Measurement of Medium Energy Alpha-Proton Elastic Scattering beyond the First Minimum Region

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The α-proton elastic scattering has been measured with α particles at equivalent incident proton energies of 438, 648, and 1036 MeV. A structure is observed at the position where a second minimum is expected in the differential cross section. Comparison with improved versions of the Glauber model are presented.

Medium-energy proton-^{4}He scattering results have shown, since the early measurements at the Brookhaven National Laboratory cosmotron,[1] at the National Aeronautics and Space Administration's Space Radiation Effects Laboratory (SREL),[2] and more recently at Saclay's magnetic spectrometer facility SPES I[3] and at Berkeley,[4] a pattern that is qualitatively explained in the framework of the Glauber model[5] as due to a destructive interference of single- and double-scattering amplitudes. In the region of the square of the momentum transfer $t \simeq -0.25$ (GeV/c)^2, where the two amplitudes are comparable in magnitude, a dip in the differential cross section has been observed. The amount of filling of this dip may be explained by introducing a real part in the elementary proton-nucleon scattering amplitude. It is also quite conceivable that some noneikonal effects, absent in the standard Glauber model, may be important in the dip region.

The next landmark of interest occurs around $t = -1.2$ (GeV/c)^2, where double and triple scattering are expected to interfere destructively. The extent to which this dip is filled or not filled should be a severe constraint on any scheme proposed to explain the filling of the first one. The real-part mechanism alone, barring a strong t dependence of the phase of the nucleon-nucleon amplitude, would require the same amount of filling for both dips. On the other hand, corrections translating the noneikonal character of the successive scatterings at high t would be expected to fill the second dip even more than the first one.

At even higher t, one can investigate large-momentum components of the nucleon wave function through the study of backward behavior in the proton-nucleus cross section.

With all this in view we have explored the realm of momentum transfers of several (GeV/c)^2, using the unconventional technique of sending an α-particle beam unto a hydrogen target. This allows the use of a fixed, double-focusing spectrometer to detect the scattered α particles. Moving the beam by only 15° around the target insures coverage of the entire kinematics, except for a region close to the maximum laboratory angle, where the forward and backward elastic peaks overlap. Details on the spectrometer[6] and the experimental procedure[7] have been published elsewhere. We present measurements performed with incident α's of 4.00, 5.08, and 6.90 GeV/c, corresponding to $T_p = 438$, 648, and 1036 MeV in the p-^{4}He configuration. The two latter energies were chosen because data had already been taken at smaller t by SPES I.

Table I lists the numerical results for the invariant cross section, $d\sigma/dt$. Those data, supplemented by measurements in the backward hemisphere that we have published elsewhere,[6] have been plotted in Fig. 1. The crosses (+) come

TABLE I. α-proton elastic cross sections. The data at 4.00 and 6.90 GeV/c were taken with an angular resolution of $\pm 0.44°$. At 5.08 GeV/c, a narrower collimator, corresponding to $\pm 0.22°$, was used. The overall uncertainty on the laboratory angle is estimated at $\pm 0.2°$.

Angle in the C.M. Degree	$-t$ $(\mathrm{GeV}/c)^2$	$d\sigma/dt$ $\mu\mathrm{b}/(\mathrm{GeV}/c)^2$
	p_α = 4.00 GeV/c	
40.8	0.274	1236 ± 62
41.3	0.280	1043 ± 52
46.4	0.336	550 ± 28
57.9	0.534	464 ± 23
71.1	0.753	90.8 ± 4.5
72.0	0.785	65.8 ± 3.3
78.4	0.898	22.0 ± 1.1
96.1	1.246	2.8 ± 0.3
	p_α = 5.08 GeV/c	
30.4	0.235	3466 ± 170
31.8	0.256	1179 ± 59
31.9	0.259	768 ± 38
35.8	0.323	737 ± 37
38.0	0.361	1022 ± 51
40.3	0.406	1198 ± 60
41.2	0.422	1159 ± 58
42.4	0.448	1125 ± 56
48.8	0.583	474 ± 24
54.4	0.715	144 ± 7
61.1	0.882	27.2 ± 1.4
65.0	0.985	16.3 ± 0.8
66.4	1.024	13.7 ± 0.7
67.0	1.040	13.0 ± 0.7
69.1	1.099	11.1 ± 0.6
73.0	1.206	9.88 ± 0.5
76.7	1.315	6.72 ± 0.34
81.8	1.464	4.14 ± 0.21
82.8	1.493	3.14 ± 0.16
86.2	1.594	1.99 ± 0.10
93.8	1.822	0.72 ± 0.07
	p_α = 6.90 GeV/c	
61.0	1.465	4.02 ± 0.20
69.0	1.826	0.98 ± 0.05
76.9	2.199	0.24 ± 0.01
83.4	2.518	0.11 ± 0.01

from SPES I published results[3] with 1.05-GeV incident protons, using the proper absolute calibration.[8] One will notice that the agreement with our data at 6.90 GeV/c is excellent, remembering that two completely independent setups were used.

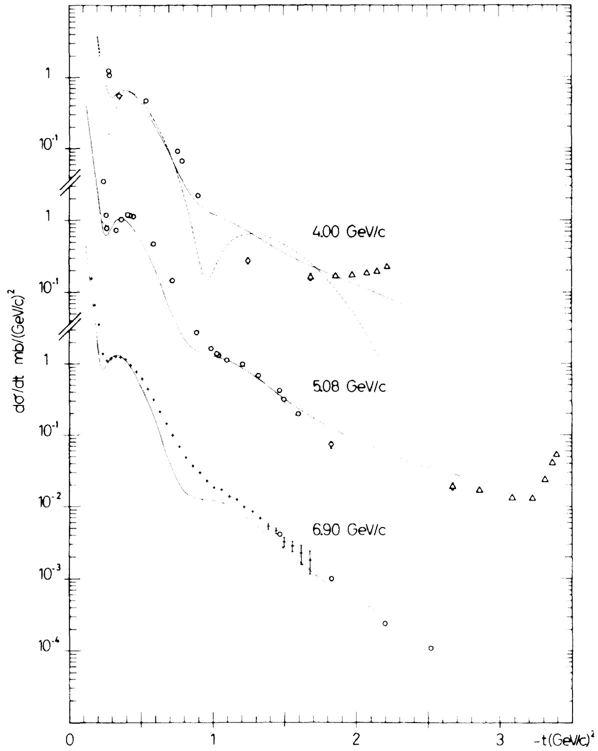

FIG. 1. Circles, experimental data from this experiment; triangles, experimental data from our previous work (Ref. 6); crosses, experimental data of SPES I (Ref. 3) using 1.05-GeV protons on a helium target. (For clarity, only every other point has been included.) Error bars have been omitted when they are smaller than the size of the symbols. Dashed line, simple Glauber model using the same nucleon-nucleon parameters as in Ref. 9 at 4.0 GeV/c; full lines, calculation by Dymarz and Małecki (Ref. 9) at 4.0, 5.08, and 6.9 GeV/c; dotted lines, calculation of Gurvitz, Alexander, and Rinat (Ref. 10) at 4.77 and 6.75 GeV/c.

Our data in the forward hemisphere present the two shallow structures: The second dip, being much more filled than the first one, shows up only as a small change in the slope of the differential cross section. This smooth behavior of the experimental data is inconsistent with the standard Glauber model which would give rise to a much more pronounced structure in the cross section. (See the dashed curve[9] in Fig. 1 at 4.0 GeV/c.)

The cross section $d\sigma/dt$ in the forward hemisphere is nearly independent of energy. This feature is explained in the Glauber model as the result of a relatively weak energy dependence of the nucleon-nucleon amplitude. In contrast to this,

TABLE II. Nucleon-nucleon parameters used in the theoretical fits of Fig. 1. The amplitude is taken as $A(t) = (\sigma_{tot} k_p/4\pi)\ (i + \alpha) \exp(-\beta t/2)$. The suffixes pp and pn refer to proton-proton and proton-neutron parameters, respectively.

Ref.	p_α (GeV/c)	k_p (GeV/c)	σ_{pp} (mb)	σ_{pn} (mb)	α_{pp}	α_{pn}	$\beta_{pp} = \beta_{pn}$ [(GeV/c)$^{-2}$]
9	4.00	1.01	27.5	33.5	−0.35	−0.35	2.5
	5.08	1.28	41.0	37.0	−0.25	−0.25	4.0
	6.90	1.74	47.5	40.5	−0.30	−0.30	5.5
10	4.77	1.20	40.0	36.0	−0.20	−0.60	3.3
	6.75	1.70	47.5	39.0	−0.50	−0.50	5.27

the sharp backward peak, described in Ref. 5, does strongly depend on energy.

The predictions of two theoretical models, claiming substantial improvements over the classical Glauber treatment, have been included in Fig. 1. The dotted lines at 5.08 and 6.90 GeV/c represent a calculation by Gurvitz, Alexander, and Rinat,[10] while the full lines at the three-momenta are the results of Dymarz and Małecki.[9] Both calculations use as an input, exponential parametrization of the nucleon-nucleon amplitude, as listed in Table II. In Ref. 10, for single scattering only, amplitudes interpolated from actual pp and np differential cross sections are introduced. This causes the single-scattering amplitude to dominate again at sufficiently high t, because of the backward rise in nucleon-nucleon cross sections. The nucleon recoil effects, as well as the off-shell propagation, have been included. The curve that we selected from Ref. 10 corresponds to the ^{4}He input which provides a good phenomenological fit to the charge form factor.

In Ref. 9 the optical-potential equivalent to the Glauber multiple scattering series was evaluated. For this calculation the ^{4}He wave function resulting from a nuclear model including short-range correlation between target nucleons has been used. The scattering cross section is obtained by solving exactly the Schrödinger wave equation with the optical potential.

In Fig. 1, the comparison between experimental data and the two models shows that the predictions of Ref. 10 are in good agreement up to $t = -1.7\ (\text{GeV}/c)^2$ at 5.08 GeV/c, while at 6.90 GeV/c (corresponding to 1.05-GeV incident protons) the fit is less satisfactory. On the other hand, the calculations of Ref. 9 are in reasonable agreement with the data at all three energies and for momentum transfer extending all the way to the base of the backward rise.[11]

In conclusion, our data show an inflection where the second dip is expected to appear. The filling of this dip is even more pronounced than the first one. The nearly structureless behavior of the cross section, being inconsistent with the standard Glauber model, may be explained by means of noneikonal propagation.

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Continuum γ-Ray Emission and Angular-Momentum Dissipation in the De-excitation of ^{39}K and Se†

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The dissipation of angular momentum during the particle-emission and photon-emission stages of de-excitation of ^{39}K and Se has been determined from measurements of the average multiplicity $\langle N_\gamma \rangle$ and the average energy $\langle E_\gamma \rangle$ of the continuum γ rays, emitted in coincidence with the heavy recoiling evaporation residues produced in reactions induced by ^{12}C projectiles. The energy and angular momentum dissipated in γ-ray emission is independent of projectile energy but increases with atomic number of the residual nucleus.

The dissipation of energy in the de-excitation of highly excited compound nuclei can be readily determined experimentally. In contrast, the simultaneous dissipation of angular momentum is much more difficult to explore. γ-ray multiplicity measurements[1-3] provide a meas of focusing on the angular momenta of excited nuclei at the beginning of the γ-ray cascade which terminates the de-excitation process. If independent information on the initial angular-momentum distributions of the de-exciting nuclei is available, the dissipation of angular momentum in the particle-emission and the γ-emission steps may be determined. In this Letter, we report on the results of experiments in which we measured the multiplicities and energies of the continuum γ rays in coincidence with the compound-nucleus evaporation residues produced in the reactions of ^{12}C projectiles with Al and Ni target nuclei. Previous measurements[4] of the limiting angular momenta for fusion in these reactions show that, at the highest projectile energy of 197 MeV, ^{39}K nuclei with angular momenta as high as $42\hbar$ and ^{70}Se nuclei with angular momenta as high as $55\hbar$ are produced.

The present data show that for the systems studied, the total energy and angular momentum dissipated by γ-ray emission remain essentially constant as the projectile energy increases from 107 to 197 MeV but increase with the atomic number of the coincident heavy product, indicating that both the additional excitation energy and the additional angular momentum are removed during particle emission. This result has significant consequences for experiments which attempt to focus on the shape or structure of highly excited nuclei with high angular momentum.

For the experiments, a single 3-in.$\times$3-in. NaI detector was used to detect the γ rays in coincidence with the heavy products observed in a counter telescope, placed at an angle of 20° to the incident-beam direction and subtending an angle of 4°. For most of the experiments, silicon ΔE-counters of thickness 4.9 or 8.4 μm were employed. In one experiment, a gas ionization counter[5] with a thickness equivalent to 3 μm of silicon was used. The energy resolution of these counters was ~100 keV. The shielded NaI detector was placed 46 cm from the target in order that time-of-flight discrimination could be used to separate neutron- and photon-induced pulses. Data were taken with the NaI detector positioned at 45°, 90°, and 135° relative to the direction of the incident beam. In Fig. 1, we present the γ-ray pulse-height distributions observed in coincidence with the entire evaporation-residue group at a projectile energy of 155 MeV and an angle of 135°. Spectra obtained at other projectile energies and other angles are not significantly different from those presented. Targets ranged from 300 to 500 μg/cm^2 in thickness. The γ-ray energy threshold was ~200 keV throughout these ex-