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Black body description of antiproton-nucleus scattering

J. Lichtenstadt and A. I. Yavin
School of Physics and Astronomy, The Raymond and Beverly Sackler Faculty of Exact Sciences, Tel Aviv University, Tel Aviv, Israel

S. Janouin, P. Birien, G. Bruge, A. Chaumeaux, D. Drake,* D. Garreta, D. Legrand, M. C. Lemaire, B. Mayer, J. Pain, and J. C. Peng*
Departement de Physique Nucléaires/Moyenne Energie, Centre d'Etudes Nucléaires de Saclay, France

M. Berrada, J. P. Bocquet, E. Monnand, J. Mougey, and P. Perrin
Departement de Recherche Fondamentale, Centre d'Etudes Nucléaires de Grenoble, France

E. Aslanides and O. Bing
Centre de Recherche Nucléaires, Strasbourg, France

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Angular distributions for elastic scattering of antiprotons from nuclei are analyzed in terms of a fuzzy black disk model. Data from ^{12}C, ^{16}O, ^{18}O, and ^{40}Ca at incident antiproton energies of 47 and 180 MeV are analyzed. The obtained fits are qualitatively good concerning the slope and position of the extrema, but are too deep in the minima.

We examine in this Brief Report the degree of blackness of the nucleus to incident antiprotons. Its purposes are twofold: (a) to show that the nucleus represents a black obstacle to an impinging antiproton, most likely more so than to any other particle (proton, alpha, pion, etc.); and (b) to point out that some features of the data are not explained by such a simple model, and more elaborate optical model analyses are called for.

Experiments of elastic scattering of antiprotons from nuclei have recently been performed at the Low Energy Antiproton Ring (LEAR) in CERN.[1,2] They yielded high quality data from which new information was derived about the $\bar{\mathrm{p}}$-nucleus interaction.[3,4] Specifically, the new experimental data extended the study of $\bar{\mathrm{p}}$-A optical potentials beyond "zero incident energy," which is the domain of $\bar{\mathrm{p}}$ atoms[5] and set meaningful limits on the depths of the real and imaginary potentials as well as on their geometrical parameters.[1,2] Furthermore, using a Fourier-Bessel expansion technique for the optical potential, these potentials could be determined with less *a priori* bias on their shape.[6,7] With the aid of this technique, realistic uncertainties could also be obtained for the potential values along the nuclear radius. All the optical analyses[1,2,6,7,11] of the elastic scattering data showed that a span of potential parameters could be used with good fits to the data, and that the resulting potentials were largely undetermined inside the strong interaction radius.

Two features clearly emerge from these analyses, namely, that the antiproton is strongly absorbed near the nuclear surface, and that the real potential is weaker in comparison with the imaginary one. Such features suggest that antiproton scattering from nuclei may approach the limit of "black disk scattering," and that this simple model could show some of the main characteristics of $\bar{\mathrm{p}}$-A scattering. While this model cannot be directly related to the basic nucleon-antinucleon interaction, it is felt that such an analysis is at least of heuristic value.

We present in this Brief Report the analysis of the recent elastic antiproton scattering data in terms of a fuzzy black disk model. The data include the angular distributions from ^{12}C and ^{40}Ca at incident antiproton energies of 47 and 180 MeV,[1,2] and of ^{16}O and ^{18}O at 180 MeV.[8]

The differential cross section in the c.m. frame for scattering from a black disk is given by

$$\sigma_{bd}(\theta)=|f_0(\theta)|^2=(kR^2)^2\left(\frac{J_1(x)}{x}\right)^2 , \tag{1}$$

with

$$x=2kR\sin(\theta/2) , \tag{2}$$

where k is the $\bar{\mathrm{p}}$ momentum, θ is the scattering angle, and R is the black disk radius. Various authors[9,10] have discussed the effect of surface diffuseness on the black disk scattering amplitude $f_0(\theta)$. Following Inopin and Berezhnoy[10] this effect takes a simple form, and is expressed by a function $F(\theta)$ so that

$$f(\theta)=f_0(\theta)F(\theta) . \tag{3}$$

Assuming a Gaussian shape for this diffuseness function, $F(\theta)$ takes the form

$$F(\theta)=e^{-\Delta^2k^2\sin^2(\theta/2)} , \tag{4}$$

with the scattering cross section given by

$$\sigma=\sigma_{bd}|F(\theta)|^2 . \tag{5}$$

In our fits to the data the black disk radius R and the diffuseness (fuzziness) parameter Δ were treated as free parameters. In each case, R is determined essentially by the locations of the diffraction minima of the angular distribution, and the diffuseness parameter Δ by its overall slope. The calculated cross sections [Eq. (5)] were averaged over the experimental angular resolution (ranging from 2°–4° in the various measurements) to account for the experimental conditions. This had the effect of smoothing the sharp

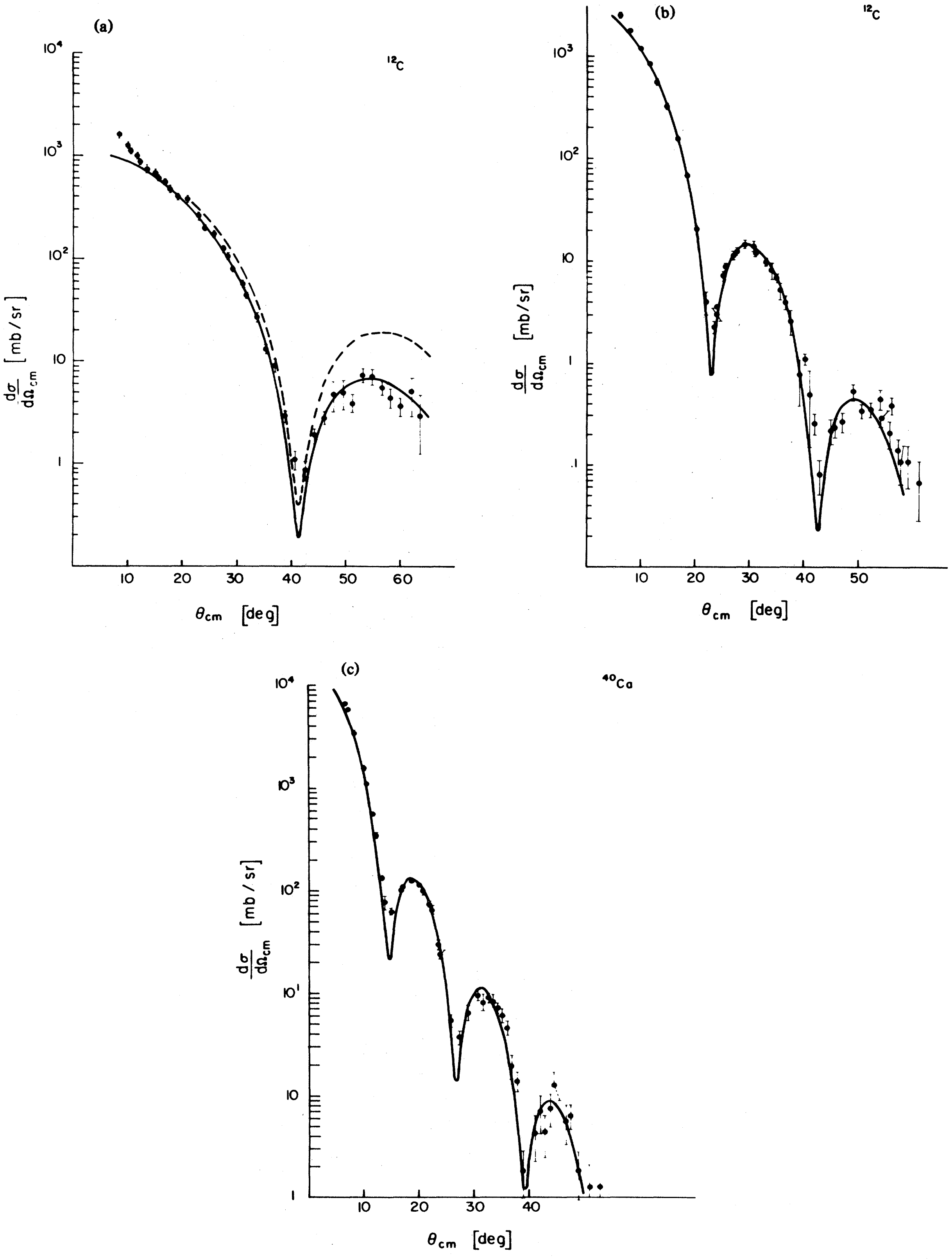

FIG. 1. (a) $\bar{p}+{}^{12}C$ at $T_{\bar{p}}=47$ MeV. Dashed line is black disk calculation with $\Delta=0$; and solid line with $\Delta=1.12$ fm; $R=3.91$ fm for both curves. (b) $\bar{p}+{}^{12}C$ at $T_{\bar{p}}=180$ MeV. Solid line is black disk calculation with $R=3.47$ fm and $\Delta=1.08$ fm. (c) $\bar{p}+{}^{40}Ca$ at $T_{\bar{p}}=180$ MeV. Solid line is black disk calculation with $R=5.09$ fm and $\Delta=1.13$ fm.

TABLE I. Radii and diffuseness parameters from black disk fits.

Energy (MeV)	Target	R (fm)	Error (%)	$R/A^{1/3}$ (fm)	Δ (fm)	Error (%)	χ^2/n (*fbd*)	χ^2/n (opt. mod.)
47	^{12}C	3.91	1.0	1.71	1.12	3.0	2.4	0.7
47	^{40}Ca	5.56	1.0	1.63	1.09	4.0	5.7	0.7
180	^{12}C	3.47	0.3	1.52	1.08	1.0	2.4	0.8
180	^{16}O	3.79	0.5	1.50	1.09	1.0	1.9	0.8
180	^{18}O	3.91	0.5	1.49	1.17	1.0	2.2	0.9
180	^{40}Ca	5.09	0.5	1.49	1.13	1.0	2.3	0.6

zeros of the $J_1(x)$ function. The best fit curves for ^{12}C and ^{40}Ca for incident antiproton energies of 47 and 180 MeV are shown in Fig. 1. It can be seen that the fits are good, except for the depths of the minima and the small scattering angles data at 47 MeV, where the cross sections are dominated by Coulomb scattering, not accounted for in our simple model. When these small angle cross sections were omitted from the fit, the χ^2/n improved, while the values of R and Δ essentially did not change. The effect of the surface diffuseness is seen in Fig. 1(a), where we also show the results of a sharp black disk calculation ($\Delta=0$) for comparison. Equally good fits were also obtained for ^{16}O and ^{18}O, at incident antiproton energy of 180 MeV. The data obtained for ^{208}Pb were not included in the analysis here because of the large effect of Coulomb scattering. We note in Table I that although the fits are qualitatively good, the χ^2/n are worse than those obtained in the optical potential anlayses.[1,2,11] This is not surprising in view of the simple assumptions involved in the black disk calculation.

The best fit values for the black disk radii and diffuseness parameters are also given in Table I. These radii are consistent with those determined from the optical potential analyses.[1,2,6,7,11] They can be parametrized by $R=R_0A^{1/3}$ with $R_0=1.5$ fm at 180 MeV and 1.7 fm at 47 MeV. The best fit values for Δ show that the width of the diffuseness function[10] is about 1.1 fm at both energies, for all the nuclei included in this analysis. Such a nonzero diffuseness indicates some penetrability into the nucleus.

In conclusion, the fuzzy black disk analysis is in agreement with the results of the optical model analyses,[1,2,6,7,11] i.e., that the information contents in the $\bar{\text{p}}$-A angular distributions is limited to the exterior of the nucleus, with only a small degree of penetrability, as demonstrated by the disk diffuseness. We recall that similar conclusions about the blackness of the nucleus were reached following the early alpha-scattering experiments[12] around 40 MeV. However, the relatively large χ^2/n values obtained with the fuzzy black disk analysis as well as its inability to reproduce the depth of the observed minima indicate that a more refined optical model analysis is still necessary.

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[*] Present address: Los Alamos National Laboratory, Los Alamos, NM 87544.

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