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Small Angle Proton-Helium Elastic and Inelastic Scattering from 8 to 500 GeV

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ABSTRACT

We propose an internal target experiment to study coherent proton-He^4 reactions in the momentum transfer range from about 0.1 $(GeV/c)^2$ to 0.3 $(GeV/c)^2$ or more and continuously in incident beam energy from 8 to 500 GeV. The main physics goals are measurement of the ratio of the real to the imaginary part of the nucleon-nucleon scattering amplitude at $t \neq 0$, investigation of inelastic shadow corrections to Glauber theory and determination of isobar-nucleon interaction cross sections. The target will be similar to the present jet target in use at C0 with the addition of a special molecular sieve to the cryosurface of the trap in order to pump helium. Sandwiches$\left(\frac{dE}{dx}, E\right)$ of silicon solid-state detectors will be used to separate alpha particles from background.

1. INTRODUCTION

Small angle p-p elastic scattering up to $|t| = 0.1\ (\mathrm{GeV/c})^2$ has been measured in Experiment 36. The slope parameter, b, and ρ, the ratio of the real to the imaginary parts of the scattering amplitude for p-p elastic scattering were determined.[1,2] These same parameters for p-d elastic scattering are being measured in Experiment 186.

These parameters and their variation with energy are basic to our understanding of the dynamics of high energy collisions. Detailed experimental and theoretical work on elastic scattering may be the first place to find the onset of some new physical phenomena in strong interactions.

We propose to extend the p-p and p-d experiments to p-He elastic and inelastic scattering. This will then add information on scattering from a $J = 0$ object to information already available from $J = 1/2$ and $J = 1$ objects. The availability of this complete set of scattering data may be very powerful in describing the high-energy scattering processes in terms of exchanged particles or trajectories.

In the p-p and p-d experiment solid-state detectors are used to define the scattering angle and energy of the recoil particle and thus separate elastic events from the inelastic background. We propose to carry out the p-He experiment by the same basic technique. Sandwiches of solid-state detectors will measure energy, angle, and separate recoiling alphas from proton, deuteron, triton, and other (e.g. pion) background.

2. PHYSICS GOALS

A. Elastic Scattering

2.1 Interference Dip

The ratio of the real to the imaginary parts of the nucleon-nucleon forward scattering amplitude, ρ, has been determined in E36[2] by studying the effect of the Coulomb-nuclear interference on the shape of the differential cross section in the region where these two amplitudes are comparable ($|t| \sim 0.002$ GeV^2). Measurements were made from $|t| = 0.001$ $(GeV/c)^2$, which is well within the Coulomb region, to $|t| = 0.04$ $(GeV/c)^2$, where the nuclear interaction dominates and it is assumed in the analysis that $\rho(s,t)$ has no t-dependence in this range.

The invariant cross section, $d\sigma/dt$, for elastic p-Nucleus Scattering will show a series of minima or breaks due to interference of single and multiple scattering. According to Glauber multiple scattering theory[3] the shape of the curves $d\sigma/dt$ around these break points is determined by the magnitude of the real part of the proton-nucleon scattering amplitude. Knowledge of the real part of the amplitude at $t \neq 0$ is a matter of great interest.

In the case of p-He scattering the break is expected around $|t| \simeq 0.24$ $(GeV/c)^2$. Data taken at low energy[4,5] and reproduced in Fig. 1 illustrate this. Figure 2 shows a prediction for the differential cross section for elastic $p\text{-}He^4$ scattering at 300 GeV. Cross sections are shown for different assumptions for ρ with and without experimental resolution folded in. The angular resolution assumed here is based on a 12 mm wide target viewed at a distance of 2.5 meters

Data will be taken using multiple traversals of the target during acceleration in the Main Ring. Thus the shape of the differential cross section will be studied as a function of s. If ρ [s, $|t| \stackrel{\sim}{\sim} 0.24$ $(GeV/c)^2$] is the same as ρ [s, $|t| \stackrel{\sim}{\sim} 0.002$ $(GeV/c)^2$] as measured in E36 then qualitatively one will see the dip sharpen as one approaches p_{lab} = 280 GeV/c where ρ goes through zero and then become shallower above that energy.

2.2 Elastic Scattering Below and Above the First Interference Dip

Measurements in the t-region below the first dip will yield a value for b and c in the diffraction cone where the cross section is usually parameterized by the form $d\sigma/dt \sim e^{-b|t| - ct^2}$. The minimum value of $|t|$ = 0.1 $(GeV/c)^2$ corresponding to $\sim$100 μ range in silicon is quite arbitrarily chosen. During the run one will attempt to use thinner detectors and measure $d\sigma/dt$ to as small values of $|t|$ as possible.

Recent measurements[6] of polarization at relatively small s show marked spin dependence. How is spin important at high energies? This important question is still open. Some authors[7,8] suggest the possibility that spin effects can survive even at ISR energies and are responsible for the well known break[9] at small $|t| \simeq 0.1 - 0.15$ $(GeV/c)^2$. Scattering of protons off a spin zero nucleus like He^4 will give important information for clarification of the role of spin.

The second break in p-He^4 elastic scattering is predicted to occur at t = 0.8 $(GeV/c)^2$. The angle, kinetic energy and range in silicon of the recoiling alpha particle are 114 mrad, 100 MeV, 3.6 mm. Although the cross section is expected to be quite small, improvements in jet density or accelerator intensity during the experiment may allow us to go to higher $|t|$ values than proposed.

2.3 Determination of the Corrections to Glauber Theory

It is well known that using nuclei as a target for studying hadron-hadron interactions introduces complexities connected with the complex character of hadron-nucleus interactions. However, at high energies and low-t the hadron-nucleus interaction can be described with good accuracy in terms of the hadron-hadron interaction with the help of Glauber theory.

In its simplest form Glauber theory takes into account only elastic rescattering of the incoming particle from the nucleons in the nucleus. At high energy the production of groups of particles with large mass, M, at small-t become important. These contributions to the hadron-nucleus amplitude can be expressed in terms of inclusive cross sections $h + N \rightarrow X + N$. At small masses, M_x, the main contributions arise from excitation of resonances and these terms have structure which is similar to elastic shadow corrections (Fig. 3a). The contribution of large M_x can be expressed as the sum of triple Regge contributions (Fig. 3b). Depending on the sign, some of these terms enlarge the Glauber correction (shadow contributions); others decrease it (antishadow contributions). Investigation of these effects is interesting both for Glauber theory and also to obtain some additional information on triple-Regge couplings.

B. Inelastic p-He^4 Scattering

The use of nuclear targets has an important advantage. In the case of production of unstable particles (resonances) there is the possibility of measuring the resonance-nucleon interaction which is impossible in ordinary hadron-hadron reactions. These reactions present a unique opportunity to investigate the space-time development of hadronic processes in contrast to the usual hadron-hadron reaction which depends only on the asymptotic properties of the amplitudes, i.e., S-matrix elements. At high energies the characteristic time for a transition is large in comparison with the transit time corresponding to a nuclear mean free path. Then the system created in an elementary hadron-hadron interaction will interact with the other nucleons in the nucleus before it reaches its asymptotic state.

2.4 Cross Section for the N^*(1400)-N Interaction

One of the most interesting problems in this region is to study N^*(1400) excitation. This resonance, which has quantum numbers identical to the nucleon is from many respects a mysterious and poorly understood object. In the t-region under consideration multiple scattering terms are important. The cross section for the reaction

$$p + He^4 \rightarrow N^*(1400) + He^4 \quad (1)$$

depends on elastic pN scattering, excitation of the N^*(1400), and also on the p-N^*(1400) amplitude. Thus by measuring the cross-section for reaction (1) we can obtain $\sigma_{tot}(N\text{-}N^*_{1400})$ and the ratio of the real to imaginary parts of the N-N^*_{1400} amplitude.

2.5 Diffractive Excitation of Large Mass Systems from He^4

He^4 as the target nucleus with its unusually tight binding gives it an advantage over other nuclei since it does not have any excited states with an excitation energy less than about 20 MeV and because all the excited states are unstable against particle emission; the detection of an identified ^4He recoil nucleus is sufficient evidence of a coherent interaction.

With the experimental arrangement discussed in Section 3 it will be possible to study the s- and t-dependencies of missing mass systems up to maximum mass shown in Table I.

TABLE I

θ_{recoil} = 200 milli radians

p_{lab}	$\|t\| = 0.1$	$\|t\| = 0.3\ (GeV/c)^2$	Maximum
50 GeV/c	2.4 GeV	2.8 GeV	2.9 GeV
400 GeV/c	6.4 GeV	7.5 GeV	7.8 GeV

It is interesting to investigate the interaction of the "nonresonant background" ($p + \pi$, $p + 2\pi$) with nucleons in He^4. Naively one would expect the interaction cross section for the system ($p + k\pi$) to be approximately equal to $\sigma_{pp} + k\sigma_{\pi p}$. However, recent measurements of the coherent generation of 3π and 5π systems[10] have shown that these systems interact with nucleons like a single π-meson. This confirms ideas, put forward by Pomeranchuk many years ago that in the early stages of creation of a many particle system particular constituents which show up later in asymptotic states do not show up initially, i.e., the system has not developed enough initially and interacts like a single hadron.

3. EXPERIMENTAL DETAILS

3.1 Jet Target

Operation of the jet target with helium is more complex than operation with hydrogen. A liquid helium cooled trap is highly efficient for pumping hydrogen gas, but not very efficient for pumping helium gas. However, the addition of molecular sieves to the cryo surfaces and some sacrifice in density makes operation with helium feasible.

The main parameters of the jet target can be estimated using the theory of a free expanding jet[11] (Fig. 4a). The density of the jet at beam center, ρ_b, is given by

$$\rho_b = 0.161\ \rho_0\left(\frac{D}{x_b}\right)^2 = 4\text{x}10^{-7}\ \text{gm/cm}^3, \quad (2)$$

where ρ_0 = density of the gas just before nozzle = $0.62\text{x}10^{-2}$ gm/cm^3 (T_0 = 5°K, P_0 = 0.5 atm), D = diameter of the nozzle = 0.03 cm, x_b = distance from nozzle to beam = 1.5 cm. The average density will be lower by a factor 2 due to angular dispersion and another factor of 3 due to the pulsed mode operation. Therefore, $\rho_b = 7\text{x}10^{-8}$ gm/cm^3.

The mass flow through the nozzle, G, is given by

$$G = \frac{\pi D^2}{4}\left(\frac{2}{\gamma + 1}\right)^{\frac{1}{\gamma - 1}}\left(\frac{2\gamma}{\gamma + 1}\right)^{\frac{1}{2}}\left(\frac{m}{kT_0}\right)^{\frac{1}{2}} \cdot P_0 = 2.4\text{x}10^{-2}\ \text{gm/sec} \quad (3)$$

where m = molecular mass = $6.65\text{x}10^{-24}$ gm, k = Boltzman constant and $\gamma = C_p/C_v = 1.33$. Thus, if the jet is 20 msec long, G = 2.7 cm^3/pulse. The mean volume of the capillary before the nozzle should be significantly larger so as to store 10 to 15 cm^3 of gas (STP).

The jet density is proportional to the mass flow through the nozzle and could be as much as 3x higher than the figures discussed above.

In order to pump the helium gas the cryosurface will be covered by a thin layer of molecular sieve.[12] At 4.2° K this sieve can absorb a $\approx$ 40 cm^3/gm of molecular sieve at relatively large sticking coefficient α ($\alpha = 0.8$ at $a = 6$ cm^3/gm of molecular sieve).[13] The sticking coefficient of molecules depends on the quantity of absorbed gas, the intensity of the molecular flux, and the heat load to the cryosurface. To make a rough estimate we assume that the helium jet target will have a cryopump with the same dimensions as the present target at C0. We assume furthermore that molecules reflect from the cryosurface uniformly. In this case the back flow from the cryopump (Fig. 4b) during the jet pulse can be determined as:

$$\frac{G_{back}}{G_{jet}} = (1 - \alpha) \frac{f_{throat}}{2\pi r^2} = 0.01, \qquad (4)$$

where G_{back} = back flow from cryopump during jet pulse, G_{jet} = jet flow, f_{throat} = throat area of cryopump, and r = distance from bottom of cryopump to throat.

The percentage of back streaming will increase as the cryopump becomes saturated. The cold surface of the cryopump is 550 cm^2. Presently available molecular sieves[12] have 0.095 gm/cm^2 and could be manufactured with twice that figure. The total quantity of molecular sieve would then be about 100 gm and the cryopump would be saturated in 1500 pulses. This is only a starting point, using the present target, and we intend to do more engineering to improve this figure. However, already at this level the target could run at 2 pulses per accelerator pulse for about an hour before sublimation is required. Operationally the molecular sieve is delicate and will have to be protected by adequate trapping from contamination by oil, air, etc.

The jet density is limited by our capability to pump the Helium. Supplementary pumps in the system, estimated at 3500 liters/second, will hold the maximum chamber pressure at the end of the pulse to 5×10^{-3} torr and after 4 seconds to 5×10^{-6} torr. The vacuum system design will use the differential pumping technique to constrain the Helium to the immediate vicinity of the target.

3.2 Detectors

This experiment will exploit detection techniques already well developed in E36 and E186. There are two important differences between p-He and p-p elastic scattering: (1) the kinematics compress the angular range of the recoil particle for the same t-range. For p-p scattering $0.1 \lesssim |t| \lesssim 0.3$ $(GeV/c)^2$ corresponds to 160-280 mrad (from 90°), whereas the same $|t|$ range in p-He scattering corresponds to 40-70 mrad. Thus the recoil particle detectors must be further away from the target in order to obtain adequate resolution; (2) the elastic cross section over the same $|t|$ range will drop much further so that good angular resolution and longer runs are necessary to separate the elastic signal from the background at high t.

In order to cover the $|t|$ range from 0.1 to 0.3 $(GeV/c)^2$ recoiling helium nuclei with kinetic energies from 13 to 38 MeV must be detected and separated from other particles. This energy range corresponds to range in silicon from 100 to 650 microns. One possible arrangement is to use as elements of the sandwich the recently developed position sensitive detectors. Thus in a single sandwich one can obtain $E, \frac{dE}{dx}$, and θ_{recoil}.

A possible arrangement is shown in Fig. 4. An extension on the E186 ion guide extends into the C0 hallway (still allowing passage of the main ring magnet transport vehicle) and provides shielding for the detectors as well as a detector to target distance of 3.4 m. Angles up to ∿200 mrad from 90° can be seen. A sandwich made of two 45 mm wide detectors covers 13 mrad; the whole dip region can be measured by such a sandwich. The front detector is a 100 μ thick totally depleted rectangular detector. The back element is a position sensitive detector. Whether position sensitive or discrete detectors are used they would be mounted on a moveable carriage.

3.3 Resolution and Background

In the center of the t range in this proposal the elastic peak and the inelastic threshold (single π^0 production) are separated by 0.8 mrad at fixed kinetic energy and by 0.75 MeV at fixed angle at a beam momentum of 300 GeV. The required energy resolution can be easily achieved by commercial solid-state detectors; the required angular resolution is more difficult to achieve due to the finite width of the jet. A 12 mm wide jet is assumed in the counting rate calculations given in the next section. This corresponds to ±1.8 mrad, adequate to separate elastic and inelastic at a beam momentum of 100 GeV.

The preliminary data from the Clermont-Ferrand/Lyon/Strasbourg collaboration on p-He^4 elastic and inelastic scattering at 24 GeV/c[5] shows interference dips in both the elastic and N^* (1400) cross sections but these dips occur at different t-values. Thus, at the elastic dip the N^* (1400) cross section is ∿3x bigger than the elastic. At the highest energies it will be necessary to improve the resolution by narrowing the jet diameter or if this proves too difficult then the jet nozzle can be plunged down close to the beam at high energies (a technique used in E36) or a slit can be installed between jet and detectors (as in E186) although this reduces the counting rate.

3.4 Monitoring

One or two sandwiches will be mounted at fixed angles, chosen where the counting rate is high and the elastic p-He^4 signal cleanly separated. These provide normalization between runs.

The Internal Target Group is continuing development on an s-independent monitor using light emitted by the hydrogen gas when the beam strikes it. It is not known if this technique can be developed to high precision (∿1%) nor if it will work with a helium jet. If such a monitor is available it will allow measurement of absolute cross sections (or cross sections normalized relative to low energies, ∿20 GeV) but most of the physics program outlined in this proposal does not depend on its existence.

3.5 Counting Rates

Table I shows the differential cross section as a function of t for 300 GeV pHe^4 elastic scattering and $\rho = 0$ without and with an angular resolution of ±2.4 mrad included (worse than expected). The last column shows the counting rate in elastic counts per accelerator pulse assuming:

Jet density	7×10^{-8} gm/cm^3
Distance target to detectors	3.4 m
Length of target along beam	12 mm
Duration of jet pulse	20 msec
Beam intensity	5×10^{12} circulating protons
Area of detectors	45 mm x 70 mm
Bin size	$\Delta t = 0.01$ (GeV/c)^2

A set of 7 sandwiches each made up of 10 mm x 45 mm position sensitive detectors arranged azimuthally to increase the counting rate (see Fig. 4) will collect data in ∿11 different t-intervals simultaneously at the rates listed in Table II.

TABLE II.

$\|t\|$ (GeV/c)^2	$d\sigma/dt$ (mb/GeV^2)	$d\sigma/dt$ (mb/GeV^2) With $\Delta\theta = \pm2.4$ mr	Counts/ Pulse
0.1	35.2	36.0	60
0.12	16.8	17.3	30
0.14	7.6	7.9	13
0.16	3.1	3.3	5.5
0.18	1.1	1.2	2.0
0.20	288×10^{-3}	345×10^{-3}	5.8×10^{-2}
0.22	31	58	1.0
0.24	5	15	0.3
0.26	55	57	1.0
0.28	114	112	1.9
0.30	160	155	2.7

At $|t| = 0.24\ (GeV/c)^2$ the counting rate is lowest and is shown in Table III for different assumed values of ρ. Four hundred counts allows one to determine ρ to $\Delta\rho = \pm 0.01$ to ± 0.02, comparable to the accuracy achieved on ρ near $t = 0$ in E36.

TABLE III.

	# of Pulses to Get 5% Statistics (400 Counts)	Hours at 600 Accelerator Pulses/Hour
$\rho = 0$	160 00	27
$\rho = 0.1$	85 00	14
$\rho = 0.2$	35 00	6

3.6 Focussing System

Quadrupole lenses could be added to simultaneously increase the counting rate and improve the angular resolution for elastic scattering in the region of the dip. We have studied this possibility and believe that if it is necessary it could be added to the experiment and made to work. The main problem is chromatic aberration. Since the focal distance varies with $|t|$, runs would be taken at different lens to detector distances. This, of course, introduces a varying solid angle. But the solid angle can be determined by comparing runs with and without field in the $|t|$ regions outside the dip where the counting rates are higher.

A possible arrangement uses a doublet to focus a parallel beam in the horizontal plane to a point at the detector.

Some parameters are summarized below:

1. Distance first quadrupole - target 60 cm.
2. Quadrupole aperture 10 cm. diam.

3. $|t|$ range .20 - .28
4. Focal point, lens to detector distance 100 - 150 cm. corresponding to above $|t|$ range.
5. Angular resolution $\Delta\theta \sim 1.5$ mrad. for 1 mm resolution in detector.
6. Counting rate improvement over Table II $\sim$7X.
7. Foreground/room background ratio will improve over no quadrupole case by $\sim$200X.

4. COMPARISON WITH OTHER EXPERIMENTS

E 186, elastic and inelastic pd scattering is presently underway. The question naturally arises as to what additional physics can be learned from p - He^4 scattering. There are at least two main reasons in favor of this experiment:

1. For measurement of ρ the specific property of He^4, J=0 is essential. In the case of the deuteron the admixture of d-wave masks the dip and the uncertainty in the d-wave contribution makes it impossible to find ρ for this case.

2. For other problems, which could in principle also be solved with deuterons, the crucial point is that the influence of nuclear structure must be understood and uncertainties arising from it excluded. For this reason it is important to have data for at least two different nuclei. Thus, data on d and He^4 are not exclusive but supplement each other.

We note that He^4 also has an advantage with its unusually tight binding; consequently it is possible to transfer relatively large momentum.

We compare this proposal to NAL Experiment #86A by G. Lubatti et al. The intention of that experiment is to investigate diffractive coherent production by pions of multipion states from He nuclei using a He streamer chamber. It is planned to take 10^6 pictures during 800 hours of accelerator running time. This sample will contain 10^5 πHe interactions of the diffractive type. As a byproduct one could get approximately the same number of elastic πHe interactions. Mostly these will be confined to the region $-t < 0.1$ $(GeV/c)^2$.

The present goals of E86A are to investigate only the πHe case and only at one particular energy of the primary beam. However, if they were to take pHe pictures then at the smallest momentum transfer (recoil energy less than 0.5 MeV) the streamer chamber may provide better resolution and be easier to use than our solid-state technique. But around the first interference break ($-t \approx 0.24$) the differential cross section drops by 4 orders of magnitude which would make the duration of their experiment prohibitively long if they were to investigate this region.

5. APPARATUS AND TIMESCALE

The major items of equipment needed and proposed division of responsibility are the following:

1. Jet target and its control system supplied by Dubna. Modifications and testing for Helium operation to be done jointly by Dubna and NAL.
2. Additional pumping for use with helium supplied by NAL.
3. Ion guide extension supplied by NAL.

4. Solid-state detectors and detector carriage supplied by U. S. collaborators.
5. Electronics and on-line PDP-11 system supplied by U. S. collaborators.

The following schedule is based on approval of this proposal in March:

A jet target similar to the present hydrogen jet target at NAL is presently under construction at Dubna. For Helium operation the conventional cryopump must be changed to a cryopump with molecular seive. The development program for forming and trapping the Helium jet can be completed during the second half of this year.

It will also take several months for the rectangular solid state detectors proposed to be fabricated by ORTEC.

The target would then be air-freighted to NAL. After the target arrives at NAL it would be set up in a laboratory building with a simulated section of main ring pipe attached and tests made to insure that the pumping system is adequate to prevent Helium overloading of main ring pumps. (A similar test was performed on the present hydrogen target before it was installed in the Main Ring). These tests and checkout could be completed in 1 - 2 months.

Installation in the tunnel would take 3 - 4 days. We then need about 200 hours of testing time and 500 hours of data taking time with some of it at 400 - 500 GeV. The experiment, including physics analysis, can be completed 8 months after we start.

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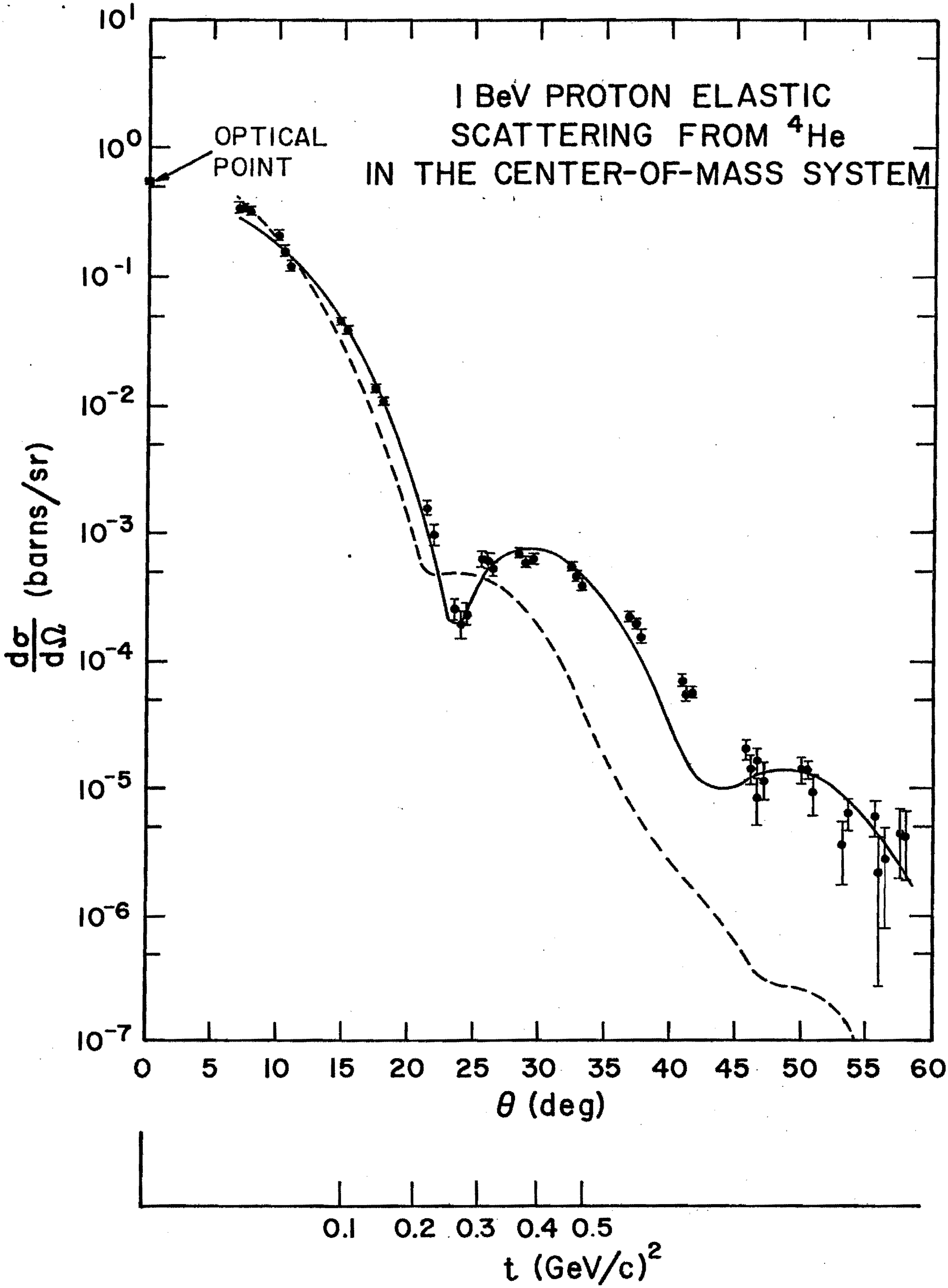


I BeV PROTON ELASTIC
SCATTERING FROM ^{4}He
IN THE CENTER-OF-MASS SYSTEM
OPTICAL
POINT
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
$\frac{d\sigma}{d\Omega}$ (barns/sr)
0 5 10 15 20 25 30 35 40 45 50 55 60
θ (deg)
0.1 0.2 0.3 0.4 0.5
t $(GeV/c)^2$

FIG. 1a

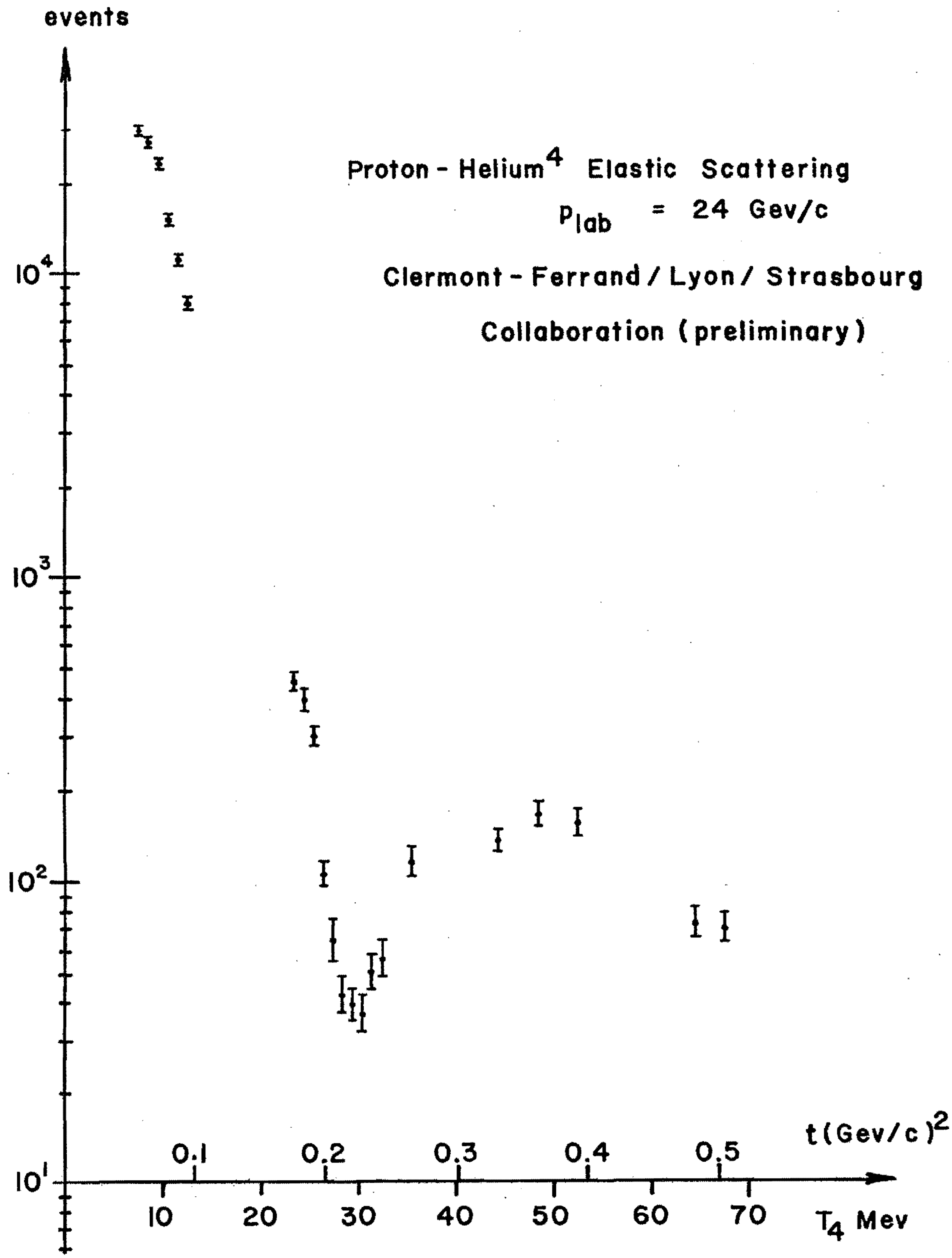
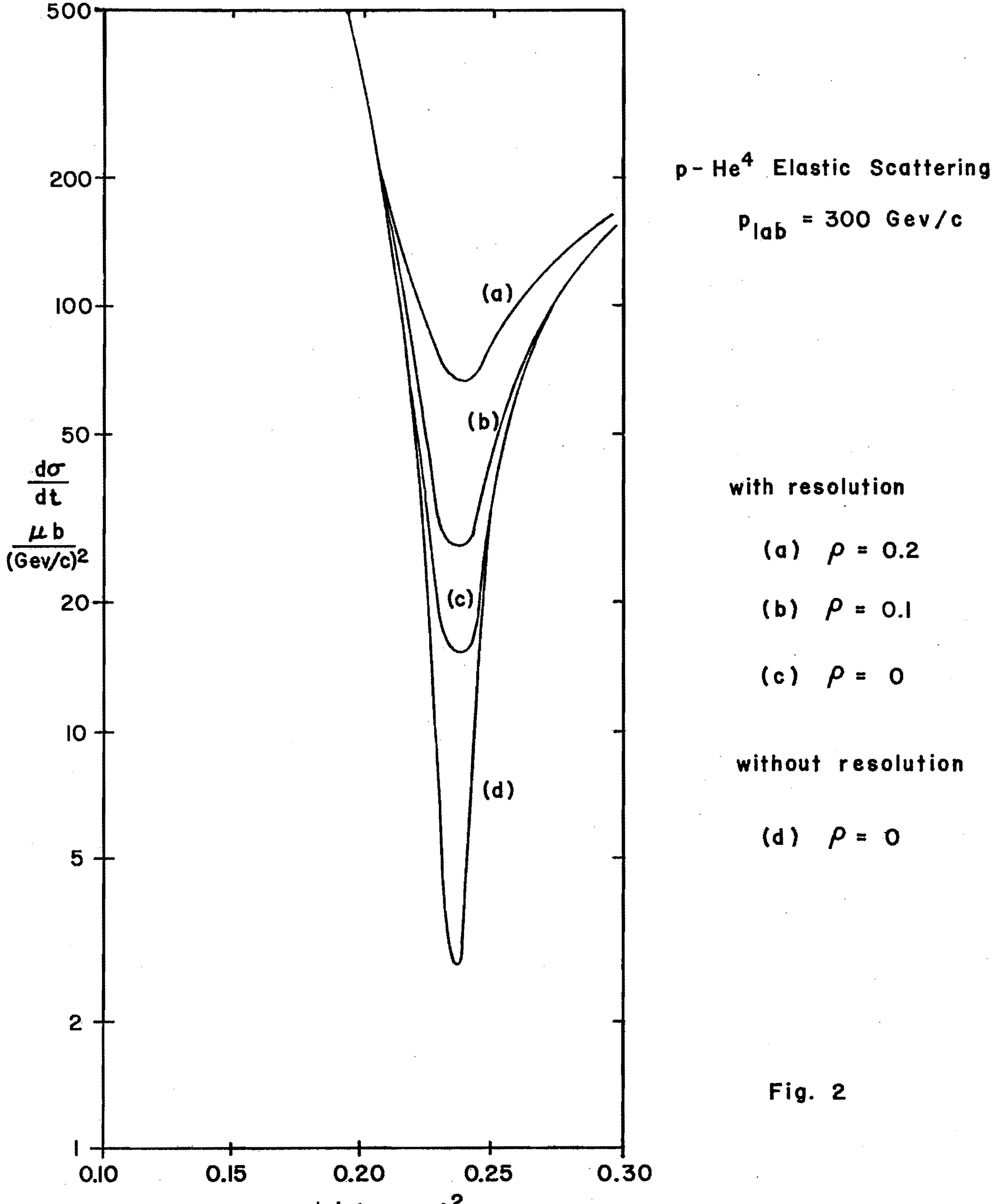

events
Proton - Helium4 Elastic Scattering
plab = 24 Gev/c
Clermont - Ferrand / Lyon / Strasbourg
Collaboration (preliminary)
10^4
10^3
10^2
10^1
0.1
0.2
0.3
0.4
0.5
t (Gev/c)^2
10
20
30
40
50
60
70
T4 Mev

Fig. 1b



500
200
100
50
20
10
5
2
1
dσ/dt
μb/(Gev/c)2
0.10
0.15
0.20
0.25
0.30
|t| (Gev/c)2
(a)
(b)
(c)
(d)
p - He4 Elastic Scattering
plab = 300 Gev/c
with resolution
(a) ρ = 0.2
(b) ρ = 0.1
(c) ρ = 0
without resolution
(d) ρ = 0

Fig. 2

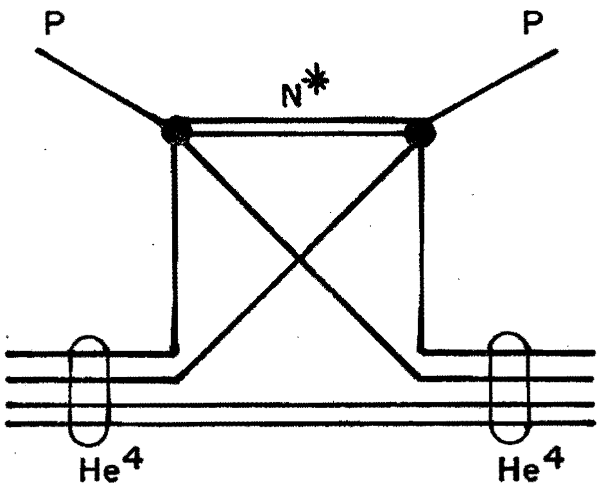


FIG. 3a

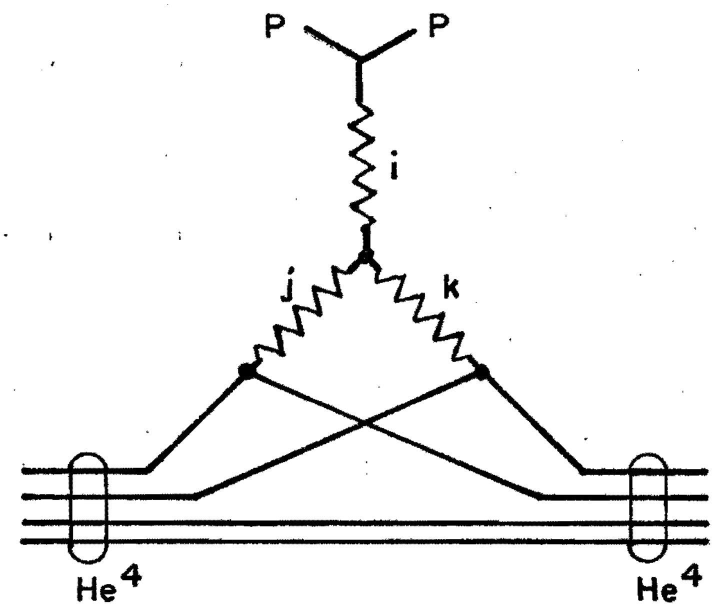


FIG. 3b

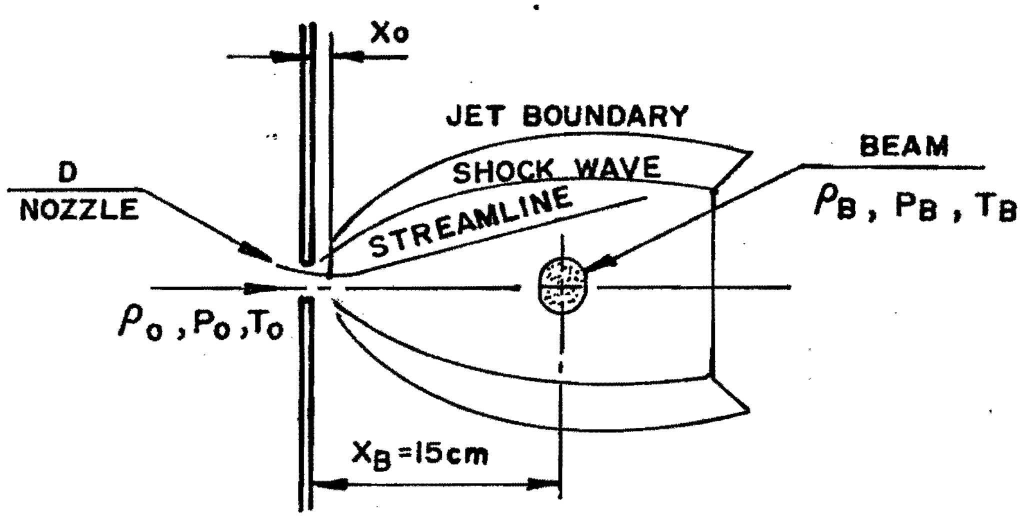


FIG. 4a

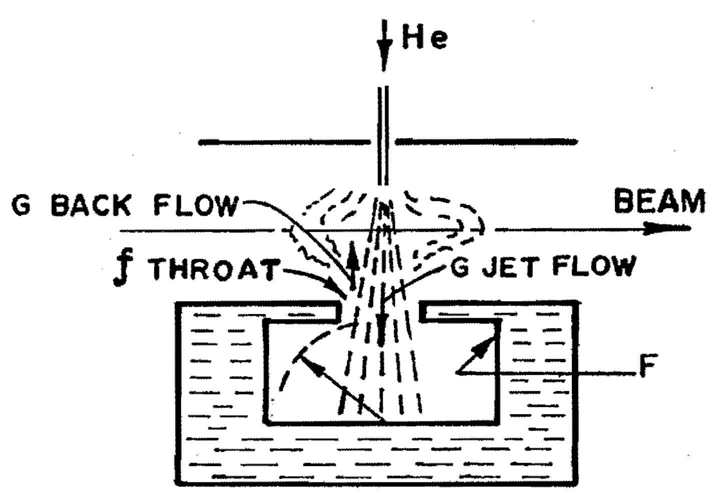


FIG. 4b

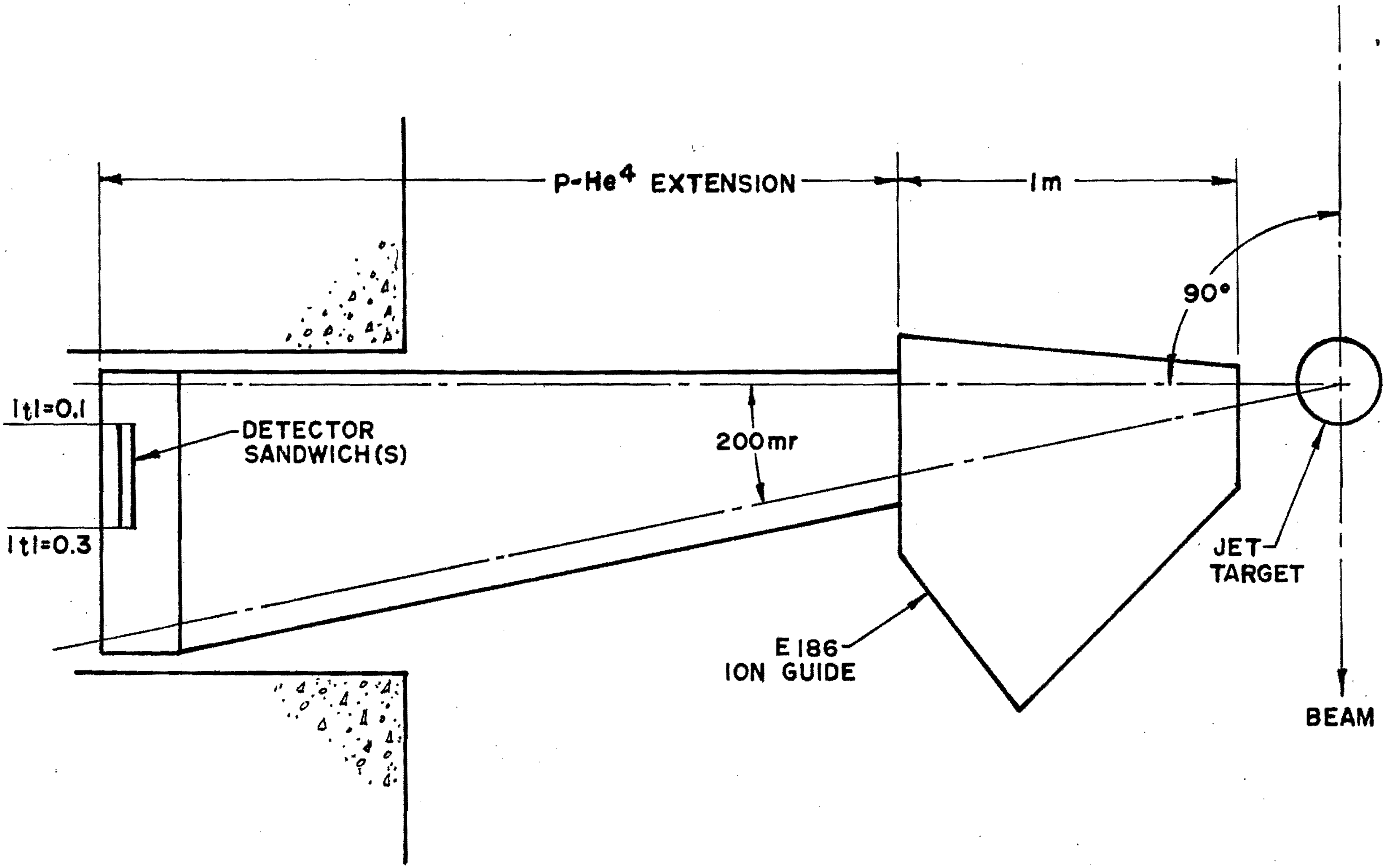

P-He4 EXTENSION
1m
90°
|t|=0.1
DETECTOR
SANDWICH(S)
200mr
|t|=0.3
JET
TARGET
E186
ION GUIDE
BEAM

FIG. 5