering. The experiment used a single-arm magnetic spectrometer to detect scattering from a liquid-helium target. The spectrometer was 30 m long and used four dipole magnets for momentum dispersion and seven quadrupole magnets to create both an intermediate and a final spatial focus. The details of the spectrometer and a plan view are given by Klem *et al.*,[11] although some modifications to that apparatus were made to obtain the large laboratory scattering angles required in this experiment. These changes included bending the incident proton beam with a