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p-^{4}He elastic scattering at 5.75 GeV/c

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A measurement of $d\sigma/dt$ between $t = 0.18$ and 2.2 (GeV/c)^2 has been made at a bombarding energy of 4.89 GeV. The shallow minimum observed between 0.4 and 2.68 GeV persists. The magnitude of $d\sigma/dt$ is intermediate between those measured at 2.68 GeV and at 23.1 GeV; $d\sigma/dt$ exhibits a change in slope near $-t = 1.0$ (GeV/c)^2, corresponding to the interference of double and triple scattering amplitudes.

[NUCLEAR REACTIONS Measured $d\sigma/dt$ for $t = 0.18$ to 2.2 (GeV/c)^2. Calculated $d\sigma/dt$.]

Recent p-^{4}He elastic differential cross section measurements[1-11] at bombarding energies T between 0.35 and 2.68 GeV are characterized by a slow variation with T of the ratio R of the cross section at the second maximum and at the first minimum. Quantitatively, R remains within the limits of 1–1.9. In addition, at fixed t, $d\sigma/dt$ varies slowly with T in the same energy range. In striking contrast, R is found to be equal to 4, and $d\sigma/dt$ at fixed t is about one order of magnitude smaller at 23.1 GeV.[12] Kofoed-Hansen and Wilkin[13] pointed out in 1971 that because the spin-flip part of the nucleon-nucleon amplitude was small in the 20 GeV range, a Glauber model calculation using non-spin-flip amplitudes should suffice to fit the elastic scattering. Auger, Gillespie, and Lombard[14] have recently verified this conjecture with an explicit calculation using the Glauber model.

On the other hand, attempts to fit the data between 0.4 and 2.68 GeV with Glauber or KMT models utilizing currently known nucleon-nucleon amplitudes have generally given too large values of R. Furthermore, the theoretical cross sections at the second maximum are too small. This has been attributed to (1) lack of knowledge of the nucleon-nucleon amplitudes, especially the spin-flip component (this question is currently being resolved in part by direct measurements[15-22] of the five components of the p-p amplitudes); (2) uncertainty in the ground state wave function of ^{4}He; and (3) the effect of the nucleon-isobar intermediate states. Recently Wallace[23] has obtained an excellent fit to data near 1 GeV by taking into account a Δ-intermediate state. The amplitude used in this calculation was determined on the basis of 70–90% of the observed strength for the reaction $pp \to N\Delta$, i.e., by setting the strength so $\sigma(pp \to N\Delta) = 15$–$20$ mb. On the other hand, the amplitude of the Δ-intermediate state at the bombarding energy selected for this experiment, 5 GeV, will be negligible. Heavier-mass nucleon-isobar intermediate states can be important and remain to be evaluated.

It is also quite obvious from the considerations in the first paragraph of this paper that the variation of $d\sigma/dt$ near 0.25 (GeV/c)^2, and, specifically, the variation of R with T between the regions where measurements have existed (0.4–2.68 and 23.1 GeV), needs to be studied.

For the measurements in the momentum transfer range, $-t = 0.18$ and 0.70 (GeV/c)^2, the experimental arrangement is identical to one described in Ref. 10 [p-^{4}He elastic scattering at 2.68 GeV]. In the momentum transfer range, $-t = 0.6$ to 2.2 (GeV/c)^2, the signal was enhanced by using liquid helium instead of a gas target. This was possible since the recoil α particle had sufficient kinetic energy, $T_\alpha \simeq -130t$ [T_α and t in units of MeV and (GeV/c)^2, respectively] to emerge from the liquid target and be particle-identified in the recoil hodoscope and range counter described in Ref. 24. When the liquid target was used, an additional beam intensity monitoring system was employed. The areal density was monitored by a pair of three-element scintillation counter telescopes viewing the target up and down in the vertical plane. The summed counting rate ratio for target full/target empty conditions was constant ($\sigma = 5\%$) over the duration of the experiment for the monitoring system.

The spectrometer momentum resolution of 0.8% full width at half maximum (FWHM) is more than sufficient to separate the elastic events from background associated events (pion production, etc.) except for those which were associated with an unbound, excited state of the ^{4}He nucleus. The latter are removed by simultaneous cuts on data from both detector arms, including the momentum of the forward scattered proton, opening angle, and coplanarity; and a very clean elastic event selection results. Application of an additional constraint, the mass identification of the α particle provides a consistency check and a means of estimating the remaining background.

Figure 1 shows distribution of momentum, opening angle, and coplanarity before and after the final cuts at a spectrometer setting, θ_{spect}, of 5.0° $[0.18 \leq -5 \leq 0.36\ (\text{GeV}/c)^2]$. The final cuts are indicated by arrows in Fig. 1. The setting of $\theta_{\text{spec}} = 5.0°$ has been chosen to be displayed in Figs. 1 and 2 because difficulties in separating elastic events are more severe here than at smaller angles due to the decrease in the cross section. At larger angles, the longer range of the recoil α particle and the use of a liquid target more than compensate for the decrease in $d\sigma/dt$. Figure 2(a) shows the time of flight spectrum of the recoil particle ($\theta_{\text{spec}} = 5.0°$) with the target full, before and after the cuts have been applied, and with the target empty before the cuts. None of the target empty events survived the final cuts. An inspection of Fig. 2(a) illustrates that the cuts are very successful in a typical spectrum in removing backgrounds and in preserving the real elastic events. To obtain an estimate of the efficiency of the cuts, we note that the ratio of the elastic events obtained after the cuts [see Fig. 2(a)] to the elastic events obtained by subtracting off a constant background equal to the average value in the wings is (95 ± 3)%. Recoil mass spectra ($\theta_{\text{spec}} = 5.0°$, target full) are calculated from time of flight and pulse height data before [Fig. 2(b)] and after [Fig. 2(c)] the final cuts. Also shown in Fig. 2(c) is the mass spectrum reconstructed from pulse height and time of flight measurements obtained from a p-^{3}He elastic scattering measurement, which was done with the same apparatus. The ^{3}He mass is overestimated as a consequence of using energy calibration and energy loss corrections appropriate to ^{4}He in the reconstruction of the mass. It can be seen from this figure that the removal of events involving ^{3}He production is very good.

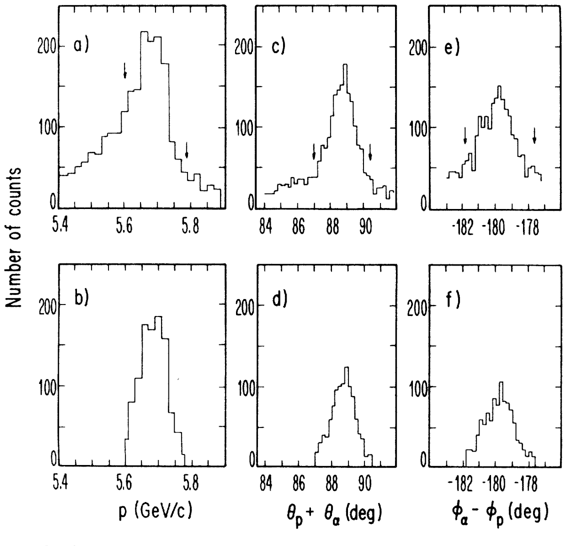

FIG. 1. Spectra obtained at $\theta_{\text{spec}} = 5.0°$ before and after application of the cuts which eliminate events outside the region between the arrows on the abscissa: (a) and (b), the momentum spectrum of particles with momentum p detected in the magnetic spectrometer before and after cuts are applied; (c) and (d), the opening angle spectrum before and after cuts are applied (θ_p and θ_α are projected angles on the scattering plane of coincident particles detected in the spectrometer and recoil telescope respectively); (e) and (f), the coplanarity spectrum (ϕ_p and ϕ_α are projected angles on the normal plane).

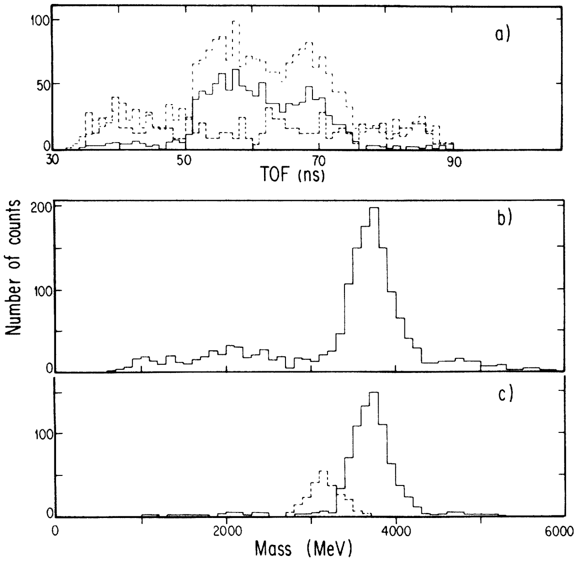

FIG. 2. (a) Time of flight spectra obtained at $\theta_{\text{spec}} = 50°$ with target filled and evacuated. The spectra have been normalized to the same beam particle flux. Dash-dot line, target full, and the cuts illustrated in Fig. 1 have not been applied; dashed line, target full, and the cuts have been applied; and solid line, target evacuated, and the cuts have not been applied. (b) The recoil mass spectrum before the cuts illustrated in Fig. 1. (c) The recoil mass spectrum after the cuts illustrated in Fig. 1 (solid line). The dashed line is a mass spectrum obtained in p-^{3}He scattering (see text for details).

The measured differential cross section for $p + {}^4$He elastic scattering is presented in Fig. 3.

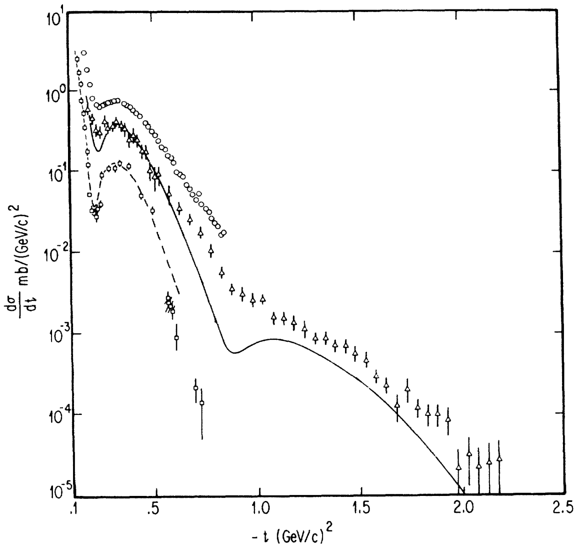

FIG. 3. The cross section $d\sigma/dt$ plotted versus $-t$ at 5.75 GeV/c measured in the present experiment (triangles); at 1.05 GeV (circles), from Geaga *et al.*, Ref. 9, and at 23.1 GeV (squares), from Berthot *et al.*, Ref. 7. The solid and dashed curves are Glauber model calculations at 4.89 and 23.1 GeV, respectively; the latter is taken from Ref. 14.

Also plotted are data obtained at 1.05 GeV (Ref. 7) and at 23.1 GeV.[12] The comparison illustrates the T behavior discussed at the beginning of this paper. A simple theoretical fit to the 4.89 GeV data is included using the Glauber model (the parameters used are listed in Table I). The Glauber model might be expected to be valid at larger $|t|$ at 4.89 GeV than at lower energies where p-^{4}He data exist and have been analyzed. At this time, we have made no comprehensive attempt to fit the data at 4.89 GeV. However, it is interesting to point out (see Fig. 3) that a simple spin-isospin averaged nucleon-nucleon interaction is not sufficient to fit the data at 4.89 GeV in contrast to the situation at 23.1 GeV. (The Glauber model calculation with a spin averaged nucleon-nucleon interaction referred to above[14] is shown for comparison.) This is not an unreasonable result. As pointed out already by Wallace and Alexander,[23] and discussed above, the effect of higher mass nuclear isobar-intermediate states in the multiple scattering process can be important near 5 GeV and of course negligible at 23.1 GeV. The spin-flip amplitude may play an important role at 5 GeV but is known to be small near 20 GeV. Processes involving nuclear isobar intermediate states and the spin-flip part of the nucleon-nucleon amplitudes will tend to fill in the minimum at 0.25 (GeV/c)^2. Their effects remain to be evaluated in p-^{4}He elastic scattering near 5 GeV. A remarkable result of this work and that of Refs. 2, 6, 8, 9, and 11 is that there is now definite evidence that the amplitude for triple scattering in ^{4}He is large relative to single and double scattering amplitudes near 1.45 (GeV/c)^2. A detailed study of this region was made by Ullo and Feshbach[25] some time ago, but they dealt only with the early data from Brookhaven.[1] The data at 4.89 GeV provide a test for the effect of Δ and N^* intermediate states in conjunction with the data at 1 GeV where Wallace and Alexander[23] find the 1232 MeV Δ plays a significant role in filling in the first minimum. The influence of the D state component in the ^{4}He wave function at the first minimum is expected to be relatively small.[26] This is because ^{4}He does not have a quadrupole form factor, which is responsible for the dramatic effect in the filling in of the proton-deuteron differential cross section at the first minimum.

TABLE I. The values of parameters describing the density functions for helium $\rho(r) = Ne^{-r^2/b^2}$ and the spin/isospin independent nucleon-nucleon scattering amplitude $f(t) = (ik\sigma/4\pi)(1 - i\alpha)\exp[\beta^2 t/2]$. The quantities σ, α, and β are averaged values of the total cross section σ_{pp} and σ_{pn} for p-p and p-n scattering, of the ratio of real to imaginary parts of the scattering amplitudes, α_{pp} and α_{pn}; and of the slope parameters, β_{pp} and β_{pn}.

$$\sigma = \tfrac{1}{2}(\sigma_{pp} + \sigma_{pn}) = 41.3 \text{ mb}$$

$$\alpha = \tfrac{1}{2}(\alpha_{pp} + \alpha_{pn}) = -0.285$$

$$\beta^2 = \tfrac{1}{2}(\beta_{pp}{}^2 + \beta_{pn}{}^2) = 7.85 \text{ (GeV/}c)^{-2}$$

$$b = 1.37 \text{ fm}$$

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