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Sharp Backward Peak in p-^{4}He Elastic Scattering at 1.05 GeV

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p-^{4}He elastic scattering has been measured at 1.05-GeV incident proton energy, close to 180° in the center of mass. The steep backward peak observed at lower energies is still present, but its slope appears to decrease.

Our previous results on elastic p-^{4}He scattering at intermediate energies and at angles close to 180° in center-of-mass system revealed the occurrence of a sharp rise in the differential cross section, which became steeper as the energy increased.[1] Various theoretical models have tried to explain this backward peak by either actual nucleon-nucleon interaction in a noneikonal scattering approach,[2] or triton exchange,[3-5] or addition of an exchange term in a Glauber model.[6]

The data in Ref. 1 were acquired with incident α particles on a hydrogen target to take advantage of the wide coverage of the kinematics: The scattered α's are fast and confined into a cone 14.6° wide. At the higher energy, when cross sections fall to the nanobarn/steradian level, background problems associated with the empty-target effect become important. However, a useful coverage of the interesting region close to 180° in the c.m. system can still be obtained by returning to the more classical method of using a proton beam and a liquid-helium target. Indeed, around 1-GeV proton kinetic energy and above, the α's recoiling from backscattering protons have enough energy to be detected with full efficiency in our spectrometer. Besides, the higher intensity of the proton beam could offset to a certain extent the decrease in cross section. When tried, this method displayed very little background associated with the walls of the target.

Except for the installation of a liquid helium target, and the use of a proton beam, the apparatus was the same double-focusing spectrometer used in Ref. 1 and described in detail elsewhere.[7] The fact that the recoiling ^{4}He is detected ensures the elastic character of the reaction.

The differential cross sections in the c.m. system are presented in Fig. 1, as a function both of $\cos\theta_{c.m.}$ and of the invariant quantity $u - u_{max}$. The numerical values are listed in Table I. It is noteworthy to point out that the smallness of the background has allowed us to make a measurement at $\theta_{c.m.} = 180°$.

We show in Fig. 2 the present data with our earlier results at different energies.[1,8] The results of Comparat *et al.*[9] at 156 MeV and of Aslanides *et al.*[10] at 1.05 GeV are also shown. The cross sections are given as a function of t. In the following, when comparing different experiments, we will use in the case of incident α particles the equivalent proton laboratory kinetic energy (i.e., giving for $p\alpha$ scattering the same c.m. energy as in αp case); when needed, the c.m. momentum will be also given. One can note in Fig. 2 that a sharp peak exists near 180° in the c.m. system except at 198 and 438 MeV. Outside the backward region, $d\sigma/dt$ is to a large extent energy invariant, as confirmed also by the results at 788 MeV,[11] and it can be described by Glauber-like[12,13] models.

At the intermediate energies Gurvitz *et al.*[13] described the large-angle p-^{4}He scattering using

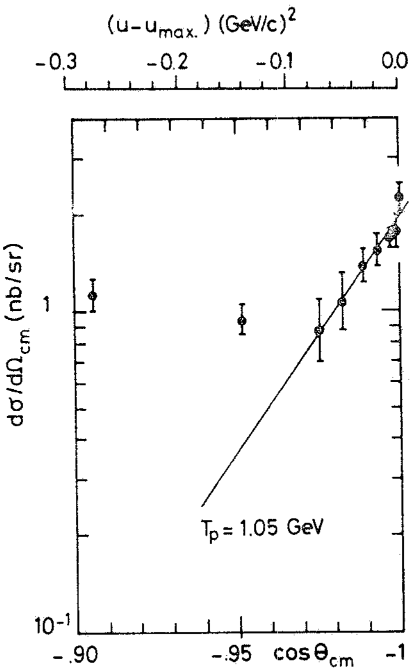

FIG. 1. c.m. differential cross section for p-^{4}He elastic scattering as a function of $\cos\theta_{c.m.}$ and of the invariant quantity $u - u_{max}$. The solid line is the result of the parametrization discussed in the text.

TABLE I. Center-of-mass differential cross section for $p + {}^4\text{He} \to {}^4\text{He} + p$ at $T_p = 1.05$ GeV. The errors shown do not include an overall 10% uncertainty accountable to the acceptance determination and to the incident flux calibration.

θ_{lab} (^{4}He) (deg)	$\cos\theta_{c.m.}$ proton	$u - u_{max}$ [(GeV/c)^2]	$d\sigma/d\Omega_{c.m.}$ (nb/sr)
0.25	−0.999 96	−0.000 12	2.21 ± 0.22
1.23	−0.998 98	−0.002 94	1.74 ± 0.19
2.20	−0.996 75	−0.009 38	1.69 ± 0.10
3.18	−0.9932	−0.0196	1.53 ± 0.17
4.15	−0.9884	−0.0333	1.39 ± 0.16
5.13	−0.9824	−0.0509	1.07 ± 0.19
6.10	−0.9751	−0.0718	0.87 ± 0.17
8.54	−0.9514	−0.1401	0.93 ± 0.10
11.95	−0.9058	−0.2718	1.17 ± 0.11

the actual nucleon-nucleon interaction. At backward angles the rise of the $I = 0$ NN interaction causes the single scattering to dominate again and a peak is predicted.[2] This method does not account simultaneously for large angles and backward scattering.[2] Kopeliovich and Potashnikova[3] predicted a backward peak using the exchange of a triton. This model was developed by Lesniak *et al.*[5] who introduced absorption for the incident and the scattered particles. They used an Eckart parametrization of the ^{4}He single-particle wave function. This calculation, not involving t-channel contributions, reproduces our results at 438 and 638 MeV for $\theta_{c.m.} \gtrsim 140°$. Also at intermediate energies, Dymarz and Małecki[6] used a Glauber model where a Majorana exchange potential is added to the equivalent potential of Ref. 1. The results of this calculation are satisfactory at 438 and 638 MeV, but difficulties appear at 1.05 GeV. It can be remarked that at low energies Thomson *et al.*[14] have shown, using the resonating-group properties, that the n-^{4}He backward scattering contains a heavy-particle exchange which can be described equivalently with a Majorana potential. This method gave satisfactory results between 30 and 156 MeV in the p-^{4}He case.[9,15,16]

In order to investigate the energy behavior of the backward cross sections we parametrized them as a function of the c.m. solid angle $\Omega_{c.m.}$:

$$d\sigma/d\Omega_{c.m.} = (d\sigma/d\Omega_{c.m.})_{180°} \exp[\xi(\Omega_{c.m.} - 4\pi)]. \quad (1)$$

The result of such a fit to our present data is shown in Fig. 1. We calculated also the slope ξ for a compilation ranging from $T_p \simeq 1.997$ to 156 MeV[9,15,17-23] and for our previous data.[1] The parameter ξ has the advantage of being insensitive to normalization uncertainties between different experiments. Figure 3(a) shows the variation of the ξ value as a function of the c.m. momentum in the energy range 1.997 MeV $\lesssim T_p \lesssim$ 1.05 GeV (49 MeV/$c \lesssim P_{c.m.} \lesssim$ 1192 MeV/c). Three different domains appear. In the low-energy region, $T_p \lesssim 156$ MeV ($P_{c.m.} \lesssim 438$ MeV/c), the slope ξ is positive. One observes a discontinuity in the energy variation of ξ at $T_p = 23.4$ MeV due to the 16.7-MeV excitation energy of ^{5}Li. Around 30–40 MeV the variation of ξ can be linked to the structure observed in the d-^{3}He elastic scattering.[19] In the intermediate region, 156 MeV $\lesssim T_p \lesssim$ 500 MeV (168 MeV/$c \lesssim P_{c.m.} \lesssim$ 800 MeV/c), the slope is close to zero, which seems to be supported by the preliminary data of Cameron *et al.*[24] At higher energies, $T_p \gtrsim 500$ MeV ($P_{c.m.} \gtrsim 800$ MeV/c), ξ is again positive. In our previous results[1] the slope, also shown in Fig. 3(a), was found to increase with energy up to 840 MeV. Our present experiment at 1.05 GeV shows that this trend has been reversed.

To get a general description of the backward p-^{4}He scattering up to our present energy 1.05

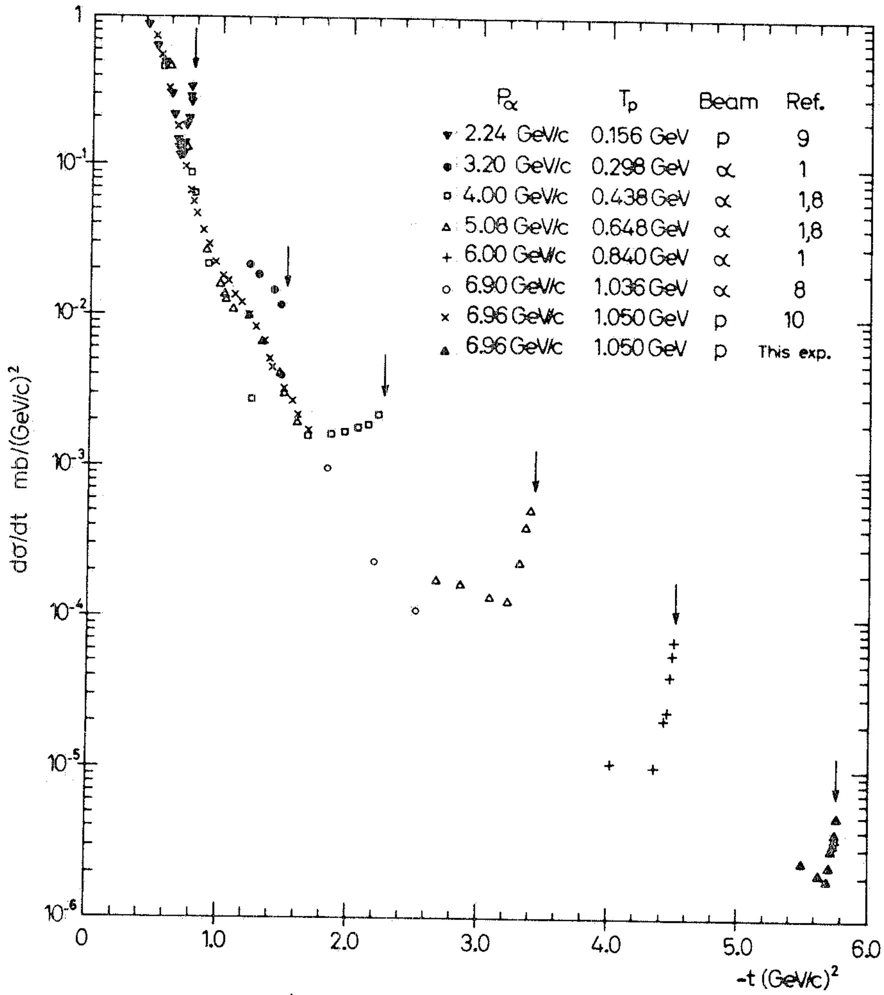

FIG. 2. Summary of high-t data for p-^{4}He elastic scattering. The arrows indicate the t value for $\theta_{c.m.} = 180°$.

GeV, we have calculated the Born triton-exchange differential cross section which is proportional[5] to $(k_\alpha^2 + Q^2)^2[H(Q)]^4$; $k_\alpha^2 = -2\mu\epsilon_S$, μ and ϵ_S being, respectively, the proton-triton reduced mass and separation energy; $H(Q)$ is the Fourier transform of the ^{4}He single-particle wave function, and Q, the momentum of the exchanged triton, is related to the c.m. momentum and scattering angle by

$$Q^2 = (\tfrac{3}{4}P_{c.m.})^2 + \tfrac{1}{2}P_{c.m.}^2(1+\cos\theta_{c.m.}). \qquad (2)$$

Our Born calculation, not including absorption corrections, leads to cross sections of about one order of magnitude above the experimental data; however, the main features of the backward scattering are qualitatively reproduced. Figure 3(a) shows the calculated slope of the backward cross sections, one can see that the ξ variation is fairly well predicted in the whole energy range. In particular at 298 MeV the calculated cross section decreases approaching 180° ($\xi < 0$). As an essential parameter of this calculation is the wave function $H(Q)$, the agreement observed in the Fig. 3(a) shows that $H(Q)$ seems to play an important role in the backward p-^{4}He elastic scattering. To illustrate this fact, $H(Q)$ has been drawn in Fig. 3(b) in its usual momentum representation: The ξ values are calculated over small $\cos\theta_{c.m.}$ regions near 180°, the related Q's in the Born cross section are near $Q(180°) = \tfrac{3}{4}P_{c.m.}$, and hence the Q scale has been determined from the $P_{c.m.}$ scale of Fig. 3(a) using this relation. Then, at the same time, Fig. 3(b) shows the momentum representation of $H(Q)$ and the values of $H(Q)$ used in the Born calculation at a given $P_{c.m.}$; as a consequence this allows to see that there is a correspondence between $H(Q)$ and the ξ variation. All the observed trends relate the experimental behavior of the p-^{4}He backward elastic scattering to the general features of the triton-exchange mechanism.

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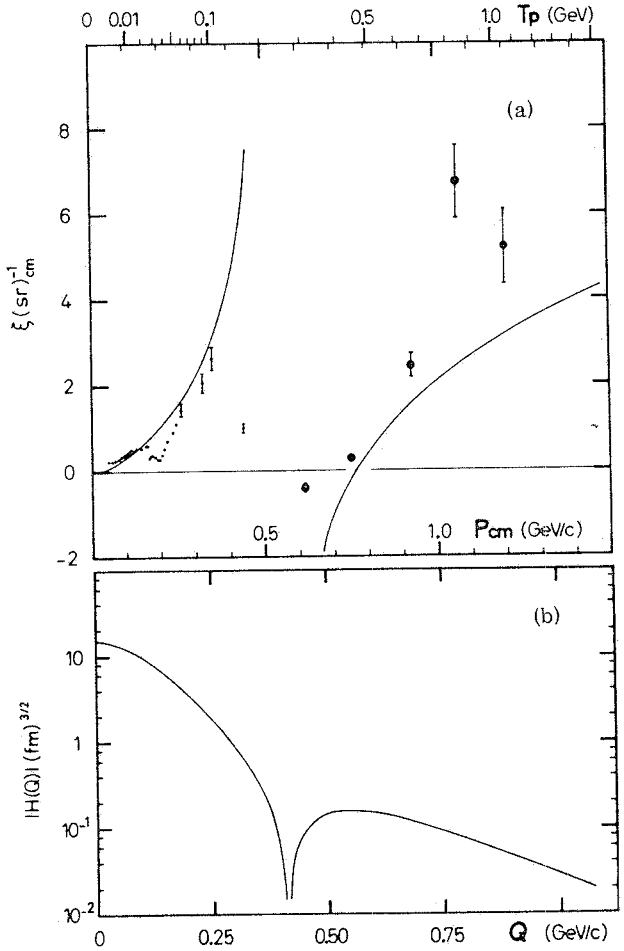

FIG. 3. (a) Slope parameter ξ as a function of the c.m. momentum, $P_{c.m.}$. The slope resulting from the triton-exchange Born approximation (Ref. 5) (solid line) has been calculated in the angular range of the backward peaks, and has been multiplied by the constant factor 3.5 for the sake of comparison. (b) Absolute value of $H(Q)$. The Q scale is drawn using the formula (2) in the text, the value of Q corresponding to a given $P_{c.m.}$ being $Q(180°) = \frac{3}{4}P_{c.m.}$. However, at a given incident energy, formula (2) shows that Q increases as $\theta_{c.m.}$ goes away from 180°. Then the Born cross section (Refs. 4 and 5), proportional to $(k_\alpha{}^2+Q^2)^2[H(Q)]^4$, has a backward peak [i.e., solid curve $\xi > 0$ in (a)] for Q values near $\theta_{c.m.} = 180°$, where $|H(Q)|$ decreases.

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