INFLUENCE OF COULOMB ATTRACTION ON THE CROSS SECTION FOR ABSORPTION OF ANTIPROTONS BY NUCLEI

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We investigate the effect of the Coulomb attraction of the nucleus on the cross section for the absorption of antiprotons whose energy is small compared with the Coulomb energy on the boundary of the nucleus. The interaction of antiprotons with nuclei is analyzed in the optical model. The calculations are carried out for C, Cu, and Pb, with attraction and repulsion potentials. It is shown that because of the Coulomb attraction the cross section for antiproton absorption, at energies below Coulomb values, is 4 to 10 times greater than the cross section for antineutrons at the same energy.

IT is known[1] that the cross sections for the interaction of antinucleons with nuclei exceed considerably the nuclear cross sections for protons and neutrons. Starting with the cross sections for the elementary nucleon-antinucleon act, we can explain the interaction between fast antinucleons and nuclei with the aid of the optical model. For antiprotons with energies comparable with the Coulomb energy on the boundary of the nucleus, the cross sections for absorption by the nucleus are substantially increased because the Coulomb field focuses the trajectories of the antiprotons in the region of the nucleus. This effect can be calculated within the framework of the optical model of the nucleus.

The calculations that follow can be used for all negatively charged particles which are strongly absorbed, particularly those for which the wavelength $\lambda\!\!\!^-$ at energies on the order of the Coulomb energy V_c on the boundary of the nucleus is small compared with the nuclear radius R:

$$\lambda\!\!\!^- (R) = \hbar/\sqrt{2\mu V_c(R)} \ll R \qquad (1)$$

(μ — reduced mass of the particle and nucleus).

The antiproton is acted upon inside the nucleus by a complex potential, whose dependence on the radius r can be assumed to be identical with the dependence of the nucleon-nucleus complex potential on r. In the present investigation we consider both the nuclear attractive potential (negative real part of the complex potential), and the nuclear potential of repulsion (positive real part). We consider attraction first.

The nuclear potential diminishes on the boundary of the nucleus gradually.[2,3] This is due to the finite radius of the NN and $N\bar{N}$ interaction and to the gradual decrease in nuclear density on the boundary of the nucleus. Such a potential leads to a larger coefficient of adhesion of the antiproton than a potential with a sharp edge. However, when $E \ll V_c(R)$ (E is the total energy of the antiproton in the c.m.s. of the antiproton and nucleus), the presence of a Coulomb interaction decreases the difference between these two cases. A calculation of the adhesion coefficient for the S-wave shows that a potential of the type

$$W = \begin{cases} -U_0(1+i\zeta) & 0 \leqslant r \leqslant r_0, \\ -U_0 e^{-\alpha(r-r_0)} & r_0 \leqslant r \leqslant R, \\ -Ze^2/r & R \leqslant r, \end{cases}$$

$$1/\alpha = 0.7\cdot10^{-13}\ \text{cm},\ r_0 = R - 1/\alpha, \qquad U_0 = \text{const} \qquad (2)$$

(U_0 includes in addition to the nuclear potential also the electrostatic potential of the antiproton in the nucleus) and

$$W = \begin{cases} -U_0(1+i\zeta) & 0 \leqslant r \leqslant R, \\ -Ze^2/r & R \leqslant r \end{cases} \qquad (3)$$

leads to results that differ by not more than 10%. At the same time, one can obtain for the potential (3) (rectangular well) an exact solution of the Schrödinger equation within the region of the nucleus.

The imaginary part of the complex potential should be much greater for antiprotons than for nucleons. Actually, when slow nucleons interact with the nucleus, the exclusion principle limits the possibility of momentum transfer to the intranuclear nucleons. This limitation is inessential in the case of antinucleons, for which annihilation plays the decisive role (it appears partially only in non-annihilation collisions).

The calculation has been made with the potential (3), using $R = 1.25 \times 10^{-13} A^{1/3}$ cm for the radius of the nucleus. The imaginary part of the potential was set equal to $-(U_0 - V_C)$, and the Coulomb potential was replaced by its value on the boundary of the nucleus. This simplification barely affects the result, which depends little on the real part of the potential.

When $r \leq R$, the solution of the Schrödinger equation can be expressed in terms of spherical Bessel functions. When $r \geq R$ the solution can be written in the quasi-classical approximation in the form

$$\Psi(r, \theta) = \sum_{l=0}^{\infty} \frac{B_l}{\sqrt{r P_r(r)}} \left\{ \exp\left[-\frac{i}{\hbar}\int P_r(r)\,dr\right] - \eta_l \exp\left[\frac{i}{\hbar}\int P_r(r)\,dr\right]\right\} Y_{l0}(\theta), \qquad (4)$$

$$P_r(r) = \{2\mu\,[E - W(r) - \hbar^2(l + {}^1/_2)^2/2\mu r^2]\}^{1/2}. \qquad (4')$$

The amplitude η_l of the scattered antiproton wave is found by fitting together the logarithmic derivatives of the wave functions with indices l.

In the case of a Coulomb potential, the quasi-classical approximation is applicable down to small distances, determined by the centrifugal potential. The condition for a quasi-classical solution on the nuclear boundary at zero energy of the incoming particle can be written in the form

$$R > \frac{\hbar}{2\mu C}\left(\frac{\hbar C}{e^2}\right)\frac{l(l+1)+1}{Z} \approx 1.37\cdot 10^{-12}\,\frac{l(l+1)+1}{Z}\,\text{cm}, \qquad (5)$$

from which we obtain for C, Cu, and Pb $l \leq 0$, $l \leq 2$, and $l \leq 5$, respectively. When $E > 0$, solution (4) is applicable for the indicated values of l down to $r = R$.

The absorption cross section can be estimated also for values of l that do not satisfy condition (5). Let us consider an uncharged particle with energy equal to the kinetic energy of the antiproton on the boundary of the nucleus, that is, with $E' = E + Ze^2/R$. The coefficient of adhesion of a particle with energy E' and a momentum l will be somewhat greater than for an antiproton of energy E, owing to the greater perveance of the centrifugal barrier in the former case. It follows therefore that this method of calculating the coefficients of adhesion gives the upper limit of the partial cross sections.

Calculation shows that in the case of carbon the values of l that do not satisfy (5) can yield a large contribution. Their contribution for copper, and particularly for lead, is insignificant.

Table I lists the calculated cross sections for the absorption of antiprotons by nuclei at $E = 0.5$ Mev.

For comparison, we calculated the absorption cross sections of antineutrons with $E = 0.5$ Mev. The parameters of the complex potential were taken to be the same as for the antiprotons, and there was no Coulomb field. The results of the calculation are listed in Table II. It should be noted that the adhesion coefficient for antiprotons remains practically constant for energies less than 0.5 Mev.

TABLE I

Nucleus	U_0, Mev	Value of l contributing to the cross section	σ_c^{max}, b
C^{12}	33	⩽1	3.2
Cu^{63}	38	⩽3	11.2
Pb^{208}	43	⩽5	⩾18

TABLE II

Nucleus	U_0, Mev	Value of l contributing to the cross section	σ_c, b	$\sigma_c^{max}(\bar{p}) / \sigma_c(\bar{n})$
C^{12}	30	⩽1	0.82	4
Cu^{63}	30	⩽2	1.12	10
Pb^{208}	30	⩽3	2	~10

The relation $\sigma_C = \text{const.}\ v^{-2}$ is satisfied for this energy interval, in agreement with the general quantum-mechanical premises for inelastic processes.[4]

The antiprotons moving in matter collide not with the nuclei, but with the atoms. Therefore, for very slow antiprotons with wavelengths on the order of the radii of the first atomic shells, the nuclear charge is partially screened and antiprotons with orbital momenta other than zero are no longer focused by the Coulomb field. However, the antiproton energy below which partial screening takes place is very low. Thus, for antiprotons with $l = 1$, in the case of lead, this energy is 100 ev, since $\lambda\!\!\!^-$ of the antiproton is equal to the radius of the K shell of lead at 100 ev.

We consider now the absorption cross section for copper under the assumption that the real part of the nuclear potential is positive. We assume here that $U_0 + V_C = 30$ Mev, and retain the same imaginary part, that is, -30 Mev. The absorption cross section of antiprotons for $E = 0.5$ Mev is found here to be 6 barns instead of 10 barns for the attraction potential. Thus, in the presence of a reasonable repulsion potential, the absorption cross section is still much greater than the geometrical cross section.

[1] Agnew, Chamberlain, Keller, Mermod, Rogers, Steiner, and Wiegand, Phys. Rev. **108**, 1545 (1957).

[2] A. E. Glassgold, Phys. Rev. **110**, 220 (1958).

[3] P. É. Nemirovskiĭ, Dokl. Akad. Nauk SSSR 112, 411 (1957), Soviet Phys.-Doklady **2**, 45 (1957).

[4] L. D. Landau and E. M. Lifshitz, Квантовая механика (Quantum Mechanics) 1948, p. 497 (Engl. Transl., Pergamon, 1958).

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