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ABSTRACT

By use of the model of the nucleon-antinucleon interaction proposed by Ball and Chew, a calculation of the complex phase shifts at 50 and 260 Mev has been made. The values of annihilation, elastic-scattering, and charge-exchange cross sections, and the angular distributions for $\bar{p}$-p and $\bar{p}$-n elastic scattering are obtained. A comparison with the experimental data shows reasonable agreement. Finally, the parameters of an optical-model potential for antinucleon interaction with complex nuclei are presented.

NUCLEON-ANTINUCLEON SCATTERING*

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A model of the nucleon-antinucleon interaction at intermediate energies has been presented recently by Ball and Chew[1] (hereafter referred to as I). They used the Gartenhaus[2] and Signell and Marshak[3] potentials, with a "black central hole" to account for the annihilation, and their WKB calculation of the cross sections and angular distributions[4] at 140 Mev has proved to be in good agreement with experiment.

In view of this success we have extended the calculation to 50 and 260 Mev, to cover the range where experimental data have become available.[5] We have assumed that these two energies are the extreme points between which the model should be reasonably valid. At higher energies the details of the annihilation boundary condition become more important and a partial penetration of the higher waves can be expected, reducing therefore the diffraction scattering. At energies lower than 50 Mev the wave length of the incident particle becomes of the same order as the wave length associated with the barrier, and the WKB method of calculation breaks down.

The transmission coefficients and the real phase shifts are given in Table I.

We have modified the singlet-isotopic-spin, singlet-spin potential by cutting off the large repulsive central region; since this potential produces an unphysical bound state in the N-N system.[3] For this reason,

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[§] A visitor from the Argentine Army.

TABLE I

Phase shifts (δ) and transmission coefficients ($T = 1 - R^2$)

State	50 Mev		140 Mev		260 Mev	
	T	δ	T	δ	T	δ
${}^3P_0^1$	1	—	1	—	1	—
${}^3S_1^1$	1	—	1	—	1	—
${}^3P_1^1$	0	-19°	0	-41°	0	-54°
${}^3D_1^1$	0	0	0	0	0	-15°
${}^3P_2^1$	1	—	1	—	1	—
${}^3D_2^1$	0	0	0	-17°	0	-23°
${}^3F_2^1$	0	0	0	0	0	-18°
${}^3D_3^1$	0	0	1	—	1	—
${}^3F_3^1$	0	0	0	0	0	-12°
${}^3F_4^1$	0	0	0	0	0	10°
${}^3P_0^3$	0	-10°	0	-33°	0	-47°
${}^3S_1^3$	1	—	1	—	1	—
${}^3P_1^3$	1	—	1	—	1	—
${}^3D_1^3$	0	0	0	-13°	0	-29°

TABLE I (cont.)

State	50 Mev		140 Mev		260 Mev	
	T	δ	T	δ	T	δ
${}^{3}P_{2}{}^{3}$	0	3°	1	—	1	—
${}^{3}D_{2}{}^{3}$	0	0	0	6°	0	11°
${}^{3}F_{2}{}^{3}$	0	0	0	0	0	-28°
${}^{3}D_{3}{}^{3}$	0	0	0	2°	0	8°
${}^{3}F_{3}{}^{3}$	0	0	0	0	0	3°
${}^{3}F_{4}{}^{3}$	0	0	0	0	0	0
${}^{1}S_{0}{}^{1}$	1	—	1	—	1	—
${}^{1}D_{2}{}^{1}$	0	11°	0	6°	0	-10°
${}^{1}D_{2}{}^{1}$	0	0	0	6°	0	6°
${}^{1}F_{3}{}^{1}$	0	0	0	0	0	3°
${}^{1}S_{0}{}^{3}$	1	—	1	—	1	—
${}^{1}P_{1}{}^{3}$	0	-1°	1	—	1	—
${}^{1}D_{2}{}^{3}$	0	0	0	0		3°
${}^{1}F_{3}{}^{3}$	0	0	0	0	0	-1°

the ${}^1S_0{}^1$ transmission coefficient at 140 Mev has been changed from that given in I, and is now consistent with the values at 50 and 260 Mev. This state is of such a small statistical weight that the change in the cross sections is negligible.

The total annihilation and scattering cross sections are given in Table II. A comparison with the experimental data available up to now is shown in Fig. 1. The agreement is fairly good, except for the value of the theoretical annihilation cross section at 260 Mev, which seems to be too small. However, by allowing partial transmission of the most strongly attractive effective potentials, we have obtained larger values of this cross section. Various possible modifications and their results are shown in Table III.

The angular distributions are plotted in Figs. 2 to 7. For their calculation we have used the method described in Reference 4. A comparison with the experimental data at 133 and 265 Mev is also given.

The general agreement of the theory with experiment in this energy range seems reasonably good in view of the crude nature of the potential description of the N-$\bar{N}$ interaction and the approximations made in our calculations. Our main conclusion is that no long-range annihilation interaction is required by the existing experimental facts; the ordinary pion-exchange force appears to be sufficiently attractive on the average to produce the observed annihilation cross sections at intermediate energies. It is also reassuring that this model leads to only a small charge-exchange cross section, as required by experiment. In fact, one may say that in its predictions our model behaves not too differently from a black absorbing sphere of radius approximately equal to the pion Compton wave length. That it should do so, however, appears to be an accident, following from the detailed nature of the pion-exchange force.

TABLE II

Cross sections (mb) for nucleon-antinucleon interactions at different energies

	50 Mev		140 Mev		260 Mev	
	$p-\bar{p}$	$\bar{p}-n$	$p-\bar{p}$	$\bar{p}-n$	$p-\bar{p}$	$\bar{p}-n$
σ_{Total}	232	184	168	148	113	101
$\sigma_{\text{Elastic Scattering}}$	91	93	73	79	58	64
$\sigma_{\text{Absorption}}$	110	91	74	69	40	37
$\sigma_{\text{Charge Exchange}}$	31	—	21	—	15	—

TABLE III

The effect of partial transmission on p-$\bar{p}$ scattering at 260 Mev

States modified		Cross Sections (mb)			
$^3D_3{}^3$	$^3F_4{}^1$	σ_{Total}	$\sigma_{Elastic}$	$\sigma_{Abs.}$	$\sigma_{Exch.}$
T = 0.5	T = 0	118	61	44	13
T = 0	T = 0.5	118	56	45	17
T = 0.5	T = 0.5	123	58	50	15

OPTICAL-MODEL POTENTIAL

An optical model for the scattering of nucleons by nuclei has been proposed and developed by many authors.[6,7] To apply it to the antinucleon-nucleus system we have followed the method of Riesenfeld and Watson,[7] suitably modified to account for the annihilation process.

The optical-model potential is then given (in units where $h = c = \mu = 1$; μ is the π meson mass) by

$$V_{opt}(x) = -\left[V_{CR} + i\,V_{CI}\right]\rho\,(x) + \left[V_{SR} + i\,V_{SI}\right]\frac{1}{x}\frac{d\rho}{dx}\,(\vec{\sigma}\cdot\vec{\ell}),$$

where

$$V_{CR} = \frac{3}{M\lambda^3}\,\mathrm{Re}\left[f(0)\right],$$

$$\mathrm{Re}\left[f(0)\right] = \frac{1}{32k}\sum_{I=0}^{1}\sum_{S=0}^{1}\sum_{J,\ell}(2I+1)\,(2J+1)\,{}^{S}R_{J,\ell}^{\;I}\,\sin 2\,{}^{S}\delta_{J,\ell}^{\;I},$$

$$V_{CI} = \frac{3}{M\lambda^3}\,\mathrm{Im}\left[f(0)\right] = \frac{k}{M}\frac{3\bar{\sigma}}{4\pi\lambda^3},$$

$$\left[V_{SR} + i\,V_{SI}\right] = \frac{3}{M\lambda^3}\,\frac{1}{4k^2}\,f_1(0),$$

$$f_1(0) = \frac{1}{32ik}\sum_{I=0}^{1}\sum_{J,\ell,S=1}(2I+1)\,(2J+1)\left[\left(1 - {}^{1}R_{J,\ell=J}^{\;I}\,e^{2i\,{}^{1}\delta_{J,\ell=J}^{\;I}}\right) -\right.$$

$$-\,(J-1)\left(1 - {}^{1}R_{J,\ell=J-1}^{\;I}\,e^{2i\,{}^{1}\delta_{J;\ell=J-1}^{\;I}}\right) +$$

$$+ (J + 2) \left(1 - {}^{1}R^{I}_{J,\ell=J+1} \; e^{2i \, {}^{1}\delta^{I}_{J,\ell=J+1}} \right) ,$$

k being the antinucleon momentum in the center-of-mass system; λ and $\rho(x)$ as defined in Reference 7.

In these expressions $\bar{\sigma}$ is the effective antinucleon-nucleon cross section given by

$$\bar{\sigma} = \frac{1}{2} \left[\sigma^{abs}_{\bar{p}-n} + \sigma^{abs}_{\bar{p}-p} \right] + \frac{1}{2} \gamma \left[\sigma^{sc}_{\bar{p}-n} + \sigma^{sc}_{\bar{p}-p} \right] ,$$

where γ is a factor that takes into account the effect of the Pauli principle upon nucleons inside the nucleus. This effect tends to forbid collisions with small momentum transfer, thereby decreasing the scattering in the forward direction.

A calculation of the γ factor is now being carried out, and will be published in the near future. For the work presented here, we have made an estimation of its value, for high-energy antinucleons, by introducing a cutoff angle and ignoring the scattering within this angle.

The calculated values of V_{CI} are large enough to make us believe that the actual value will not be very important. Therefore we have calculated V_{CI} for the two extreme values with $\gamma = 0$ and $\gamma = 1$ as well as with the cutoff procedure at the higher energies. The results are shown in Table IV. Using these potentials, Fernbach et al. are now carrying out an optical-model calculation of the scattering of antiprotons from several light nuclei.

ACKNOWLEDGMENTS

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TABLE IV

Optical-model potential depths for $\lambda = 0.8571$

V (Mev)		E (in Mev)		
		50	140	260
V_{CR}		-0.66	-12.1	-14.8
V_{SR}		3.5	2.9	5.4
V_{SI}		-4.2	1.7	-1.2
V_{CI}	$\gamma = 1$	90	106	108
	$\gamma = 0$	44.2	51.7	38.8
	cutoff	—	92	99

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FIGURE CAPTIONS

Fig. 1. $\bar{N}$-N cross sections as a function of energy.

Fig. 2. Differential scattering cross sections in the c.m. system for $\bar{p}$-p (neglecting Coulomb scattering) and $\bar{n}$-n at $E_{lab} \cong 50$ Mev.

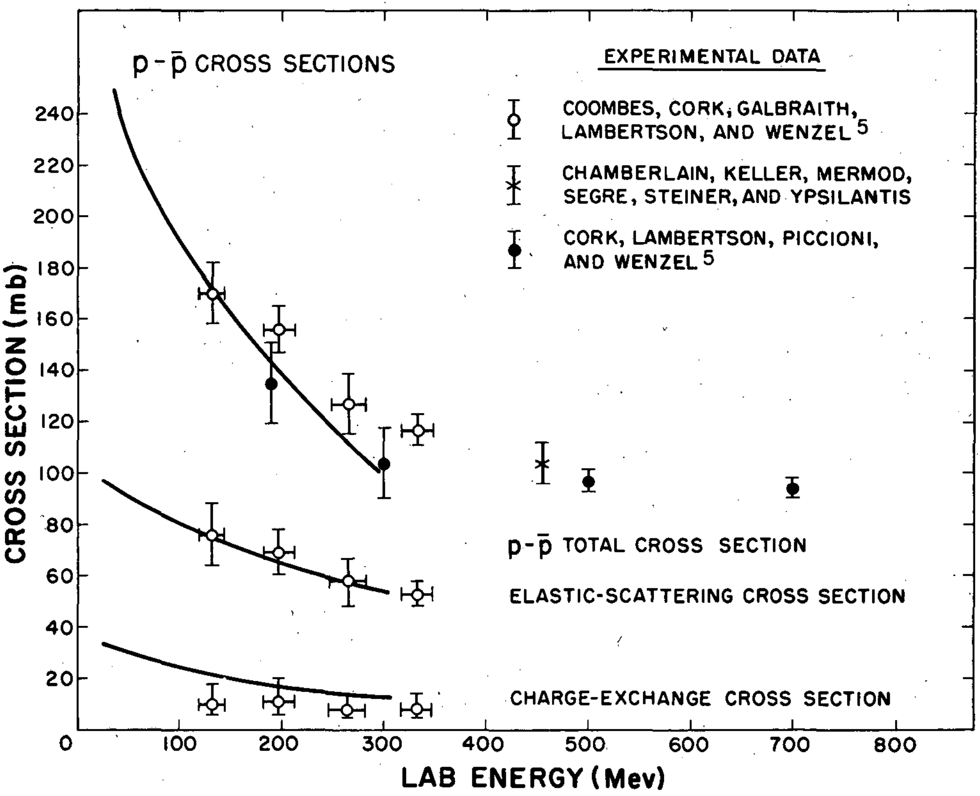
Fig. 3. Differential scattering cross sections (in the c.m. system) of $\bar{p}$-n and $\bar{n}$-p at $E_{lab} \cong 50$ Mev.

Fig. 4. Differential scattering cross section (in the c.m. system) of $\bar{p}$-n (neglecting Coulomb scattering) and $\bar{n}$-n at $E_{lab} \cong 140$ Mev.

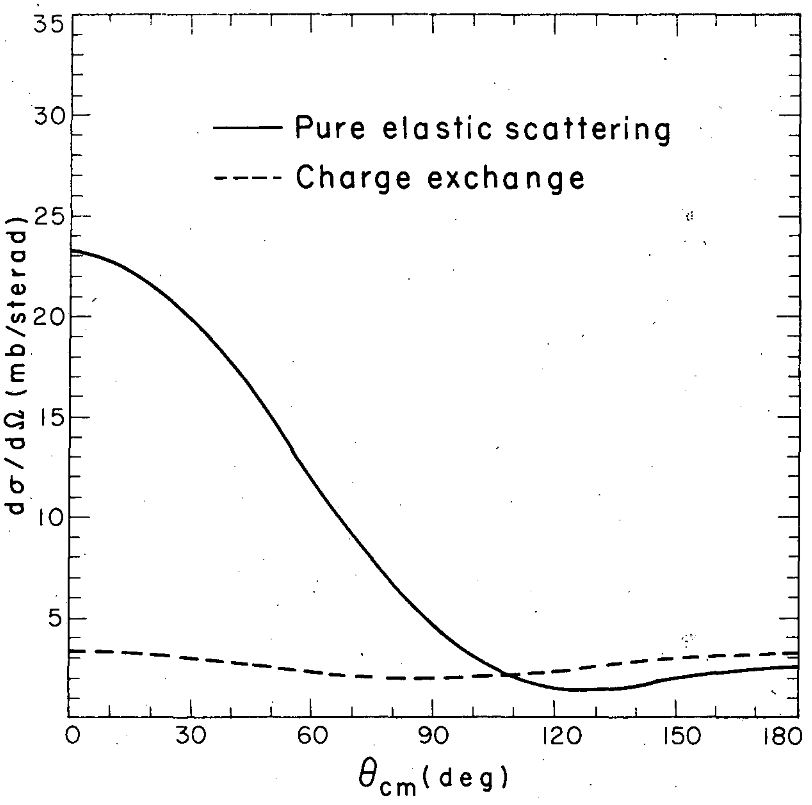
Fig. 5. Differential scattering cross sections (in the c.m. system) of $\bar{p}$-n and $\bar{n}$-p at $E_{lab} \cong 140$ Mev.

Fig. 6. Differential scattering cross section (in the c.m. system) of $\bar{p}$-p (neglecting Coulomb scattering) and $\bar{n}$-n at $E_{lab} \cong 260$ Mev.

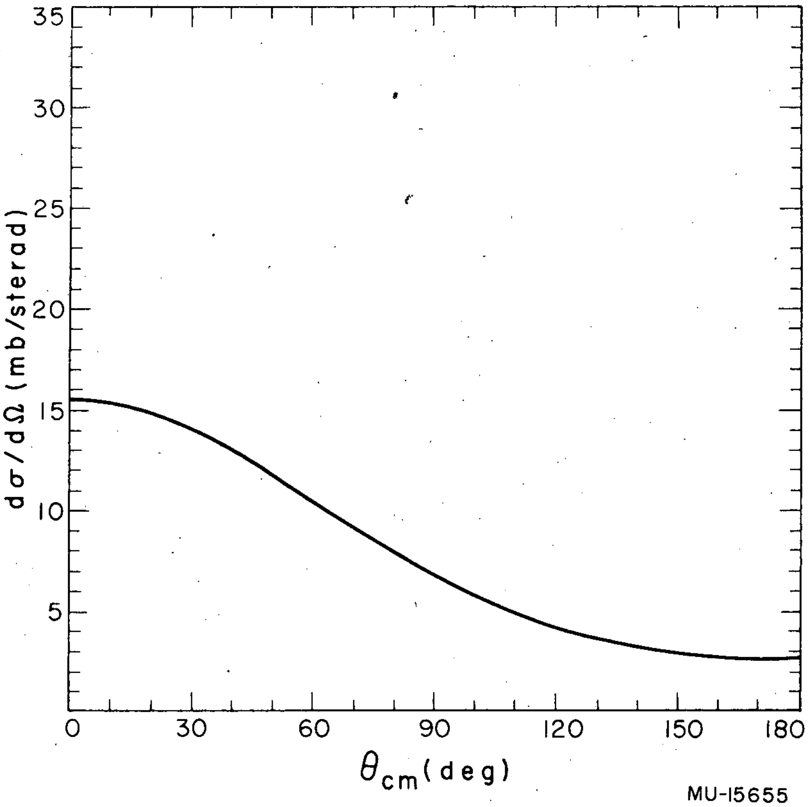
Fig. 7. Differential scattering cross sections (in the c.m. system) of $\bar{p}$-n (neglecting Coulomb scattering) and $\bar{n}$-p at $E_{lab} \cong 260$ Mev.


p - p̄ CROSS SECTIONS
EXPERIMENTAL DATA
COOMBES, CORK, GALBRAITH, LAMBERTSON, AND WENZEL 5
CHAMBERLAIN, KELLER, MERMOD, SEGRE, STEINER, AND YPSILANTIS
CORK, LAMBERTSON, PICCIONI, AND WENZEL 5
p-p̄ TOTAL CROSS SECTION
ELASTIC-SCATTERING CROSS SECTION
CHARGE-EXCHANGE CROSS SECTION
CROSS SECTION (mb)
240
220
200
180
160
140
120
100
80
60
40
20
0
100
200
300
400
500
600
700
800
LAB ENERGY (Mev)

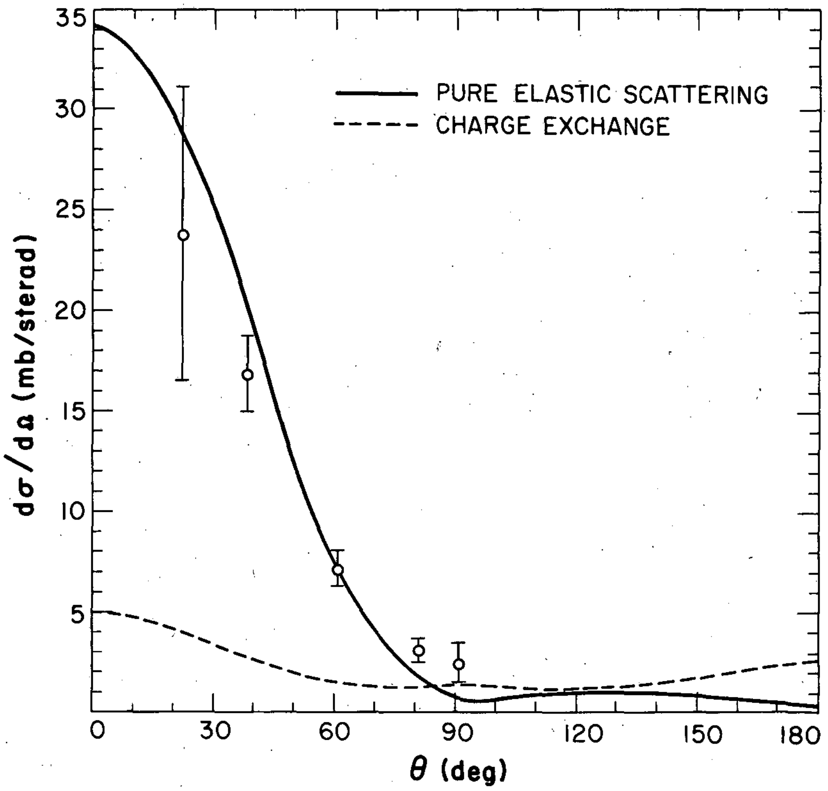
MU-15654


Pure elastic scattering
Charge exchange
$d\sigma/d\Omega$ (mb/sterad)
35
30
25
20
15
10
5
0
30
60
90
120
150
180
θ_{cm} (deg)

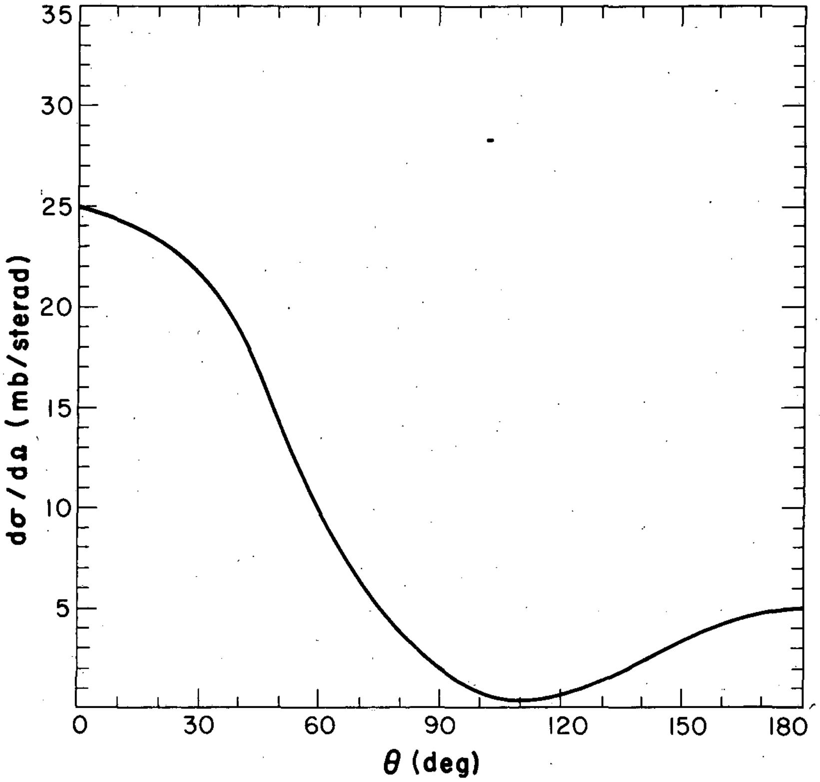
MU-15653


35
30
25
20
15
10
5
dσ/dΩ (mb/sterad)
0
30
60
90
120
150
180
θ_{cm}(deg)

MU-15655


PURE ELASTIC SCATTERING
CHARGE EXCHANGE
dσ/dΩ (mb/sterad)
35
30
25
20
15
10
5
0
30
60
90
120
150
180
θ (deg)

MU-15656



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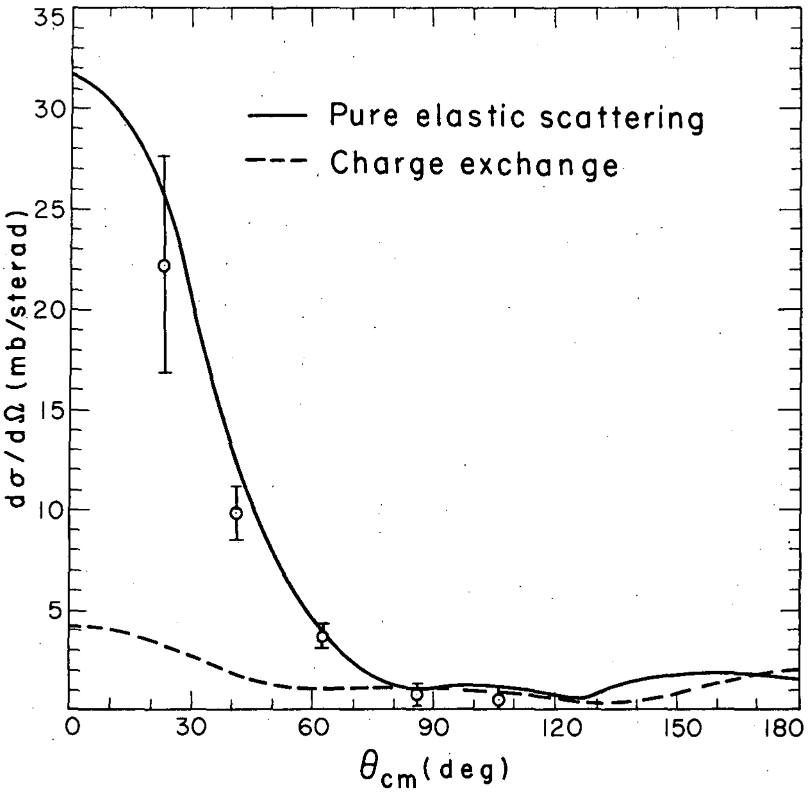
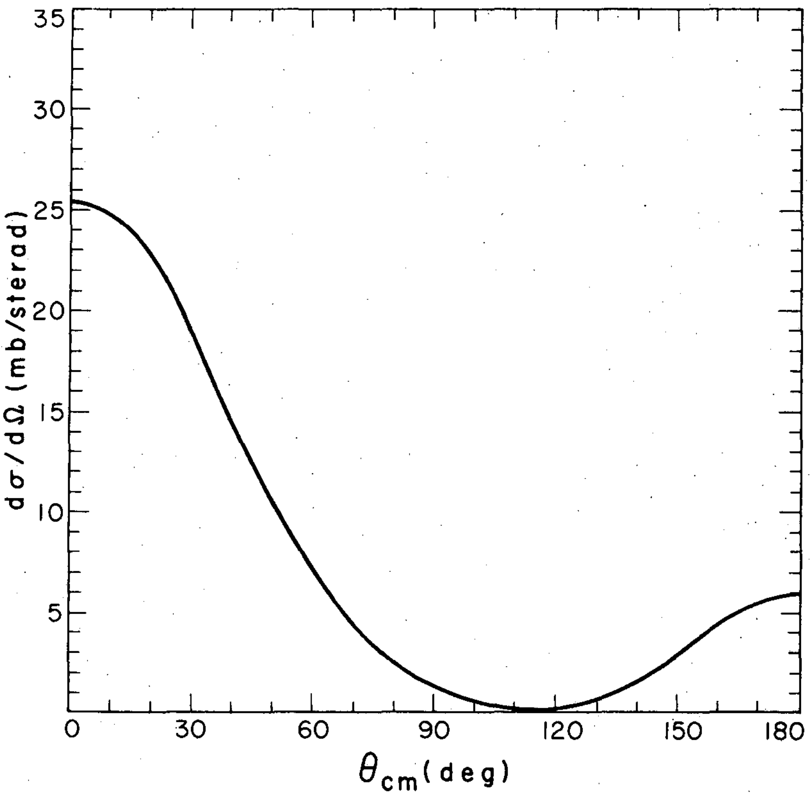


Pure elastic scattering
Charge exchange
$d\sigma/d\Omega$ (mb/sterad)
35
30
25
20
15
10
5
0
30
60
90
120
150
180
θ_{cm} (deg)

MU-15658



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