Scattering of low-energy antiprotons by carbon and oxygen nuclei

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The differential cross sections for elastic scattering of low-energy antiprotons by ^{12}C and ^{16}O nuclei have been calculated. The cross sections for level excitation by low-energy antiprotons have also been calculated. The results agree with experimental data obtained at 46.8 MeV on the LEAR antiproton storage ring. The differential cross sections for the excitation of a nucleus with a given spin projection are predicted. These cross sections determine the angular distributions of γ rays from $(\bar{p}, \bar{p}\gamma)$ reactions induced by nuclei.

A recent experiment carried out on the LEAR antiproton storage ring[1] has yielded the first measurement of the differential cross section for the elastic scattering of the $\bar{p}$ with an energy of 46.8 MeV by a ^{12}C nucleus and also the cross section for the excitation of low-lying levels of the residual nucleus. It follows from the experimental data that the elastic scattering of the $\bar{p}$ by the ^{12}C nucleus at this energy exhibits a clearly defined diffractive behavior (in contrast with the scattering of protons of the same energy). The ^{12}C levels are observed against a much fainter background than in the $^{12}C(p, p')^{12}C^*$ reaction.

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In this letter we show that these results can be described surprisingly well in the Glauber approximation. This approach has proved extremely successful in describing corresponding processes in the scattering of high-energy π mesons and protons by nuclei.[2] The energies of the antiprotons in the experiments which we are discussing here are low (a few tens of MeV), so that it might be expected that the Glauber approximation would not work well in this case. However, the amplitude for the elementary $\bar{p}p$ scattering in this case (in contrast with pp and πp scattering) has a sharply defined forward directionality; with decreasing energy, the slope of the cone increases[1)] (by way of comparison, the slope of the cone in $\bar{p}p$ scattering at 46.8 MeV is[5] 35.6 GeV^{-2}, the cross section for pp scattering is essentially isotropic at this energy,[6] and the slope of the cone for pp scattering at higher energies does not exceed $\lesssim 6$ GeV^{-2}). This fact may be taken as the reason why the range of applicability of the Glauber approximation, down to very low energies of the incident antiprotons (this assertion undoubtedly require further study). As for nonadiabatic corrections, we note that they have been shown[7] to be canceled to a large extent by the descent of the amplitude for the elementary process from the mass shell. The application of the Glauber theory to $\bar{p}d$ scattering at low and intermediate energies has yielded reasonable results.[8]

In the Glauber approximation, the amplitude for elastic scattering by a nucleus A can be written in the standard form[2]

$$F_{ii}(\mathbf{q}) = ik \int_0^\infty (1 - \exp(i\chi(b)) J_0(qb) b\,db, \tag{1}$$

where

$$\chi(b) = \frac{A}{2\pi k} \int e^{-i\mathbf{qb}} f_N(q)\, \Phi(q)\, d^2q\,. \tag{2}$$

Here Φ (q) is the elastic form factor of the nucleus, parametrized as follows[9] (for $4 \leqslant A \leqslant 16$):

$$\Phi(q) = \left(1 - \frac{A-4}{6A} R^2 q^2\right) \exp\left(-\frac{R^2 q^2}{4}\right), \tag{3}$$

where q is the momentum transferred to the nucleus, and k is the momentum of the incident hadron. Here $R^2 = 2.50\ \text{F}^2$ for ^{12}C and $R^2 = 2.92\ \text{F}^2$ for ^{16}O (Ref.9).The amplitude for scattering by the nucleon is

$$f_N(q) = \frac{k\sigma(i+\epsilon)}{4\pi}\, e^{-\frac{1}{2}Bq^2} \tag{4}$$

At the energy $E_{\bar{p}} = 46.8$ MeV we use the following parameters for the $\bar{p}N$ amplitudes[5,10]: $\sigma_{\bar{p}p} = 240$ mb, $\sigma_{\bar{p}n} = 200$ mb, $\epsilon_{\bar{p}p} = \epsilon_{pn} = -0.25$, and $B_{\bar{p}p} = B_{\bar{p}n} = 35.6$ $(\text{GeV}/c)^{-2} = 1.4\ \text{F}^2$. We find a value for $\sigma_{\bar{p}n}$ by working from the value of[11] $\sigma_{\bar{p}d} = 380$ mb, allowing for the Glauber screening correction.[2]

The amplitude for inelastic scattering accompanied by excitation of a nuclear level of natural parity, spin J, and spin projection (M) onto the direction of the incident beam is expressed in terms of the electromagnetic form factor of the transition and the elastic-scattering amplitude in the approximation of a single inelastic collision.[12] The expression derived in Ref. 12 for the amplitude is conveniently rewritten

$$F_{fi}^{M}(q) = \frac{2\sqrt{\pi}A}{\sqrt{2J+1}} f_N(0)(-1)^M Y_{JM}^{*}\left(\frac{\pi}{2}, 0\right) \int_0^\infty \widetilde{S}_{JM}(b)\, e^{i\chi(b)} J_M(qb)\, b\,db, \tag{5}$$

where

$$\widetilde{S}_{JM}(b) = \int_0^\infty S_J(q)\, e^{-\frac{1}{2}Bq^2} J_M(bq)\, q\,dq\,; \tag{6}$$

here $S_J(q)$ determines the form factor of the inelastic transition and is parametrized

$$S_J(q) = q^J (a_1 + b_1 q^2 + c_1 q^4)\, e^{-\alpha q^2}, \tag{7}$$

so that the integral in (6) can be evaluated analytically. The parameters in (7) are known from data on inelastic electron scattering. We used the following values: $a_1 = 0.25$, $b_1 = -0.021$, $c_1 = 0.0004$, and $\alpha = 0.54$ [q in expression (7) is in units of reciprocal femtometers] for excitation of the 2^+ level (4.44 MeV) of the ^{12}C nucleus[13]; and $a_1 = 0.195$, $b_1 = -0.008$, $c_1 = 0$, and $\alpha = 0.8125$ for excitation of the 3^- level (6.13 MeV) of the ^{16}O nucleus.[14] In Eqs. (1) and (5) we have made the changes required to allow for the difference between the amplitudes for scattering by the proton and the

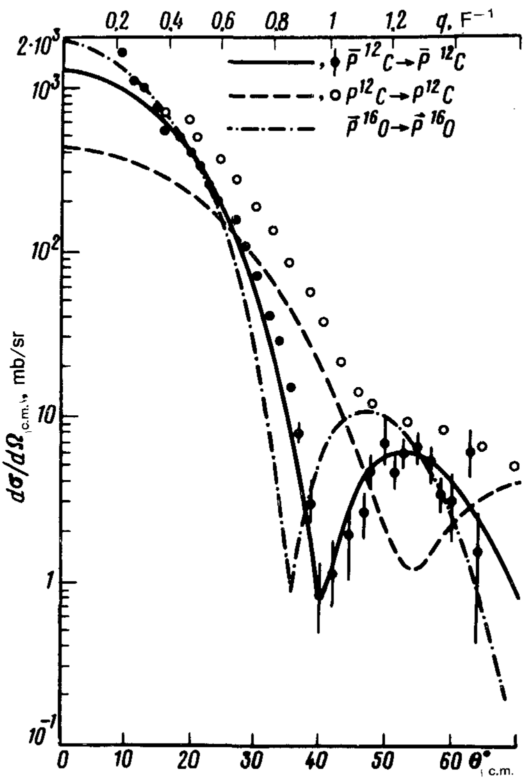

FIG. 1. Differential cross sections for elastic scattering at a beam energy $E = 46.8$ MeV for $\bar{p}^{12}C$, $p^{12}C$, and $\bar{p}^{16}O$; the experimental data are from Ref. 1.

neutron. Amplitudes (1) and (7) were multiplied by a factor exp $(q^2R^2/4A)$ to allow for recoil of the nucleus. For comparison, we carried out calculations on the scattering of protons of the same energy by ^{12}C with the following parameters for the pN amplitudes[6]: $\sigma_{pp} = 44$ mb, $\sigma_{pn} = 204$ mb, $\epsilon_{pp} = 1.85$, $\epsilon_{pn} = 0.25$, and $B_{pp} = B_{pn} = 0$.

Figure 1 shows the calculated cross sections for elastic scattering of $\bar{p}$ and p by ^{12}C. The calculated results (the solid curve) agree well with the antiproton data. On the other hand, the calculated proton cross section (dashed curve) is markedly at odds with experiment.[1] We believe that this circumstance confirms that the good description of the antiproton data by the Glauber theory is not simply fortuitous but instead a consequence of the particularly narrow cone in $\bar{p}N$ scattering. Also shown in Fig. 1 are the predictions for elastic scattering of the $\bar{p}$ by ^{16}O (dot-dashed curve).

Figure 2 shows results calculated on the cross sections for the inelastic scattering of $\bar{p}$ and p by ^{12}C accompanied by the excitation of the 2^+ level (4.44 MeV). There is a satisfactory description of the antiproton data (the solid curve). In the case of the proton data, the calculated results (dashed curve) do not agree with experiment, as we found in the case of elastic scattering.

Also shown in Fig. 2 are predictions for the antiproton cross sections with spin projections (M) of the excited nucleus onto the beam axis of 0 and 2 $((d\sigma)/$

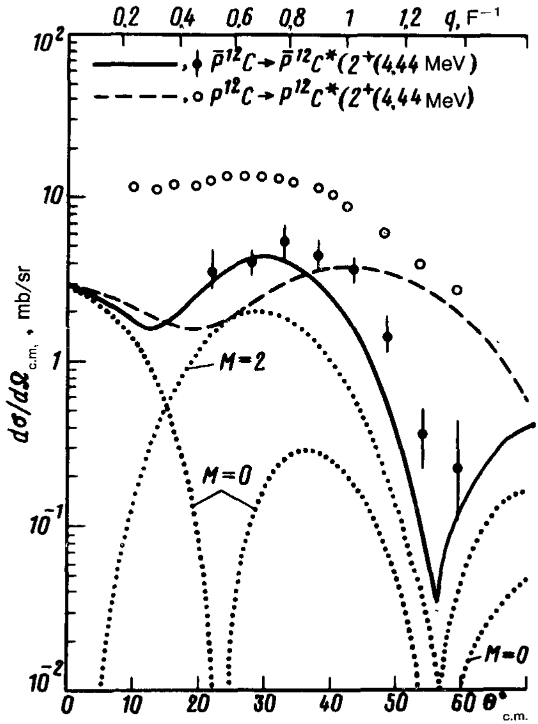

FIG. 2. Differential cross section for inelastic scattering of $\bar{p}$ and p ($E = 46.8$ MeV) by ^{12}C, accompanied by excitation of the 2^+ level (4.44 MeV). The dotted curves are the cross sections $d\sigma_0/d\Omega$ and $d\sigma_2/d\Omega$ with projections $M = 0$ and 2 of the spin of the $^{12}C^*$ (2^+) nucleus onto the beam axis $2[(d\sigma/d\Omega) = (d\sigma_0/d\Omega) + 2(d\sigma_2/d\Omega)]$. The experimental data are from Ref. 1.

$(d\Omega) = (d\sigma_0)/(d\Omega) + 2(d\sigma_2)/(d\Omega)$; according to the Glauber approach, $d\sigma_1/d\Omega = 0$). Measurements of these cross sections, which have an extremely complicated angular dependence, as can be seen from this figure, would provide a more detailed test of the theory. The cross section $d\sigma_M/d\Omega$ can easily be found from the distribution of γ rays emitted in the reaction $^{12}C(\bar{p}, \bar{p}\gamma)^{12}C$, accompanied by a transition of the $^{12}C^*(2^+)$ nucleus to the ground state. These experiments have been carried out[15] (the data of Ref. 15 were cited in Ref. ^{16}O nucleus in high-energy π and p beams. Expressions for the angular distributions of γ rays in terms of the cross sections $d\sigma_M/d\Omega$ for these nuclei and these levels are given in Ref. 17.

There are several factors which might explain why the antiproton data are slightly higher than the calculated values in Fig. 2 at $\theta > 35°(q > 0.8\ F^{-1})$: a) uncertainties in the transition form factor (7), b) a worsening of the Glauber approximation in the case of large-angle scattering, and c) a collective nature of the 2^+ excited level, with the result that the approximation of a single inelastic collision is invalid. In connection with possibility c) we note that experimental data have also been found to be higher than the calculations based on the approximation of a single inelastic collision in a region to the right of the maximum in the cross section for excitation of the $^{16}O^*(3^-;$ 6.13 MeV) level ($M = 1$) by high-energy π mesons. This discrepancy disappears if the model assumes the 3^- level (6.13 MeV) to be collective (rotational); these calculations were carried out without the approximation of a single inelastic collision but in the Glauber theory (see Fig. 8 in Ref. 16). It would therefore be of definite interest to carry

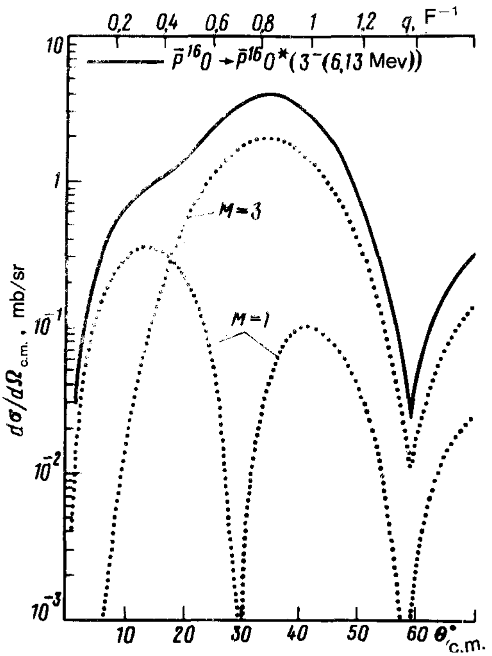

FIG. 3. Differential cross section for the inelastic scattering of the $\bar{p}$ ($E_{\bar{p}} = 46.8$ MeV) by ^{16}O, accompanied by excitation of the 3^- level (6.13 MeV). The dotted curves are the cross sections $d\sigma_1/d\Omega$ and $d\sigma_3/d\Omega$ with projections $M = 1$ and 3 of the spin of the ^{16}O nucleus (3^-) onto the beam axis $[(d\sigma/d\Omega) = 2(d\sigma_1/d\Omega) + 2(d\sigma_3/d\Omega)]$.

out a corresponding study for the interaction of antiprotons with nuclei.

Figure 3 shows predictions of the cross sections for the reaction $\bar{p}^{16}O \rightarrow \bar{p}^{16}O^*(3^-; 6.13\ MeV)$. We might note that the value of the cross section $d\sigma_1/d\Omega$ at the first maximum is three times that of the second, while in the case of a beam of high-energy hadrons the first maximum was essentially unobservable (smaller than the second by a factor of 10–30; see Figs. 6–9 in Ref. 16).

It can thus be seen from the figures in the present paper that the theoretical curves agree well with the experimental antiproton data available. The parameters of the elementary amplitude for $\bar{p}N$ scattering which are required for these calculations will be measured very accurately in the near future in experiments on the LEAR antiproton storage ring. This improved accuracy will in turn improve the accuracy of the calculations of the present paper. Calculations on the elastic and inelastic scattering of the $\bar{p}$ by nuclei over a broad energy range, calculations of the angular distributions of γ rays in $(\bar{p}, \bar{p}\gamma)$ processes, and calculations of other characteristics will be published in a detailed paper.

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[1)]The appearance of such a narrow cone at low energies and its contraction with decreasing energy occur because even at the lowest energies the contributions of several partial waves corresponding to a nonzero orbital angular momentum are important in $\bar{N}N$ scattering. As was shown in Ref. 3, this phenomenon is a consequence of not annihilation processes but the presence of a spectrum of quasinuclear $\bar{N}N$ states corresponding to a nonvanishing orbital angular momentum l of the relative motion of the N and $\bar{N}$ (these levels exist in essentially all spin-isospin states).[4] This factor is responsible for the significant increase in the contribution of partial waves with l up to 3 in low-energy $\bar{p}p$ scattering.

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