Electromagnetic Annihilation of Antiprotons

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(Received December 27, 1955; revised manuscript received May 1, 1956)

The familiar model of a nucleon as a Dirac particle with Pauli anomalous magnetic moment is used to obtain cross sections for antiproton annihilation into two photons, two electrons, or two muons. The two-photon lifetime of the $n\,^1S_0$ state of the proton-antiproton atom is $\approx 2\times 10^{-15}n^3$ sec.

As a consequence of the observation of antiprotons at Berkeley,[1] it may be of interest to note the cross sections for electromagnetic annihilation of Dirac particles possessing anomalous magnetic moments. These cross sections are small compared to the unknown relevant cross sections for annihilation into pions. Since they are obtained by standard methods,[2] we have omitted details of the calculation.

I. TWO-PHOTON ANNIHILATION

In the c.m. system, βc is the velocity of the antiproton and θ is the acute angle between photon and proton directions. $r_0=e^2/Mc^2$, with M the nucleon mass; $\omega^2=(1-\beta^2)^{-1}$; $\eta=(1-\beta^2\cos^2\theta)^{-1}$. The differential cross section is

$$\begin{aligned}d\sigma=\pi r_0^2 \sin\theta d\theta(4\beta\omega^2)^{-1}&\\ \times\{[\eta(1+\beta^2+\beta^2\sin^2\theta)-2\eta^2\beta^4\sin^4\theta]&\\ +\lambda[4\eta]+\lambda^2[4\omega^2+\eta]+\lambda^3[4\omega^2-2\eta]&\\ +\lambda^4[(4\eta)^{-1}\omega^4+\tfrac{1}{2}(\omega^2-\eta)]\}.&\quad(1)\end{aligned}$$

The first term in square brackets is the usual pair-annihilation formula. The remaining terms represent the effect of the anomalous moment λ. This result has been obtained, in essence, by Powell,[3] who calculated Compton scattering and bremsstrahlung by protons. In contrast to Powell's cases where the effects were small at small energies, the anomalous moment here gives very large effects even for β near zero.

The total cross section (c.m. system) is

$$\begin{aligned}\sigma=\pi r_0^2(2\beta\omega^2)^{-1}\{[\beta^2-2+(3-\beta^4)\mathcal{L}]&\\ +\lambda[4\mathcal{L}]+\lambda^2[4\omega^2+\mathcal{L}]+\lambda^3[4\omega^2-2\mathcal{L}]&\\ +\lambda^4[\tfrac{1}{12}(2\omega^4+7\omega^2)-\tfrac{1}{2}\mathcal{L}]\},&\quad(2)\end{aligned}$$

with

$$\mathcal{L}=(2\beta)^{-1}\log[(1+\beta)/(1-\beta)].$$

In the nonrelativistic limit, this becomes

$$\sigma_{\rm NR}=\pi r_0^2(c/v)X,\tag{3}$$

where the relative velocity $v=2\beta c$ and

$$X=1+4\lambda+5\lambda^2+2\lambda^3+\tfrac{1}{4}\lambda^4=38.5.\tag{3a}$$

II. TWO-ELECTRON OR TWO-MUON ANNIHILATION

In the c.m. system a proton and antiproton of mass M, anomalous moment λ_1, each having energy E and momentum p_0, annihilate, producing a pair of Dirac particles each with corresponding parameters m, λ_2, E, p. The angle between the proton momentum and that of the negative electron (or muon) is θ. The cross section for the negative electron or muon to go into solid angle $d\Omega$ at θ is

$$d\sigma=\tfrac{1}{2}\pi r_0^2(Mc^2/2E)^2(p/p_0)\sin\theta d\theta U,\tag{4}$$

where

$$\begin{aligned}U=3(1+\lambda_1)^2(1+\lambda_2)^2-(1+\lambda_1)^2G_2&\\ -(1+\lambda_2)^2G_1+G_1G_2\cos^2\theta,&\quad(4a)\end{aligned}$$

$$\left.\begin{aligned}G_1&=(p_0/E)^2-\lambda_1^2(p_0/M)^2,\\ G_2&=(p/E)-\lambda_2^2(p/m)^2.\end{aligned}\right.\quad(4b)$$

The total cross section is

$$\sigma=\pi r_0^2(Mc^2/2E)^2(p/p_0)U_T,\tag{5}$$

where U_T is U with $\cos^2\theta$ replaced by $\tfrac{1}{3}$.

In the nonrelativistic limit, $p_0\to 0$,

$$\sigma_{\rm NR}=\tfrac{1}{2}\pi r_0^2(c/v)(1-\gamma^2)^{\frac{1}{2}}U_{T,\rm NR}\tag{6}$$

with $\gamma=M/m$, $v=2p_0/E$, and

$$U_{T,\rm NR}=(1+\lambda_1)^2[2+\gamma^2+6\lambda_2+\lambda_2^2(2+\gamma^{-2})].\tag{6a}$$

Neglecting γ^2 and putting $\lambda_2=0$, we obtain

$$\sigma_{\rm NR}=\pi r_0^2(c/v)X',\tag{7}$$

with

$$X'=(1+\lambda_1)^2=7.8.\tag{7a}$$

If $\lambda_2=0$, the cross sections for electrons and for muons are identical up to term of order γ^4. The term $\lambda_2^2\gamma^{-2}\approx 4.5$ for electrons if λ_2 is taken to be the Schwinger moment $\alpha/2\pi$. However, use of this value is unjustified since the electron's anomalous moment is spread over the electron Compton wavelength and will produce a negligible effect upon the process considered here.

The results given here have been averaged over proton and antiproton spin states. For the spin-singlet configuration the lowest order electromagnetic annihila-

[1] Chamberlain, Segrè, Wiegand, and Ypsilantis, Phys. Rev. **100**, 947 (1955).

[2] For example, see R. P. Feynman, Phys. Rev. **84**, 108 (1951). We have used his notation and normalization. The Pauli moment has been included by replacing the vertex operator γ_μ by $\gamma_\mu+(\lambda k_\nu/4M)(\gamma_\mu\gamma_\nu-\gamma_\nu\gamma_\mu)$, where k_ν is the fermion's momentum transfer at the vertex and the anomalous moment is $\lambda e\hbar/2Mc$.

[3] J. L. Powell, Phys. Rev. **75**, 32 (1949).

tion into the electron or muon pairs vanishes for all energies.

III. PROTON-ANTIPROTON ATOM

As an application of the above formulas we consider the two-photon lifetime of the $n\ ^1S_0$ state of the protonic analog of positronium.[4] Using the approximation of Wheeler[5] and Eq. (3), we find

$$\tau_{2\gamma}=1.8\times10^{-15}n^3 \text{ sec.} \tag{8}$$

The effect of the Pauli moment here is to decrease the two-photon lifetime by the factor $X=38.5$. This will be reduced if the anomalous moment is spread over the pion Compton wavelength, rather than being an effective point moment as we have assumed.

It is a pleasure to acknowledge the assistance of Mr. Isadore Harris with these calculations.

[4] We have estimated the probability of slowing down in hydrogen or in heavy matter and of capture into atomic orbits in liquid hydrogen. We find that when Bevatron-produced antiprotons are slowed in heavy matter, then even if the high-energy cross section for annihilation in flight is twice geometric, at least a few percent of them will be captured into inner orbits so that the effects of selection rules will be observable. For slowing in liquid hydrogen we can make only a rough estimate. Using reasonable assumed annihilation and scattering cross sections, we find that at least thirty percent will probably be captured.

[5] J. A. Wheeler, Ann. N. Y. Acad. Sci. **48**, 219 (1946). For $l\neq0$, $\psi(0)$ vanishes and this method does not apply.

PHYSICAL REVIEW VOLUME 103, NUMBER 3 AUGUST 1, 1956

Effect of π-π Interaction on High-Energy π-p Scattering

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(Received December 19, 1955, revised manuscript received April 11, 1956)

The object of this paper is to examine the possibility of explaining the second maximum in (π-p) scattering in the framework of the Tamm-Dancoff approximation for (π-p) interaction, by postulating a resonant π-π interaction in the isotopic spin state $I=0$ of the π-π system. For this purpose the Tamm-Dancoff method in pseudoscalar theory, as formulated by Dyson and others, is first extended so as to include the effects of a π-π interaction. This is achieved by introducing a Green's function whose form is determined on the assumption of a zero-range π-π interaction in the state $I=0$ of the π-π system. The solution of the "modified" integral equation is greatly simplified by assuming the π-p interaction to be weak compared with the π-π interaction (the reasons for which are given). The total inelastic cross section is then derived by using the unitary property of the S matrix.

It is found that the Tamm-Dancoff approximation is unable to explain the (π-p) maximum on the basis of the proposed model. This is contrary to the result derived by other authors, who used the impulse approximation for the interaction of the incident meson with the meson cloud surrounding the nucleon.

1. INTRODUCTION

THE Brookhaven experiments on π-p scattering near 1 Bev have shown a definite maximum in the total π^--p cross section around this energy. There has been a natural tendency to explain this maximum as a resonant interaction. An attempt to explain it as a single-meson resonant state has so far given a negative result.[1] This perhaps may not be too surprising, for at this energy the inelastic processes play a very important part, so that their effects have to be taken into account more adequately than was possible in B. In fact the cross section for the production of an extra meson is larger than the elastic cross section above 1 Bev.

There was a suggestion by the Brookhaven theoretical group that a resonant $P_{\frac{3}{2},\frac{3}{2}}$ interaction of each of the two mesons with the nucleon in the final state might account for the observed maximum. However, such an explanation meets with the immediate difficulty that it gives rise to a nonzero contribution to the total $T=\frac{3}{2}$ state of the π-p system, as a result of which the π^+-p scattering would also show a maximum at the same energy. Since, on the other hand, such a maximum has not been observed, the strength of this argument is somewhat reduced. Dyson[2] has recently proposed another mechanism which successfully avoids the difficulty of enhancement in the $T=\frac{3}{2}$ state of the π-p system. He postulates a short-range π-π interaction in the state of isotopic spin $I=0$ of the meson-meson system.[3] Taking the impulse approximation for the interaction of the incident meson with the meson cloud surrounding the proton, he finds that the observed magnitude of the π^--p cross section can be explained on this basis. It is clear that this sort of interaction can affect only the state $T=\frac{1}{2}$ of the π-p system. Moreover, it involves no assumption about the relative angular momentum of the pion and the nucleon, so that a number of partial waves can be simultaneously affected.

A consequence of this hypothesis is that only neutrons

[1] A. N. Mitra, Phys. Rev. **99**, 957 (1955); referred to as B.

[2] F. J. Dyson, Phys. Rev. **99**, 1037 (1955).

[3] We are using the notation "I" for the total isotopic spin of the π-π system, as distinguished from "T" which stands for the total isotopic spin of the resultant π-p system.