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# ON BACK-ANGLE SCATTERING OF ANTIPROTONS FROM NUCLEI

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ABSTRACT

The large-angle, elastic scattering of antiprotons from $^{12}C$ is calculated in the center-of-mass kinetic energy range $100 < T < 400$ MeV. The optical model is constructed by adding a folded annihilation potential to the central G-parity transformed $p+{}^{12}C$ impulse approximation Dirac optical potential. It is found that the annihilation potential affects the scattering mainly in backward hemisphere. We predict large back-angle cross sections. The $180^{o}$-excitation is found to exhibit resonance-like energy oscillation with a 25-45 MeV period. We find negligible spin polarization in the whole angular range.

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There has recently been a great deal of theoretical interest in the interactions of antinucleons with nuclei[1-6]. This interest stems from the obvious question of finding inter-relation between the antinucleon nucleus interaction and the more basic antinucleon-nucleon one. Further, data on anti-proton-nucleus scattering have recently been measured[6-8], and will hopefully be extended to wider angle, requiring, clearly the parallel theoretical development alluded to above.

A question which has been considered recently by several authors is whether resonance phenomena in the $\bar{p}$+A system, which would result in anomalously large back-angle cross-sections and corresponding oscillatory excitation function, could occur at low energies. The motivation behind this query is the occurrence of narrow structures in antinucleon-nucleon scattering cross-sections, widely believed to correspond to "baryonium" states predicted in the quark model of hadrons. How would the nuclear medium affect these resonances is clearly a valid question to address.

Auerbach et al.[1] and, more recently, Kahana and Sainio[3], made several predictions of the back-angle elastic scattering differential cross-section for $\bar{p}+{}^{16}O$, $\bar{p}+{}^{40}Ca$ and $\bar{p}+{}^{12}C$ at low energies. Among the findings of Ref. 1), (based on an optical potential characterized by a real part extending beyond the range of the imaginary part), was the occurrence of $\bar{p}$+A resonances of typical widths 15-150 MeV, in the $180^{o}$-excitation function, and corresponding enhanced back-angle angular distribution and spin polarization. The question of the ambiguity present in $\bar{p}$+A optical potentials has been addressed by Wong et al.[2].

In a recent paper[6], we suggested that a reasonably unambiguous $\bar{p}$+A optical potential, can be constructed from the G-parity transformed impulse approximation Dirac p+A optical potential, with an a posteriori added $\bar{p}$+A annihilation potential (see also Ref. 5)). We have shown further, that the small-angle scattering p+A[8] is quite accurately accounted for without the $\bar{p}$+A annihilation potential. The purpose of the present paper is to extend the calculation of Ref. 6) by including fully the annihilation potential obtained from a folding procedure. With the resulting $\bar{p}$+A optical potential we calculate the back-angle scattering of $\bar{p}+{}^{12}C$ in the energy range 100–400 MeV.

We take, as a starting point the impulse approximation Dirac p+A optical potential of McNeil et al.[9], which contains complex, scalar $V_s$ and the fourth component of a vector potentials $V_o$. They appear in the p+A Dirac equation, in the form

$$V_{p+A} = \beta V_s + V_o \tag{1}$$

where $\beta$ is the Dirac matrix.

The corresponding potential for the $\bar{p}$+A system is given by the G-parity transformed $V_{p+A}$, namely[6],

$$V^{(o)}_{\bar{p}+A} = \beta V_s^{*} - V_o^{*} \tag{2}$$

We emphasize that the $\bar{p}$+A potential above, Eq. (2) does not take into account the effect of the $\bar{p}$-nucleon annihilation processes (mainly into a number of pions). To proceed, we write $V_s(r) = V_s(E)\hat{\rho}_s(r) \equiv V_s\hat{\rho}_s(r)$ and similarly $V_o = V_o\hat{\rho}_v(r)$ where $\hat{\rho}(r)$ and $\hat{\rho}_v(r)$ are the shapes of the nuclear scalar and vector densities. We further set $\hat{\rho}_s(r) = \hat{\rho}_v(r) = \hat{\rho}(r)$, and use for $\hat{\rho}(r)$ the density shapes extracted from electron scattering. The energy-dependent strengths $V_o$ and $V_s$ are



calculated according to McNeil et al.[9].

The central and spin-orbit interactions that would appear in the equation determining the upper component of the antiproton wave function, are easily obtained. The point we would like to mention here is that owing to the nature of $V_s$ and $V_o$, (which have comparable strengths), namely, $\mathrm{Re}V_o > 0$, $\mathrm{Re}V_s < 0$, $\mathrm{Im}V_o < 0$ and $\mathrm{Im}V_s > 0$, the central $\bar{p}$+A interaction, $U_c(r)$, contains a very large real attraction component that follows the shape of $\hat{\rho}(r)$ and a much smaller repulsive component that follows $(\hat{\rho}(r))^2$. The imaginary part of $U_c(r)$ has similar features, except that its over-all strength is almost a factor 3 smaller than the real strength.

The above discussion shows that a reasonable treatment of $\bar{p}$+A scattering can be performed with optical potentials that behave like $\hat{\rho}(r)$ (e.g. with Woods-Saxon shapes). However, the numerical disparity between $\mathrm{Re}U_c(r)$ and $\mathrm{Im}U_c(r)$, in favor of the former, has to be maintained. Further, because of the lack of knowledge about the Lorentz structure of the annihilation $\bar{p}$+nucleon potential, we will be content here with using the non-relativistic Schrödinger equation. The optical $\bar{p}$+A potential we use in our non-relativistic calculation is constructed as

$$U_{\bar{p}+A}(r) = U_G(r) + U_{ann.}(r) + U_{Coul.}(r) \tag{3}$$

where $U_G(r)$ is the central potential discussed above, $U_{ann.}(r)$ is the $\bar{p}$+A annihilation potential (see below) and $U_{Coul}(r)$ is the attractive $\bar{p}$+A Coulomb interaction.

We construct $U_{ann}(r)$, as done by several authors[10–13] from a folding of the $\bar{p}$+nucleon annihilation potential, $V^{\bar{p}+N}_{ann.}$ with the target density $\rho^A(\vec{r})$

$$U_{ann.}(\vec{r}_{\bar{p}}) = \int d\vec{r}\, V^{\bar{p}+N}_{ann.}(\vec{r}_{\bar{p}}-\vec{r})\, \rho^A(\vec{r}) \qquad (4)$$

As a result of the very short-ranged nature of $V^{\bar{p}+N}_{ann.}$, it is expected that $U^{\bar{p}+A}_{ann.}(\vec{r}_{\bar{p}})$ would come out much weaker. Simple estimate based on using square well shapes for both $V^{\bar{p}+N}_{ann.}$ and $\rho(r)$ gives[14] $U^{\bar{p}+A}_{ann.} \cong V_o \left(\frac{r_n}{r_o}\right)^3 \theta(R-r_n-r)$, where $R = r_o A^{1/3}$ is the target radius, $r_n$ and $V_o$ are the range and strength (either real or imaginary) of $V^{\bar{p}+N}_{ann.}$ respectively. Taking for $V_o = 500$ MeV, $r_o = 1.2$ fm and $r_n = 0.2$ fm[12], one obtains for $U^{\bar{p}+A}_{ann.} \cong -2.5\,(1+i)\,\theta(R-r_n-r)$ MeV.

In Fig. (1) we present the result of our exact folding calculation, Eq. (4), for $\bar{p}+{}^{12}C$, taking for $V^{\bar{p}+N}_{ann.} = \dfrac{-500(1+i)}{1+\exp\left(\frac{r-0.2}{0.2}\right)}$ MeV[12] and for $\rho(r)$ a realistic density shape for ${}^{12}C$. The diffuseness of both $V^{\bar{p}+N}_{ann.}$ and $\rho^A(r)$ result in a much larger strength for $U^{\bar{p}+A}_{ann.}$ compared to the square-well estimate given above. Therefore the estimate given in Ref. 13) is to be considered, at most, qualitative.

We apply the procedure above to $\bar{p}+{}^{12}C$ at a center-of-mass kinetic energy of 109.35 MeV. At this energy, the central part of the "G-parity" $\bar{p}$+A potential, $U_G$ is found to be, to a very good approximation

$$U_G(r) = -(1128.59 + 290.5\, i) \cdot \left(1 + \exp\frac{r-2.355}{0.522}\right)^{-1} [\mathrm{MeV}]$$

In Figure (2) we show our result for $\frac{d\sigma}{d\Omega}$ at



$T_{CM} = 109.35$ MeV with and without the annihilation component. At small angles, (Fig. (2a)), there is hardly any effect of $U_{ann.}$. This is due mainly to the very strong refractive effect of $U_G$, which makes the far-side component of the elastic scattering amplitude completely dominant over its near-side one[14]. The addition of an equal amount of real and imaginary strength, coming from $U^{\bar{p}+A}_{ann.}$, does not alter the picture. The effect of $U^{\bar{p}+A}_{ann.}$, however, is seen more conspicuously at larger angles, as Fig. (2b) indicates.

It is important to note that our 180° elastic scattering cross-section is quite enhanced owing to the large refractive G-parity potential. In fact we obtain a larger cross-section at back angles than that of Ref. 1) without having to make the real potential extending farther out than the imaginary part, as was done in that reference. This is in accord with the findings of Wong et al.[3].

We have also calculated the 180°-excitation function, in the kinetic energy range $100 < T_{CM} < 400$ MeV. We exhibit our result in Fig. (3). It is clear that resonance-like energy oscillations are dominant in $\frac{d\sigma}{d\Omega}(180^o)$. The local period of these undulations ranges from about 25.0 MeV in the energy range $100 < T < 200$ to about 45.0 MeV at higher energies. The average value of the cross section increase with energy almost exponentially. These features are reminiscent of an optical effect known as back-ward glory which is conspicuous when nuclear refraction is dominant, as in the present case.

In our calculation above we have left out completely the spin-orbit interaction. Within the Dirac description of $\bar{p}$+A scattering, the spin-orbit strength comes out to be proportional to $-(V^*_o + V^*_s)/(E+m+V^*_s+V^*_o)(2m)$, which is very small, since $V_o^r$ ($V_o^I$) is comparable to $V_s^r$ ($V_s^I$) but with opposite sign. Accordingly very small spin polarization and spin rotation is predicted[6]. The addition of $U_{ann.}$ does not alter this feature very much. The situation at back-angles was discussed in Ref. 1), where its authors predicted large spin polarization (~100%). We do not find such large spin polarization. In fact we find a maximum of $10^{-2}$% spin polarization in the back-angle region.

All of our calculation above was performed non-relativistically. It would be interesting to test the adequacy of the non-relativistic treatment of $\bar{p}$+A scattering, where internal local velocities may reach high values due to the very large attraction present.

In conclusion, we have calculated the $\bar{p}+^{12}C$ elastic scattering angular distribution and the $180^o$-elastic excitation function in the center-of-mass kinetic energy range $100 < T < 400$ MeV, using an optical potential composed of a G-parity transformed impulse approximation Dirac $p+^{12}C$ potential and an annihilation piece obtained from folding procedure. We have found that the angular distribution is enhanced at back-angles (compared to that of protons). Further the $180^o$-excitation function was found to exhibit 25-45 MeV period energy oscillations, of the type discussed by Auerbach et al.[1]. In contrast to Ref. 1), however, we find vanishingly small spin polarization in the backward hemisphere.



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FIGURE CAPTIONS

Figure 1 - The $\bar{p}+{}^{12}C$ annihilation potential obtained from the folding prescription (see text for details).

Figure 2 - The $T_{CM}$ = 109.35 MeV elastic scattering angular distribution antiprotons on ${}^{12}C$. Calculated with (full curve) and without (dashed curve) the annihilation potential. Fig. (2a) shows the scattering at small angles and Fig. (2b) shows the large-angle scattering.

Figure 3 - The calculated 180°-excitation function for the elastic scattering of $\bar{p}$ on ${}^{12}C$ in the center-of-mass energy range 100-400 MeV.

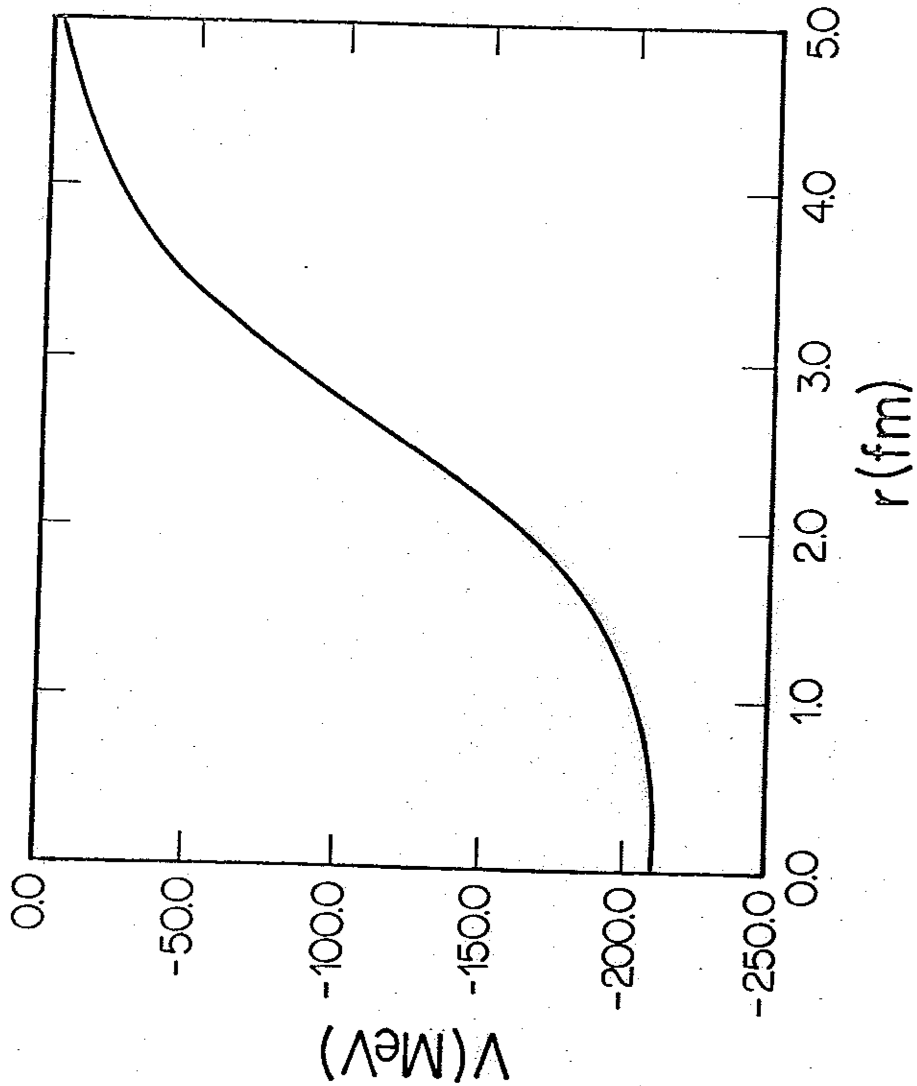
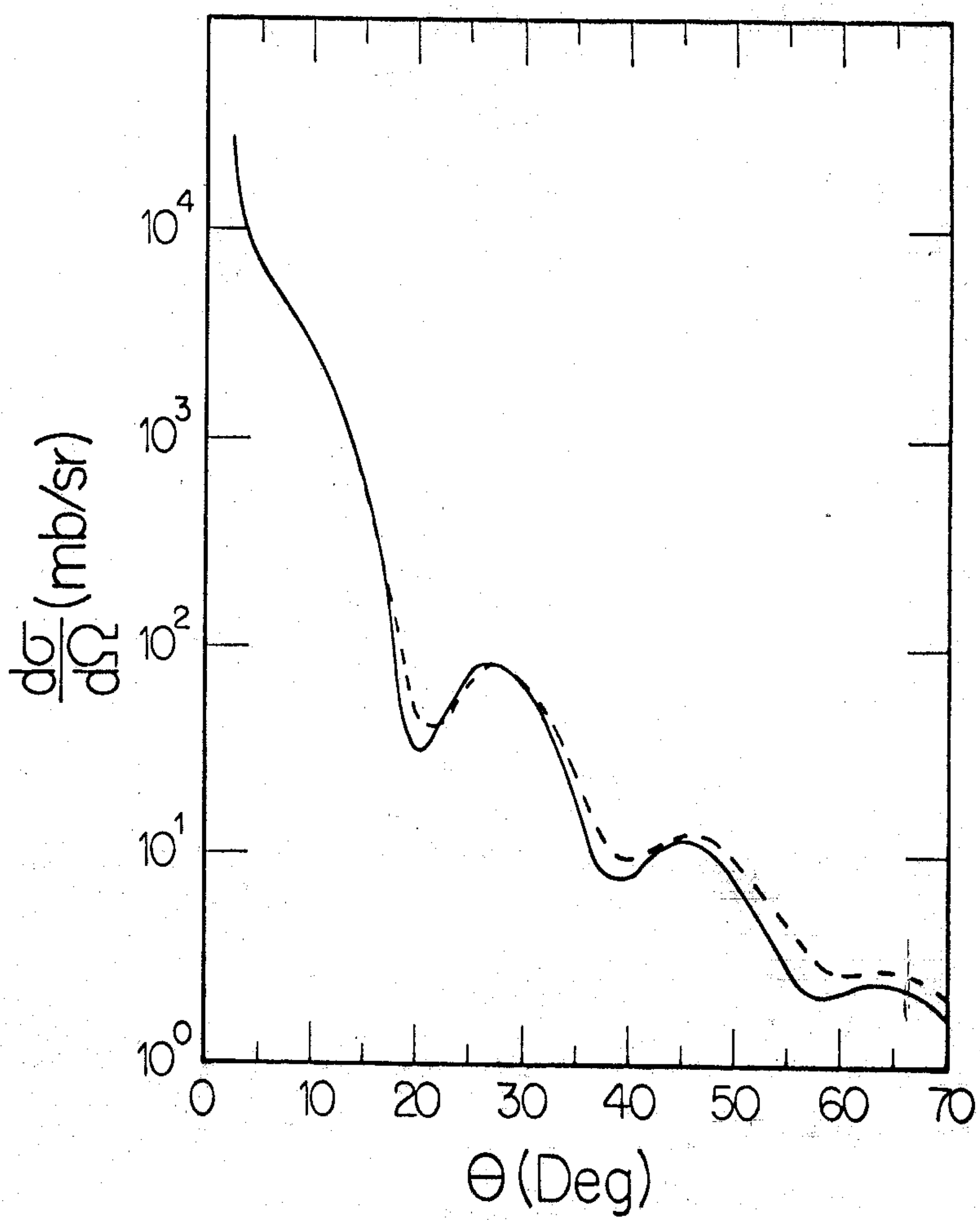
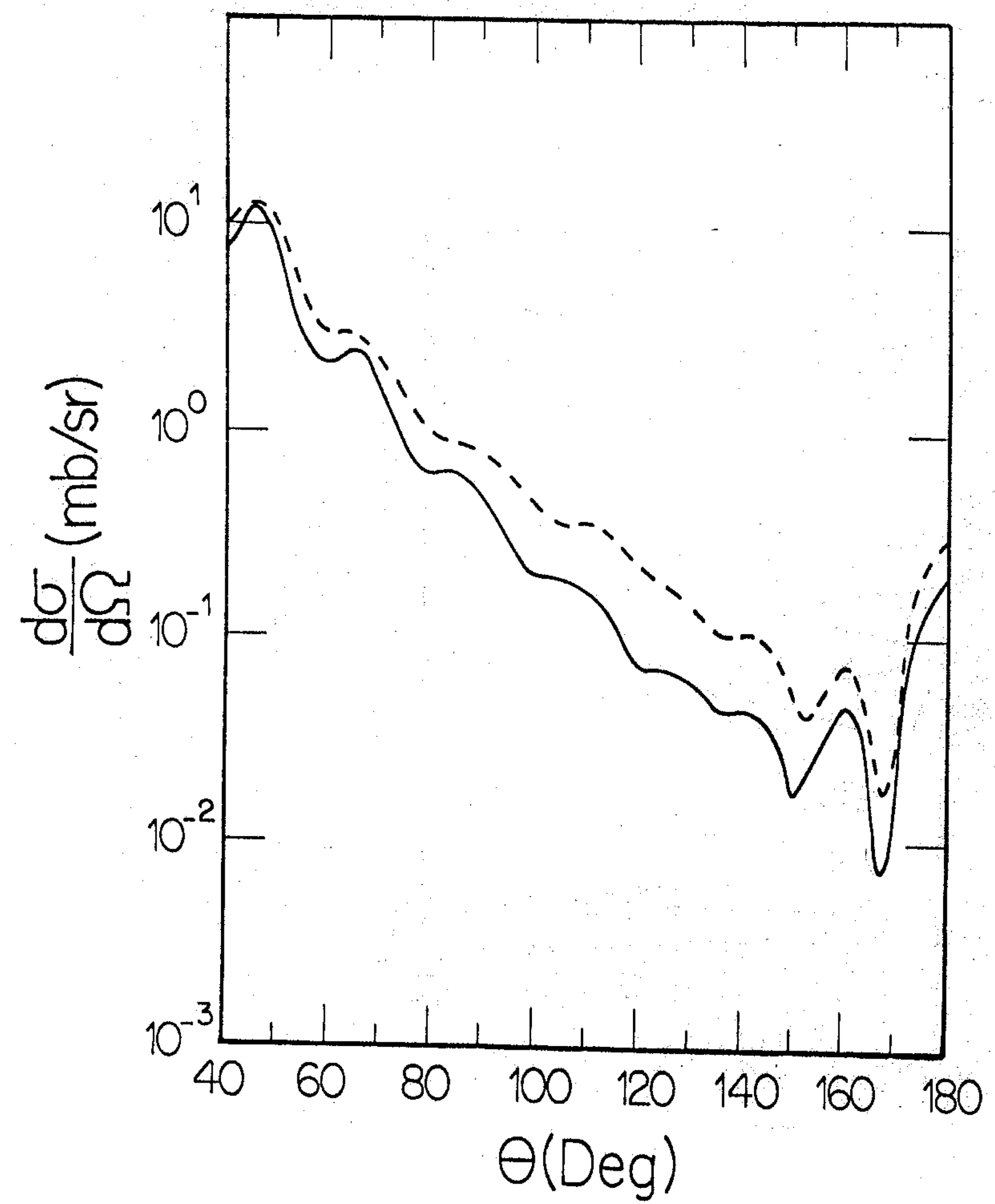



Fig. 1



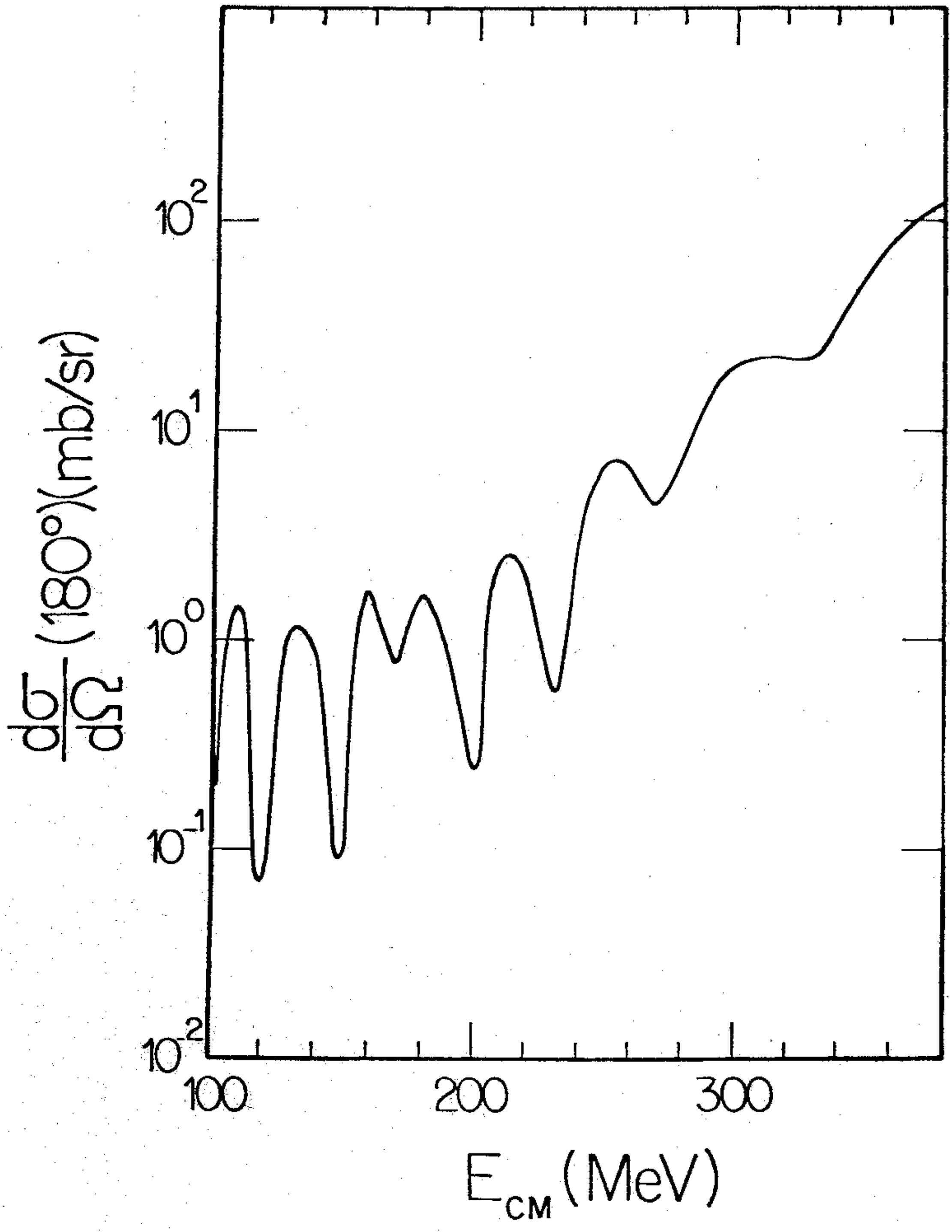
$10^4$
$10^3$
$10^2$
$10^1$
$10^0$
$\frac{d\sigma}{d\Omega}$ (mb/sr)
0
10
20
30
40
50
60
70
Θ (Deg)


Fig. 2a



$10^1$
$10^0$
$10^{-1}$
$10^{-2}$
$10^{-3}$
$\frac{d\sigma}{d\Omega}$ (mb/sr)
40
60
80
100
120
140
160
180
Θ(Deg)


Fig. 2b



$\frac{d\sigma}{d\Omega}$ (180°)(mb/sr)
$10^2$
$10^1$
$10^0$
$10^{-1}$
$10^{-2}$
100
200
300
$E_{CM}$ (MeV)


Fig. 3