SLAC-PUB-916
(TH) and (EXP)
May 1971

A DETERMINATION OF THE RHO-NUCLEON CROSS SECTION FROM ELASTIC RHO-PHOTOPRODUCTION ON DEUTERIUM*

R. L. Anderson, D. Gustavson, J. Johnson, I. Overman
D. M. Ritson, and B. H. Wiik
Stanford Linear Accelerator Center
Stanford, California

R. Talman
Cornell University
Ithaca, New York

D. Worcester+
Harvard University
Cambridge, Massachusetts

ABSTRACT

The cross section for $\gamma + d \rightarrow \rho^o + d$ has been measured at 6, 12, and 18 GeV for t between $-.15(\mathrm{GeV/c})^2$ and $-1.4(\mathrm{GeV/c})^2$. From these measurements the total and differential ρ^o-nucleon cross sections have been determined together with $\gamma_\rho^2/4\pi$.

(Submitted for publication)

*Work supported by the U.S. Atomic Energy Commission.

+Present address: Daresbury Nuclear Physics Lab., Lancashire, England.

The differential cross section for the reaction $\gamma + d \rightarrow \rho^{o} + d$ has been determined at the Stanford Linear Accelerator Center by measuring the yield of recoil deuterons as a function of missing mass with the SLAC 1.6 GeV/c spectrometer. Data were taken for incident photon energies of 6, 12, and 18 GeV and for values of the four-momentum transfer t from $-.15(\mathrm{GeV/c})^2$ to $-1.4(\mathrm{GeV/c})^2$.

By comparing the results of this experiment with our earlier measurements(1) of ρ^{o}-photoproduction on the proton we have extracted both the differential and the total ρ^{o}-nucleon cross section together with the ρ^{o}-gamma coupling constant. Previous determinations(2,3,4,5) of these quantities from forward ρ^{o}-photoproduction on complex nuclei have been subject to large systematic errors(6) caused by the dependence of the extracted values on both the nuclear parameters and the phase of the elastic ρ^{o}-nucleon scattering amplitude. The present determination has the advantage that the deuteron wave functions are well known in the range of momentum transfers important to this experiment and the results are insensitive to the phase of the ρ^{o}-nucleon scattering amplitude.

The cross section for elastic ρ^{o}-photoproduction on deuterium can, except for small corrections due to the finite ρ^{o}-mass, be treated as an elastic scattering process. Therefore, since elastic πd scattering(7,8) is well described by the Glauber theory(9,10), we would also expect the same to be true for elastic ρ^{o}-photoproduction. This theory predicts the ρ^{o}-photoproduction cross section for small $|t|$-values to be given by the impulse approximation, that is, an isovector photon produces a ρ^{o}-meson by interaction with only one nucleon and the struck nucleon then rescatters and transfers half of its momentum to the spectator nucleon in order for the deuteron to remain bound. The cross section for small values of $|t|$ can therefore be written as:

$$\frac{d\sigma}{dt}(t\to 0)\bigg|_{\gamma d\to \rho d} \simeq 4 \cdot \frac{d\sigma}{dt}(t\to 0)\bigg|_{\rho N\to \rho N} \cdot \left(S_0^2(\tfrac{q}{2}) + S_2^2(\tfrac{q}{2})\right)$$

In this expression $S_0(q/2)$ and $S_2(q/2)$ are quantities proportional to the deuteron charge and quadrupole form factor and are defined as:

$$S_0(\tfrac{q}{2}) = \int_0^\infty dr\ [u^2(r) + w^2(r)] \cdot j_0(\tfrac{q}{2}\, r)$$

$$S_2(\tfrac{q}{2}) = \int_0^\infty dr\ 2w(r)\ [u(r) - \tfrac{1}{\sqrt{8}}\, w(r)]\ j_2(\tfrac{q}{2}\, r)$$

Here $u(r)$ and $w(r)$ are the radial wave functions for the S and D-states of the deuteron(11). It is clear from this expression that, apart from projecting out the isovector part of the photon, a measurement of ρ^0-photoproduction on deuterium at small $|t|$-values does not tell us anything new. However, since the contribution to the cross section from the single scattering term is proportional to the deuteron form factor, it will decrease rapidly with increasing $|t|$ and for large momentum transfers the cross section will be dominated by the double scattering term. Here the incident photon first produces a ρ^0 on one of the nucleons, and the struck nucleon recoils with momentum $\vec{q}/2 + \vec{\Delta}$ perpendicular to and $2\vec{\Delta}_{\parallel}$ parallel to the direction of the incident photon. The longitudinal momentum transfer $2\Delta_{\parallel} = m_\rho^2/2k$ results from the photon converting into a ρ^0. The produced ρ^0 subsequently scatters elastically off the second nucleon with a momentum transfer of $\vec{q}/2 - \vec{\Delta}$. After the collision the deuteron will recoil with a total momentum of $\vec{q} + 2\vec{\Delta}_{\parallel}$ and a relative momentum of $2\vec{\Delta} + 2\vec{\Delta}_{\parallel}$ between the two nucleons. In order for the deuteron to remain bound there must be a momentum transfer of $\vec{\Delta} + \vec{\Delta}_{\parallel}$ between the nucleons where $\vec{\Delta}$ can vary from 0 to 2k. Hence the second scattering term will be proportional to the cross section for photoproducing a ρ^o on a single nucleon multiplied by the elastic ρ^o-nucleon cross section. Therefore in the region $|t| \geq .7(\text{GeV/c})^2$ the cross section can be written as:

$$\frac{d\sigma}{dt}(t)\Big|_{\gamma d\to \rho d} \simeq \frac{1}{4\pi^3} \cdot (K_0^2 + \frac{1}{4} K_2^2) \cdot \frac{d\sigma}{dt}(\frac{t}{4})\Big|_{\gamma N\to \rho N} \cdot \frac{d\sigma}{dt}(\frac{t}{4})\Big|_{\rho N\to \rho N} + \text{correction terms}$$

The constants K_0 and K_2 are to a good approximation given by:

$$K_0 = 2\pi \int_0^k \Delta\, d\Delta\, S_0 \left(\sqrt{\Delta^2 + \Delta_{\shortparallel}^2}\right) e^{(A+B)\Delta^2/2}$$

$$K_2 = 2\pi \int_0^k \Delta\, d\Delta\, S_2 \left(\sqrt{\Delta^2 + \Delta_{\shortparallel}^2}\right) e^{(A+B)\Delta^2/2}$$

Here S_0 and S_2 are the form factors as defined above. A and B are the slopes of the ρ^o-photoproduction and the ρ^o-nucleon scattering cross section and are approximately equal.

To a first approximation the correction terms can be neglected (they are of course included in the final analysis) and the ρ^o-nucleon differential cross section can be written as:

$$\frac{d\sigma}{dt}(t/4)_{\rho N\to \rho N} = \frac{4\pi^3}{(K_0^2 + \frac{1}{4} K_2^2)} \cdot \frac{\frac{d\sigma}{dt}(t)_{\gamma d\to \rho d}}{\frac{d\sigma}{dt}(t/4)_{\gamma p\to \rho p}}$$

Since K_0 and K_2 are well defined quantities, the ratio of the elastic ρ^o-photoproduction cross section on deuterium to that on the proton directly determines the ρ^o-nucleon differential cross section for $4|t| \geq .7(\text{GeV/c})^2$. It is clear that this determination of the ρ^o-nucleon cross section is independent of the Vector Dominance Model. Furthermore, since we are using only our own data, systematic errors due to the acceptance of the spectrometer or the shape of the ρ^o used to extract the cross section will cancel. Assuming the cross section for photoproducing a ρ^o is proportional to the elastic ρ^o-nucleon scattering cross section we can define a constant of proportionality $(\gamma_\rho^2/4\pi)$ as:

$$\gamma_\rho^2/4\pi = \frac{\alpha}{4} \frac{\frac{d\sigma}{dt}(t/4)_{\rho N\rightarrow\rho N}}{\frac{d\sigma}{dt}(t/4)_{\gamma p\rightarrow\rho p}}$$

Using the above expression for the ρ -nucleon differential cross section we have:

$$\gamma_\rho^2/4\pi = \frac{\alpha\,\pi^3}{(K_0^2 + \frac{1}{4}K_2^2)} \cdot \frac{\frac{d\sigma}{dt}(t)_{\gamma d\rightarrow\rho d}}{\left|\frac{d\sigma}{dt}(t/4)_{\gamma p\rightarrow\rho p}\right|^2}$$

Thus $\gamma_\rho^2/4\pi$ is determined from the measured ρ^o-cross section without extrapolating to t=0. However this ratio will be affected by the systematic uncertainties.

The experimental arrangement was similar to that used in our earlier experiments on photoproduction on hydrogen[1]. The beam was prepared by modulating the grid of the electron gun of the accelerator with a high voltage signal. The resulting electron beam consisted of bunches about 5 nsec wide spaced typically 50 nsec apart within the usual 1.6-μsec-long beam pulse. The momentum analyzed electron beam was focussed onto a .03 radiation length aluminum radiator and the produced photon beam passed through several collimators and sweeping magnets before impinging on the hydrogen target. The beam was stopped in a Secondary Emission Quantameter which served as the primary beam monitor. The intensity of the photon beam was also measured by a Cerenkov monitor located in front of the target. For

$|t| \geq .4(\text{GeV/c})^2$ a conventional liquid target was used. For smaller $|t|$-values the liquid target was replaced by a high-pressure, low-temperature gas target[12].

The angle and momentum of the recoil deuteron were determined by the SLAC 1.6 GeV/c spectrometer. The trigger counters consisted of a range telescope, a lucite threshold Cerenkov counter to veto π's, and eight hodoscope counters. The ratio of protons to deuterons incident on the counters was typically 1000 to 1, making it difficult to achieve a clean separation by using pulse height and range only. However, since the photons arrive in well defined bunches at the target, particles with the same mass will arrive simultaneously at the top of the spectrometer. Therefore by timing and gating the trigger system relative to the modulating signal the deuterons can be selected. With this time-of-flight criterion deuterons and protons could be separated cleanly using only the two first trigger counters. Fig. 1a shows a time-of-flight spectrum for 18 GeV and $|t| \simeq .5(\text{GeV/c})^2$ gated with deuteron biases in the two trigger counters. The deuterons are cleanly separated from the pions and the protons. Since the experiment consists of measuring a step height on a smoothly varying background, a small residual amount of protons and pions under the deuteron peak does not change the results of the experiment.

The spectrometer focuses p and θ onto a focal plane normal to the particle trajectory. For a fixed photon energy deuterons corresponding to a given missing mass will fall along a straight line over the small p-θ acceptance of the spectrometer. With the hodoscope properly aligned, data were collected by keeping the recoil momentum of the deuteron fixed and measuring the yield as a function of the production angle in the laboratory. Since, for a given photon energy, there is an approximately linear relationship between the laboratory angle of the recoil deuteron and the missing mass squared, the onset of ρ^o-photoproduction will show up as a step on the yield curve[1]. Fig. 1b shows a yield curve for an incident photon energy of 18 GeV and $t = -.5(\text{GeV}/c)^2$. The prominant step in the yield curve is due to ρ^o and ω production. The resolution is not sufficient to separate the two reactions and the ω contribution was therefore subtracted assuming the ratio of ω to ρ^o-photoproduction to be 1 to 9[13]. The ρ^o-contribution was extracted from this yield curve using the same fitting procedure as we used earlier to extract the ρ^o-cross section on the protpn. The important quantity in determining the ρ^o-nucleon cross section is the ratio of the ρ^o-photoproduction cross section on deuterium to that on protons for the same value of momentum transfer. This ratio is rather insensitive to assumptions made about the background as well as the ρ^o-shape provided they are the same in the two analyses.

The extracted step heights were corrected for counter inefficiencies, loss of deuterons in the target or in the counters due to breakup of the deuteron, and the change in the $\Delta p/p$ acceptance caused by the energy loss of the deuterons in traversing the target. These corrections were typically 15%. In addition to the momentum dependent errors we also have a 3% uncertainty in the acceptance of the spectrometer and a 2% uncertainty in the calibration of the beam monitors.

In computing the errors on the data points we assumed a systematic uncertainty of $\pm$ 30% of the non-resonant background under the ρ^o-step. The quoted error on the points is this systematic error added in quadrature with the statistical errors.

The measured cross sections are plotted versus t for 6, 12, and 18 GeV in Fig. 2. The observed t-dependence is the characteristic one for an elastic process on deuterium. It consists of a single scattering region where the cross section decreases rapidly with increasing $|t|$, a flattening out around $t = -.5(\mathrm{GeV}/c)^2$ where the interference terms and the contributions from the D-state in deuterium are important, and then finally for $|t| \geq .7(\mathrm{GeV}/c)^2$ a region where the cross section is dominated by contributions from the double scattering terms. The solid line is a least squares fit to the data including the interference term between the single and double scattering amplitude. The fits were based on the following assumptions:

(1) The ρ^0-photoproduction cross sections were taken from our earlier measurements[1] on hydrogen, assuming the contribution of isovector exchange could be neglected. Recent measurements[14] at Cornell have shown this to be justified for photon energies above 6 GeV. We further assumed for the fit shown that the ρ^0-nucleon elastic scattering cross section and the ρ^0-photoproduction cross section have the same t-dependence. For this t-dependence we used our published quark-model fit[1] as well as a least-squares fit to the proton data of the form $Ae^{Bt + Ct^2}$. This last fit was done independently at each photon energy. The differences between these two fits produced a change in the extracted ρ^0-nucleon total cross section of less than .5mb for 12 and 18 GeV. At 6 GeV the change was about 3mb. This large variation is caused by the large errors on the ρ^0-photoproduction data at 6 GeV. The final fits were all done with the quark fit.

(2) We used the Hamada-Johnston[15] wave functions for the deuteron. These wave functions fit the static properties of the deuteron as well as the elastic electron-deuteron cross section. Other wave functions[16] give the same answers to good accuracy. The reason for this is that the wave functions only have to be known for $|t|$ less than $.6(\mathrm{GeV}/c)^2$ and for such values of the momentum transfer all realistic wave functions look more or less the same. To evaluate the integrals for K_0 and K_2 the hydrogen data for $|t|$ less

than $.6(\mathrm{GeV}/c)^2$ were fitted to the form $\sim e^{Aq^2}$ leading to a value of $A = 6 \pm .5(\mathrm{GeV}/c)^{-2}$. This uncertainty in A produced a 1% change in K_0 and a 5% change in K_2. Due to the finite ρ^0-mass, K_0 varied from $.188\mathrm{mb}^{-1}$ at 6 GeV to $.192\mathrm{mb}^{-1}$ at 18 GeV while $K_2 = .072\mathrm{mb}^{-1}$ was nearly independent of energy.

(3) In the fit only data with $|t| \geq .7(\mathrm{GeV}/c)^2$ were used. The reason for this is that for $|t| \simeq .4(\mathrm{GeV}/c)^2$ the single and double scattering amplitudes are approximately equal, hence the interference term is important and we need to assume a ρ^0-nucleon phase in order to compute the cross section. Also the contribution from the less-well-known D-state of the deuteron has a maximum here. By using data in a region where the double scattering term is dominant these undertainties can be avoided. The fit, extrapolated to smaller t-values, assuming a 7% D-state probability and a real-to-imaginary-part of the ρ^0-nucleon amplitude varying from -.27 at 6 GeV to -.16 at 18 GeV, seems to represent the data reasonably well except in a region around $|t| = .5(\mathrm{GeV}/c)^2$. However since the theoretical uncertainties are the largest in this region, this discrepancy can probably not be used to determine the phase of the ρ^0-nucleon amplitude or the D-state probability.

Using these assumptions each energy was fitted independently and the total ρ^0-nucleon cross section and the ρ^0-gamma coupling constant as determined from the fit are all listed in Table I. Also listed in Table I is a prediction from the quark model: $\sigma_T(\rho N) = \frac{1}{2}(\sigma_T(\pi^+ p) + \sigma_T(\pi^- p))$. The error quoted on the ρ^0-nucleon cross section is the statistical error only; in addition we have a systematic uncertainty of $\pm$ 2mb. These values are in reasonable agreement with the values determined from the experiments[2,3,4,5] on complex nuclei and indicate a ρ^0-nucleon total cross section a few mb larger than the quark model prediction. The value for the ρ^0-gamma coupling constant is independent of energy and is given by $\gamma_\rho^2/4\pi \simeq (.68 \pm .03)$ plus a maximum systematic error of $\pm$ .15. This value is also in good agreement with the values determined from the earlier experiments, and favors a coupling constant somewhat larger than the value determined from colliding beam experiments.

The Glauber theory contains several approximations; for example, the internal motion of the nucleons are neglected[17]. We have made a fit to the data including the internal motion and found that this leads to a change in the ρ^o-nucleon total cross section of less than 1mb. However since the Glauber theory contains several approximations, it might not be beneficial to correct only for one of them. Thus our quoted values do not include this correction.

It is desirable, because of the apparent similarity between π-nucleon and ρ^o-nucleon scattering[1], to compare the ρ^o-photoproduction cross sections on deuterium with the elastic π d cross sections. In such a comparison, defects in the Glauber theory could be expected to influence both processes similarly, and we should be able to extract a value largely independent of systematic uncertainties. We have compared our data at 6 GeV with π^-d data of M. Fellinger, et al.[7] at 5.5 GeV. From this comparison we find a ρ^o-nucleon cross section a few mb larger than the πd cross section, in good agreement with the direct computation. A comparison at higher energies with the data of F. Bradamante, et al.[8] is not meaningful since they quote large systematic errors. Furthermore these data, when scaled to 5.5 GeV, are in bad agreement with the measurements of M. Fellinger, et al. Also the high energy πd data seem to indicate large inelastic contributions to the double scattering amplitude, in contradiction to our finding.

In Fig. 3 the differential cross section for ρ^o-nucleon scattering is plotted versus t for 6, 12, and 18 GeV. In this fit no assumption was made on the slope of the ρ^o-nucleon cross section. For comparison the π^-p differential cross sections[18] are indicated for the different energies. The agreement between these two cross sections is remarkably good, and there is no evidence that the slope of the ρ^o-nucleon cross section is very different from that of elastic π-nucleon scattering.

Acknowledgements

J. Grant, E. Cheatham and J. Schroder gave us invaluable support with the setup and the preparations for the experiment. We wish to acknowledge the help we received from the operations and support crew at SLAC, especially we wish to thank R. Miller and A. Golde.

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FIGURE CAPTIONS

Fig. 1: For a bremsstrahlung end-point energy of 18 GeV and a four-momentum transfer $t = -0.5(\mathrm{GeV}/c)^2$, shown are:

a) the time-of-flight spectrum of particles in the 1.6 GeV/c spectrometer gated with deuteron biases in the counters;

b) the observed yield of deuterons as a function of decreasing laboratory angle.

Fig. 2: Cross sections measured in this experiment at 6, 12, and 18 GeV are plotted as $d\sigma/dt$ in $\mu b/(\mathrm{GeV}/c)^2$ versus $|t|$ in $(\mathrm{GeV}/c)^2$. The solid lines were produced by the fits described in the text. The corresponding values of $\sigma_T(\rho^0 N)$ are shown.

Fig. 3: The differential ρ^0-nucleon scattering cross sections as derived from this experiment are plotted versus $|t|$. Only the experimental error is shown. In addition there is a theoretical uncertainty on the

order of 10% which could change the slope as well as the absolute magnitude of the cross section. For comparison, the solid lines represent $\pi^- p$ elastic scattering results from Ref. 18 at 7, 13, and 17 GeV incident energies.

TABLE I

Energy	$\gamma_\rho^2/4\pi$	σ_T	$\frac{1}{2}(\sigma_T(\pi^+p) + \sigma_T(\pi^-p))$
GeV		mb	mb
6	.61 ± .06	28.6 ± 1.4	26.9
12	.70 ± .04	28.5 ± .8	25.4
18	.70 ± .03	27.6 ± .6	24.6

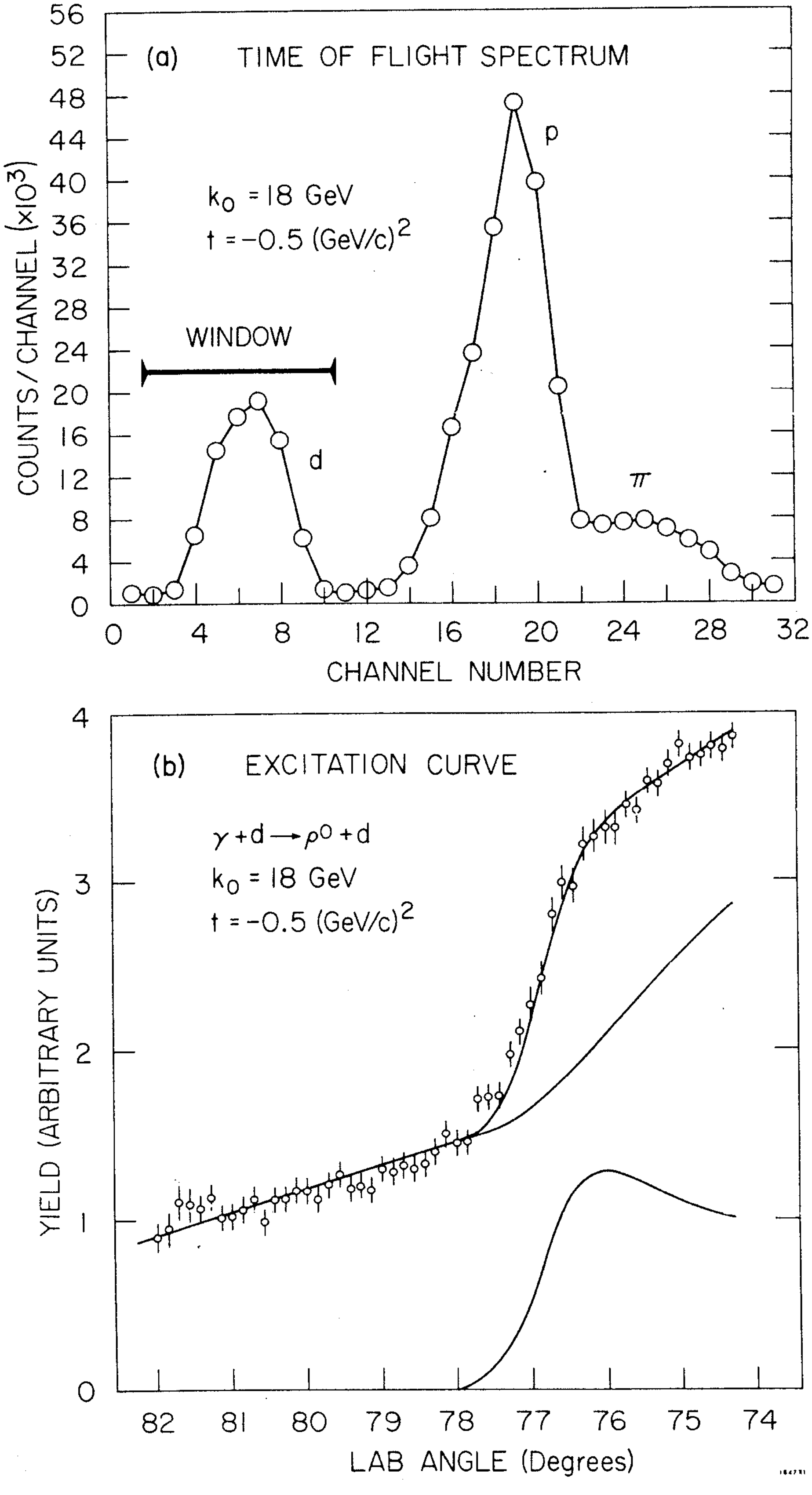
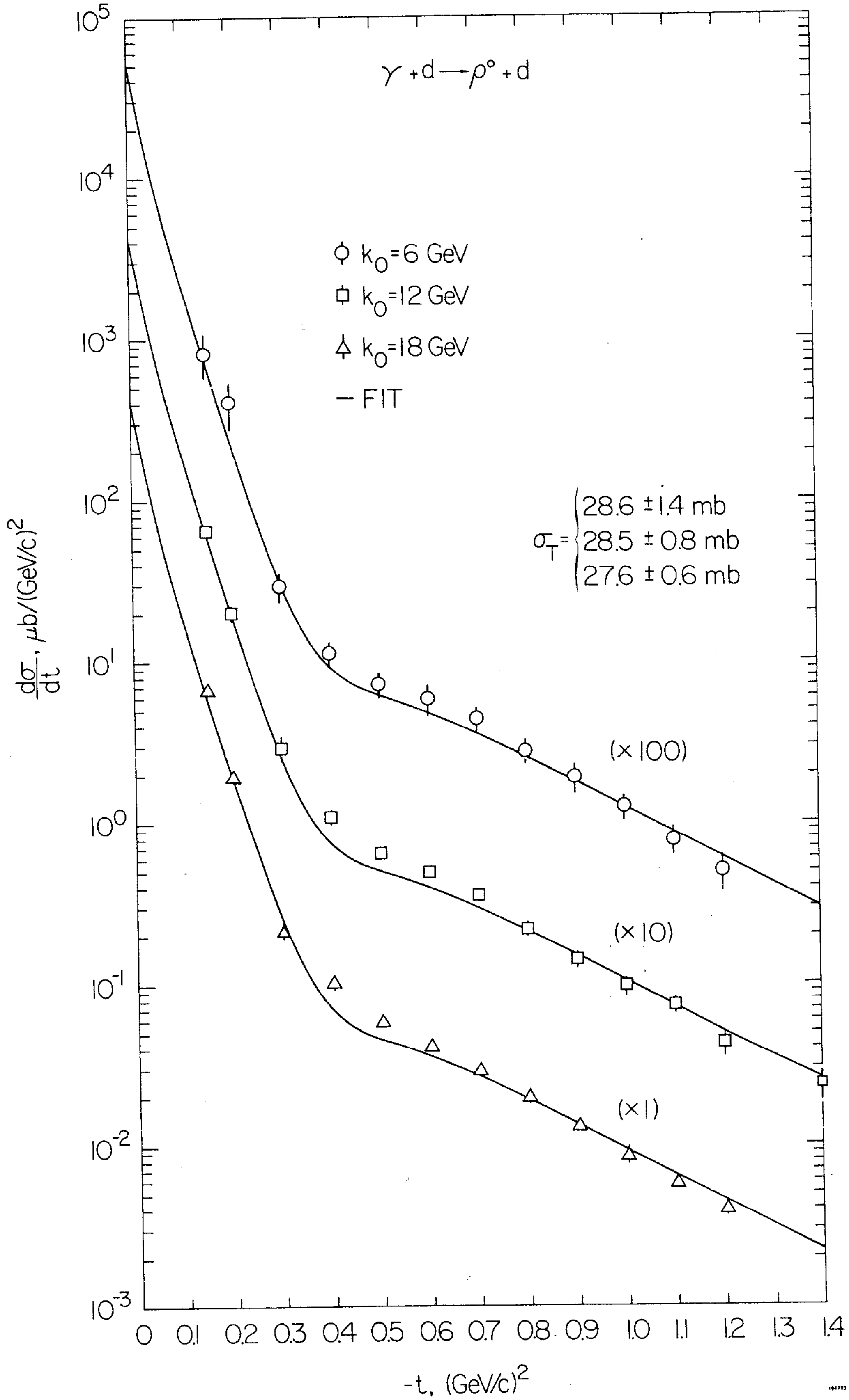
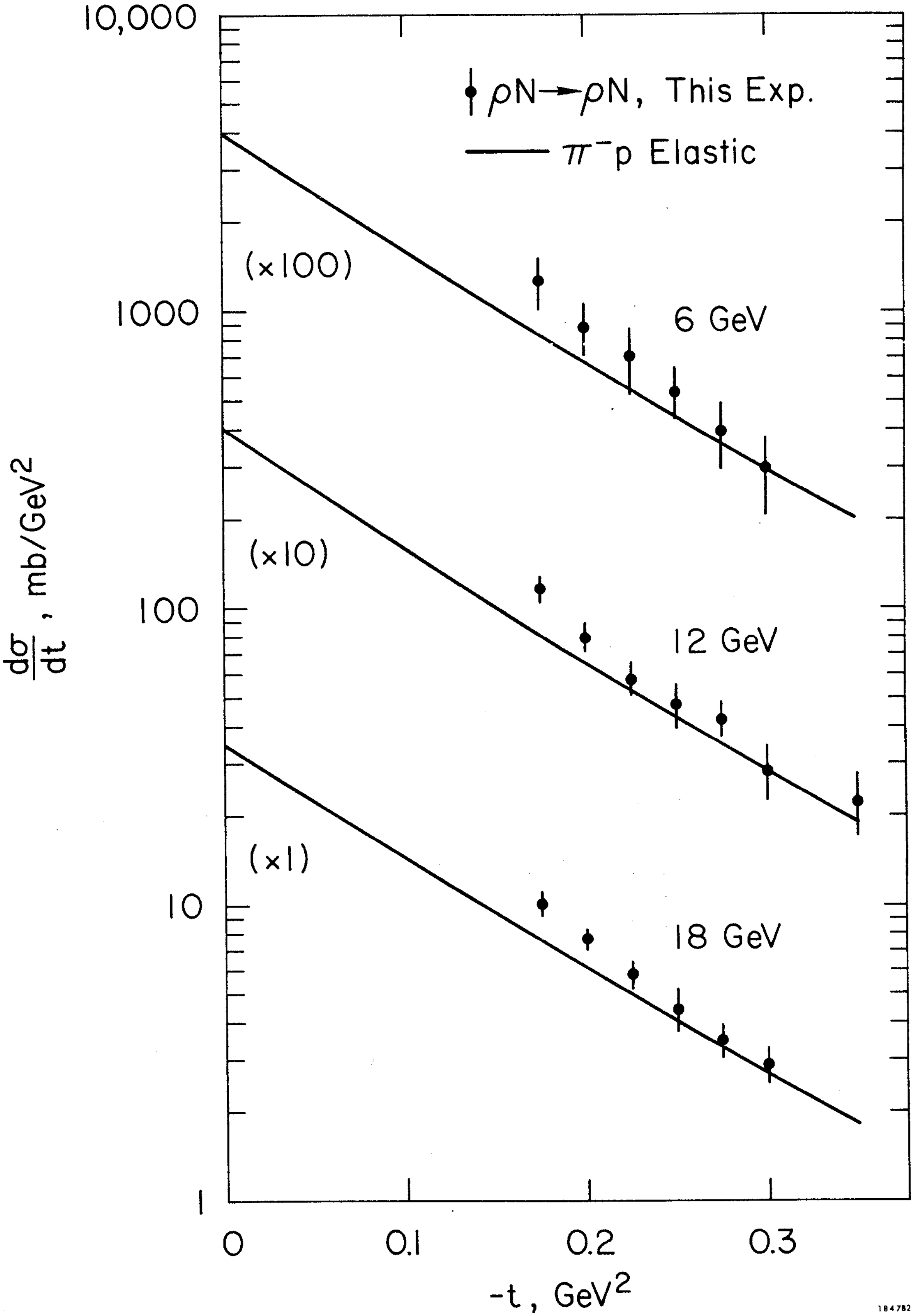

(a) TIME OF FLIGHT SPECTRUM
COUNTS/CHANNEL (×10³)
CHANNEL NUMBER
k₀ = 18 GeV
t = −0.5 (GeV/c)²
WINDOW
d
p
π
(b) EXCITATION CURVE
γ + d → ρ⁰ + d
k₀ = 18 GeV
t = −0.5 (GeV/c)²
YIELD (ARBITRARY UNITS)
LAB ANGLE (Degrees)

Fig. 1



γ + d → ρ° + d
k0 = 6 GeV
k0 = 12 GeV
k0 = 18 GeV
— FIT
σT = 28.6 ± 1.4 mb
28.5 ± 0.8 mb
27.6 ± 0.6 mb
(×100)
(×10)
(×1)
dσ/dt, μb/(GeV/c)²
-t, (GeV/c)²
10^5
10^4
10^3
10^2
10^1
10^0
10^-1
10^-2
10^-3
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0 1.1 1.2 1.3 1.4

Fig. 2



10,000
1000
100
10
1
0
0.1
0.2
0.3
-t , GeV²
dσ/dt , mb/GeV²
ρN → ρN, This Exp.
π⁻p Elastic
(×100)
6 GeV
(×10)
12 GeV
(×1)
18 GeV
184782

Fig. 3