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DESCRIPTION OF ANTIPROTON-NUCLEUS SCATTERING WITH THE PROTON-NUCLEUS DIRAC IMPULSE APPROXIMATION OPTICAL POTENTIAL

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ABSTRACT

The antiproton-nucleus scattering problem is formulated as the charge-conjugated Dirac equation for proton-nucleus scattering. The Dirac impulse approximation optical potential is used to calculate within the eikonal approximation the scattering observables for $\bar{p}$ + ^{12}C, $\bar{p}$ + ^{27}Al and $\bar{p}$ + ^{63}Cu in the beam momentum range 400-1000 MeV/C. Good agreement with the data is obtained.

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A great of amount of theoretical interest has recently been placed on antiproton-scattering off nuclei[1-5]. This arises from the very promising data which is coming out and will continue to come out from the low-energy anti-proton ring (LEAR) facility at CERN, as well a from other laboratories. Further, the antiproton-nucleus system is a good "laboratory" that would help better our understanding of the more basic antiproton-nucleon interaction, and would, eventually test the more fundamental theory, QCD, at a level where hadronic cross-sections are large.

In a recent letter, Nakamura et al.[6] presented the absorption and small angle scattering of antiprotons by ^{12}C, ^{27}Al and ^{63}Cu nuclei in the range of beam momentum 470-880 MeV/C. This is a good set of data that can be used to test different theoretical approaches to $\bar{p}$-nucleus scattering. A popular approach starts with the conventional, non-relativistic, optical model Schrödinger equation. Dover et al.[1] and Kahana and Saino[5] have used this model, with a non-relativistic folded optical model of the "tρ" variety, to discuss possible existence of resonances and corresponding back angle enhancement of the elastic scattering differential cross section of the $\bar{p}$ + A system at low energies.

In this letter, we take a completely different point of view concerning the $\bar{p}$ + A scattering system. Owing to the greatly successful Dirac description of proton-nucleus

scattering and spin polarization and rotation[7], we suggest that if this Dirac description is relativistically consistent, the antiproton-nucleus scattering system should be as successfully described by a charge-conjugated Dirac equation. We compare our calculation with the data of ret.[6] and make several predictions.

The Dirac equation describing the elastic scattering of a proton treated as a Dirac particle from a spin saturated, N = Z, nucleus, is usually written in the form, using a time-independent description

$$[\vec{\alpha}\cdot\vec{p} + \beta(m+V_s) + V_o]\Psi_p = E\Psi_p \qquad (1)$$

where it is assumed that the average, complex, nucleon-nucleus potential is a sum of a scalar component V_s, and the fourth (time) component of a vector potentials V_o which also contains the point Coulomb potential. The matrices α and β are Dirac's and ψ_p in the proton four component vector wave function.

Phenomenological applications[8], as well as calculation with a microscopic impulse approximation optical potential[9,10] have clearly shown that Eq. (1) is an excellent representation of the average relativistic interaction of protons with nuclei.

We take the obvious point of view that $\bar{p}$, being

the antiparticle of the proton is described, ignoring its internal structure, by the wave function[11]

$$\Psi_{\bar{p}} = C\beta\Psi_p^* \qquad (2)$$

where C in the charge conjugation operation. Thus to obtain the antiproton-nucleus Dirac equation, we (1) take the complex conjugate of Eq. (1), (2) multiply by $C\beta$ and (3) replace the vector potential V_o by $-V_o$. Thus we propose that the Dirac equation, describing $\bar{p}$ + nucleus scattering is given by (<u>without</u> taking into account $\bar{N}N$ annihilation effects)

$$[\vec{\alpha}\cdot\vec{p} + \beta(m+V_s^*) + (-V_o^*)]\Psi_{\bar{p}} = E\Psi_{\bar{p}} \qquad (3)$$

with V_s and V_o being the proton-nucleus potentials. One can reach several immediate conclusions concerning the optical potential for the $\bar{p}$ + nucleus system. Dirac phenomenological analysis supported by impulse approximation "tρ" type theory for the p + nucleus optical potential have convincingly shown that the scalar potential, V_s is regenerative (position imaginary part) whereas V_o is absorptive. Further, the real part of $V_o(V_s)$ is large and repulsive (attractive). From Eq. (3), we could immediately reach the conclusion that for $\bar{p}$ + nucleus

system, the signs of the real and imaginary parts of the scalar and fourth component of the vector interaction are all negative. This implies very strong attraction and very strong absorption.

Within a Dirac-impulse approximation, the strengths of the scalar and vector interactions for antiprotons scattering are thus exactly equal to those of protons. These were calculated by McNeil et al.[9]. We use their results in our calculation of the elastic scattering of antiprotons based on Eq. (3).

We write $V_s(r)$ and $V_o(r)$ as

$$V_s(r) = V_s(E)\,\hat{\rho}_s(r) \equiv V_s\,\hat{\rho}_s(r) \tag{4}$$

$$V_o(r) = V_o(E)\,\hat{\rho}_v(r) \equiv V_o\,\hat{\rho}_v(r) \tag{5}$$

where $\hat{\rho}_s(r)$ and $\hat{\rho}_v(r)$ are the shapes of the nuclear scalar and vector densities. In all our applications below we 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.

In Figure 1, we show the real and imaginary strengths of V_s and V_o, constructed from the relativistic "to" prescrisption of McNeil et al.[9]. The density shapes were

taken from De Vries and Peng[12]. It is useful at this point to analyse the central and spin-orbit interactions that would appear in the equation determining the upper component of the Dirac $\psi_{\bar{p}}$. These are given by

$$V_c(r) = \left[V_s^* + \frac{E}{m}\left(-V_o^*\right)\right]\hat{\rho}(r) + \frac{V_s^{*2} - V_o^{*2}}{2m}\left(\hat{\rho}(r)\right)^2 \tag{6}$$

$$V_{so}(r) = \frac{\left(-V_o^* - V_s^*\right)}{2mA(r)}\,\frac{1}{r}\,\frac{d}{dr}\,\hat{\rho}(r) \tag{7}$$

$$A(r) = E + m + V_s^* + V_o^* \tag{8}$$

Then, since $\mathrm{Re}V_o > 0$, $\mathrm{Re}V_s < 0$, $\mathrm{Im}V_o < 0$ and $\mathrm{Im}V_s < 0$, we expect very weak spin-orbit interaction in $\bar{p}$-nucleus scattering and accordingly very small spin polarization and spin rotation. This is made quantitive in our calculation below. Further, the real part of the central potential, $V_c(r)$, is dominated by the first term in Eq. (6). Consequently a Wood-Saxon parametrization should work reasonably well in a non-relativistic treatment. This is in contrast to proton nucleus scattering where a more exotic shape namely of the wine bottle bottom variety seems to be required[13]. The reason resides in the $\hat{\rho}(r)^2$ term in $V_c(r)$ which is equal in both p and $\bar{p}$ cases except

that it is the dominant term in ReV_c^p, whereas it contributes about 5% in $ReV_c^{\bar{p}}$ E.g. at k = 879 MeV/c for $\bar{p}$ + ^{12}C and p + ^{12}C,

$$Re\, V_c^{\bar{p}}(r) = -693.7\,\hat{\rho}(r) + 32.2\left(\hat{\rho}(r)\right)^2 \ [Mev] \quad (9)$$

$$Re\, V_c^{p}(r) = -6.3\,\hat{\rho}(r) + 32.2\left(\hat{\rho}(r)\right)^2 \ [Mev] \quad (10)$$

Similar considerations can be applied to ImV_c,

$$Im\, V_c^{\bar{p}}(r) = -201.9\,\hat{\rho}(r) + 9.1\left(\hat{\rho}(r)\right)^2 \ [Mev] \quad (11)$$

$$Im\, V_c^{p}(r) = -31.9\,\hat{\rho}(r) - 9.1\left(\hat{\rho}(r)\right)^2 \ [Mev] \quad (12)$$

Thus the $\hat{\rho}^2(r)$ term contributes 4.5% to $ImV_c^{\bar{p}}(r)$ compared to 28.5% to $ImV_c^{p}(r)$. A representation of $ImV_c^{\bar{p}}(r)$ that follows $\hat{\rho}(r)$ should be quite reasonable.

The elastic scattering differential cross section, spin polarization, P, and spin rotation Q, for $\bar{p}$ + ^{12}C were calculated using the eikonal approximation following Amado et al.[14]. This approximation should be quite adequate at the

energies and small angles considered here and in Ref.[6]. The results of our calculation are presented in Figure 2. In all of our calculations we have payed due attention to the long range Coulomb attraction by appropriately modifying the Amado et al. eikonal amplitudes[15].

The elastic scattering differential cross section for the $\bar{p}$ + A system at k $\geq$ 400 MeV/c is structureless and drops rapidly several orders of magnitude in an angle interval of about 20^o. This is in great contrast to the p + A case where strong Fraunhoffer diffraction oscillation are seen. We interpret this as arising from the dominance of the far-side contribution over the near-side one in the elastic scattering amplitude at small angles[16,17]. (Where by far-side and near--side contributions we are referring to the decomposition of the amplitude into two "running waves". This is done using the well-known decomposition of the Bessel function $J_o(qb)$, which enters in the amplitude, into the form $J_o(qb) = \frac{1}{2}\left[H_o^{(1)}(qb) + H_o^{(2)}(qb)\right]$, with $H_o^{1(2)}(qb) \xrightarrow[qb\ \to\ large]{} e^{+(-)iqb}$, being the Hankel function). The reason for this is the strong nuclear refraction in $\bar{p}$ + A.

In contrast, in p + A scattering refractive effects are small (see Eq. 10) and thus one has a situation where the far-side and near-side contributions are roughly equal giving rise to the usual two-bright spots "Fraunhoffer" interference

structure. The detailed near/far decomposition of the p + A scattering systems will be published elsewhere[18].

As discussed earlier, the spin-orbit interaction in the $\bar{p}$ + A system is expected to be very weak. Our calculated spin polarization and p spin rotation (Fig. 2b and 2c) for $\bar{p}$ + ^{12}C at $k_{\bar{p}}$ = 879 MeV/c lends support to our earlier discussion. In contrast to p + A systems where p and Q could reach 90%, the $\bar{p}$ + A exhibits only 2% to 4% spin polarization and rotation. It would be very interesting to verify our predictions above for the recently reported measurement of Nakamura et al.[6]. We have also calculated the total reaction cross section, σ_R, for $\bar{p}$ + ^{12}C, $\bar{p}$ + ^{27}Al and $\bar{p}$ + ^{63}Cu, in the incident linear momentum range $400 \leq k \leq 1000$ MeV/c. The results shown in Fig.3,are in good agreement with the data[6], and do not show the dip seen in the calculated σ_R for proton scattering[19].

We should emphasize that in all our calculation above we have ignored the effect on the $\bar{p}$ + A optical potential arising from the $\bar{N}N$ annihilation process[20].

From various theoretical studies, it is expected that $\bar{N}N$ annihilation may be taken into account through the introduction of an average complex potential whose real and imaginary strengths are very big (∿-500 MeV) and diffuse characterized by a small radius (0.8 fm) and a very small diffuseness (0.2 fm). When folded with the target nuclear density, this

interaction would result in an effective annihilation $\bar{p}$ + A interaction, which resembles very much a hard core. This would, on the average, lead to a slight increase in absorption and would lower our calculated $d\sigma/d\Omega$ and increase σ_R, exactly in the direction required (see Fig. 2a. and 3).

In conclusion, we have presented in this letter,a parameter-free calculation of the $\bar{p}$ + A scattering observables based on the charge-conjugated, Dirac impulse approximation p + A optical potential. Our results indicate clearly that our theory is correct in so far as it reproduces reasonably well the data. It also lends great support to the consistency of the Dirac-equation-based description of proton scattering from nuclei. The only missing element in our calculation is the effective $\bar{p}$ + A "annihilation" potential. Our results, however, should serve as a starting point in assessing its importance in $\bar{p}$ + A scattering.

Further measurements and calculation will be required for a fuller unraveling of the physics of nucleon-nucleus and antinucleon-nucleus scattering.

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FIGURE CAPTIONS

Figure 1. The strengths $V_o(E)$ (full line), $V_s^r(E)$ (dashed line), $V_o^I(E)$ (lower full line) and $V_s^I(E)$ (lower dashed line) for $\bar{p}$ + ^{12}C scattering.

Figure 2. 2a. The elastic scattering differential cross section for $\bar{p}$ + ^{12}C at $k_{\bar{p}}$ = 470 MeV/c, obtained with the Dirac impulse approximation using $V_s^{\bar{p}} = V_s^{p*}$ and $V_o^{\bar{p}} = -V_o^{p*}$ (see text for details). The dotted curve in the Schrödinger fit to the data of Ref. 6 (see Ref. 6 for details)

2b. The spin polarization for $\bar{p}$ + ^{12}C (see fig.2a)

2c. The spin rotation for $\bar{p}$ + ^{12}C (see fig. 2c).

Figure 3. The total reaction cross section for $\bar{p}$ + ^{12}C, ^{27}Al, ^{63}Cu obtained within the Dirac impulse approximation. Also shown are the data point taken from Ref. 6.

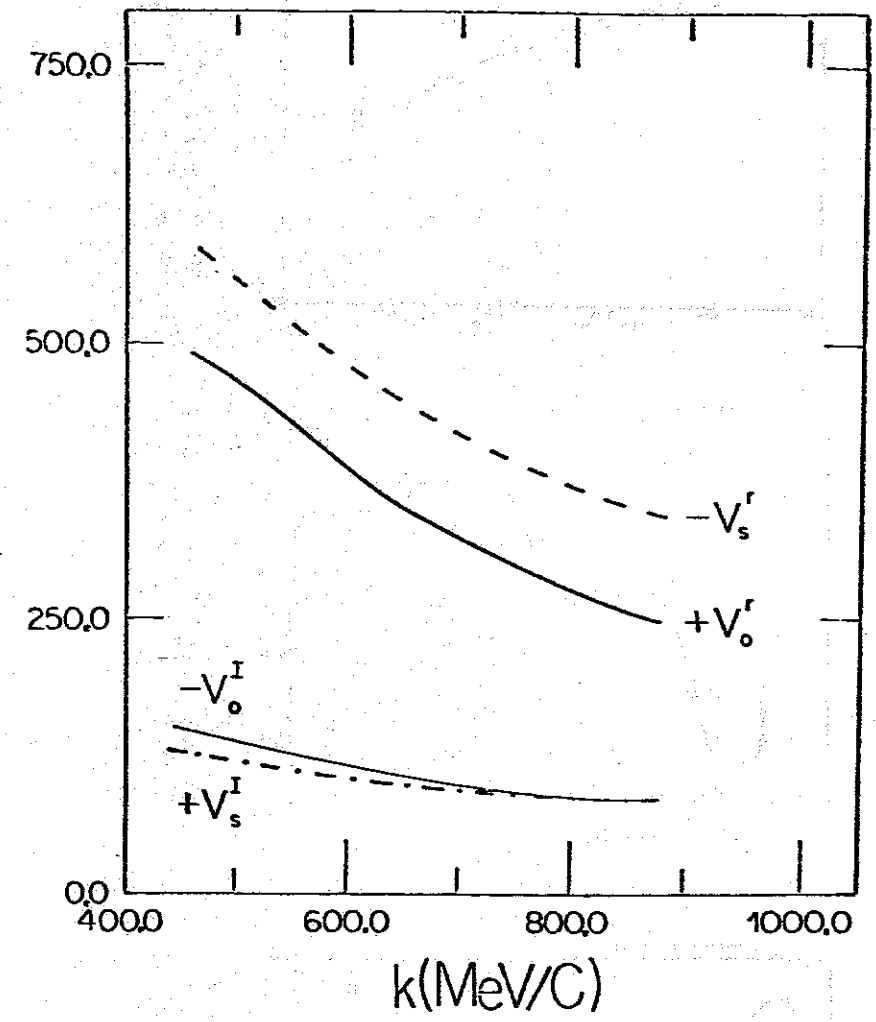

Fig. 1

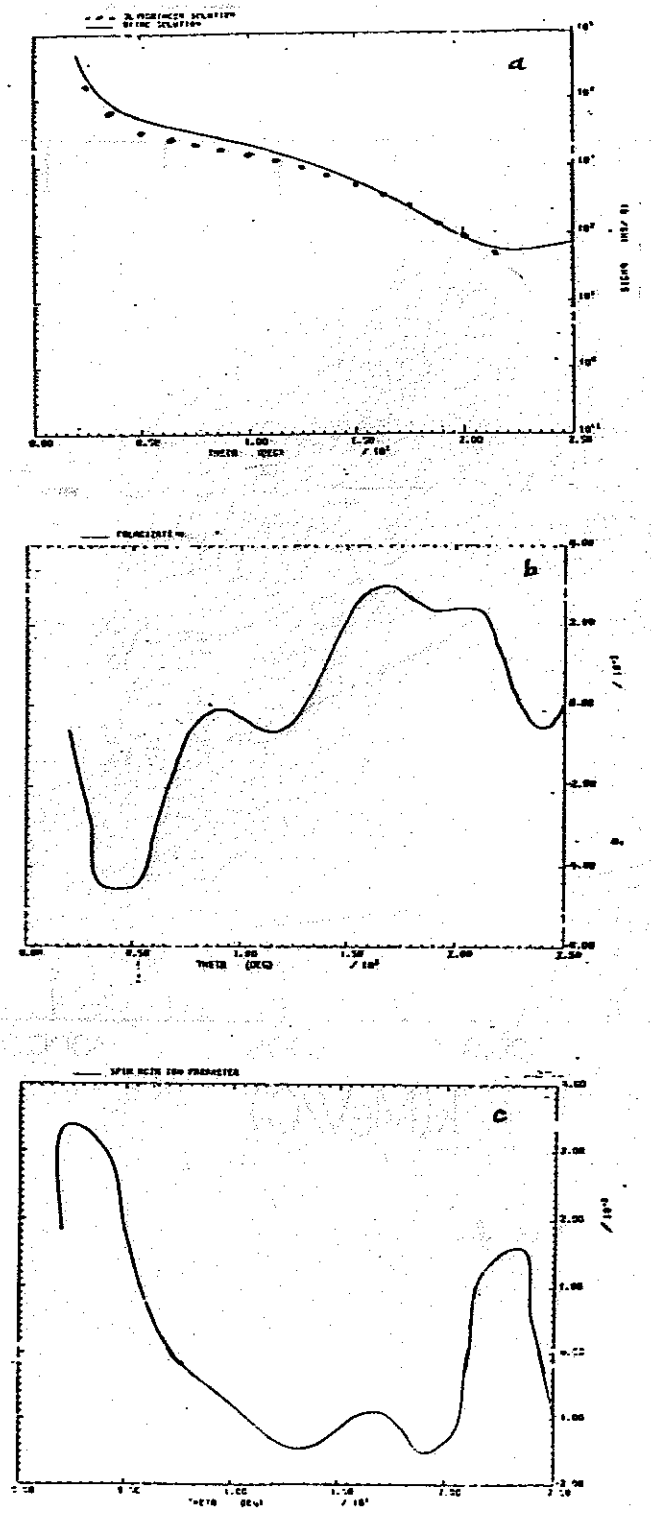
a
b
c

Fig. 2

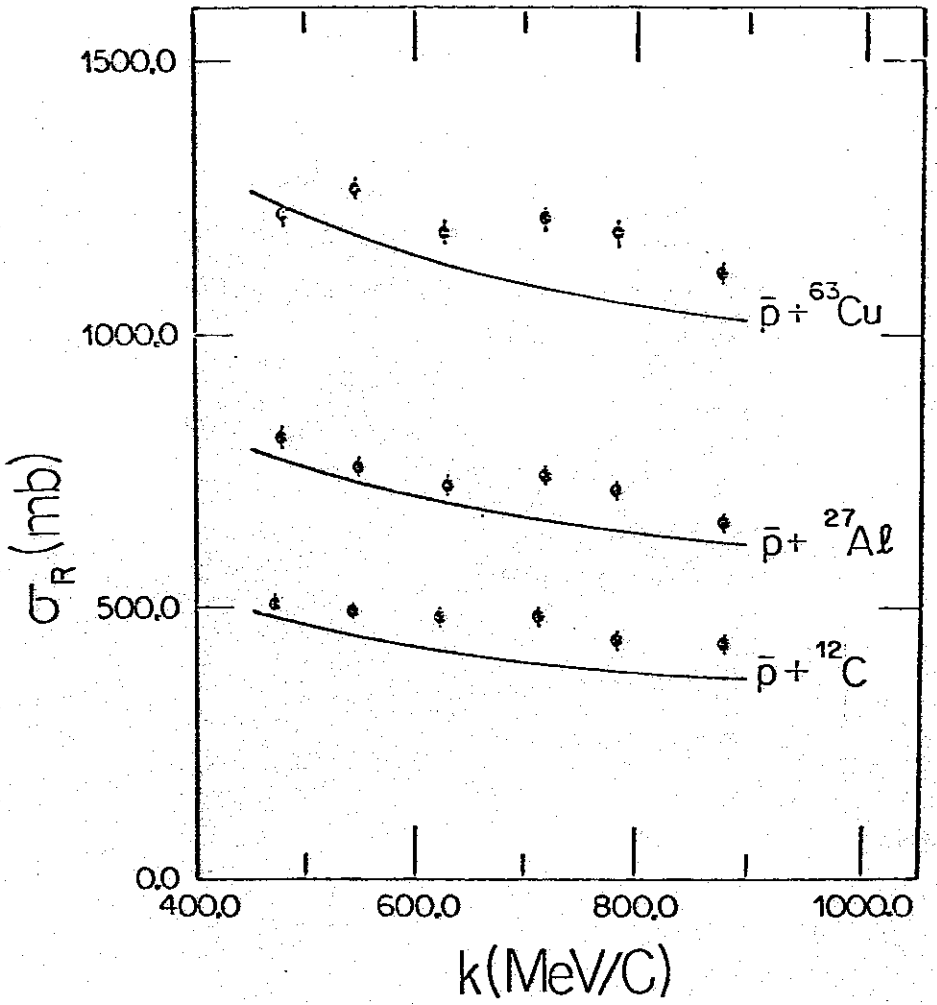
1500.0
1000.0
500.0
0.0
400.0
600.0
800.0
1000.0
σ_R (mb)
k(MeV/C)
$\bar{p} + {}^{63}Cu$
$\bar{p} + {}^{27}Al$
$\bar{p} + {}^{12}C$

Fig. 3