Annihilation of antiprotons stopped in hydrogen

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The assumption that antiprotons stopped in hydrogen are annihilated directly from atomic states of the pp system contradicts the experimental data. The experimentally observed large contribution of the odd orbital momenta to the $p\bar{p}$ annihilation cross section can be attributed to the fact that the annihilation comes from the quasinuclear states of the $p\bar{p}$ system.

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It is customary to assume[1] that annihilation of stopped antiprotons in hydrogen proceeds directly from the atomic states of the $p\bar{p}$ system. It follows, however, from the results of recent theoretical[2] and experimental[3] investigations that in addition to the usual Coulomb atomic levels there can be formed in the $N\bar{N}$ system, owing to the strong interaction, also bound states of the quasinuclear type.[2] These states should manifest themselves in experiment as heavy mesic resonances with masses close to double the nucleon mass. Most quasinuclear mesons have nonzero orbital angular momenta of the relative motion of $N\bar{N}$. The purpose of the present paper is to explain the role of quasinuclear mesons in the annihilation of stopped antiprotons in hydrogen.

An investigation of the annihilation of the stopped $\bar{p}$ via the $p\bar{p}\to 2\pi^0$ channel (this reaction can proceed only from states of the $p\bar{p}$ system with odd orbital momenta) has shown that the contribution of the odd orbital momenta to the cross section of the two-pion $p\bar{p}$ annihilation amounts to approximately 40%.[4] Let us estimate the ratio of the annihilation widths of the $p\bar{p}$ atom for the P and S states of this atom. When $\bar{p}$ is stopped in hydrogen, it is captured by an atomic level having a radius on the order of the Bohr radius of hydrogen a_0, i.e., by a level with principal quantum number $n \sim 30$. The $p\bar{p}$ atom has a kinetic energy ~1 eV, corresponding to a velocity $v \sim 10^6$ cm/sec in liquid hydrogen. Owing to the radiative transitions and the external Auger effect, the antiproton then goes over to an orbit whose radius is small in comparison with a_0. When the $p\bar{p}$ atom moving in the hydrogen falls in the region of action of the electric field of the neighboring protons, a Stark mixing of n^2 degenerate levels of the $p\bar{p}$ atom takes place, including a mixing of the S and P states (the so-called Day-Snow-Sucher mechanism[5]). The frequency of the transitions between the mixed states, which is equal to the matrix element of the perturbation, is given by

$$V_e^{l-1} = < n, \ l-1|Fr|n, \ l > \sim \frac{e^2}{a_0^2} < n, \ l-1| r\cos\theta | n, \ l >$$
$$\sim 2n(n^2 - l^2)^{1/2} \cdot 10^{-2} \text{ eV}. \quad (1)$$

Here F is the intensity of the field acting on the antiproton, $F \sim e^2/a_0^2$. The reciprocal of the time of passage through the region of action of the electric field is of the order of

$$\tau^{-1} \sim \left(\frac{2}{3}\,\frac{2a_0}{v}\right)^{-1} \sim 10^{-1} \text{ eV}. \quad (2)$$

Therefore, for levels with $n \gtrsim 4$, the collision time is sufficient to permit many transitions between the mixed states.

Stark mixing for $\pi^- p$ and $k^- p$ atoms was considered in detail in[6], where it was shown, in particular, that the projection of the orbital angular momentum m is conserved in this mixing with high degree of accuracy. Thus, the S state is mixed with the $(n-1)$ states with $m=0$ and the cross section of the Stark mixing is of the order of

$$\sigma_{st}(n) \sim \frac{\pi a_0^2}{n}, \quad (3)$$

where a_0 characterizes the radius of the screened Coulomb field of the hydrogen atom, and the factor n^{-1} corresponds to the fact that in the case of total mixing of the n states the time-averaged probability of the atom being in any of them is equal to n^{-1}. The "Stark width" corresponding to the cross section (3) is equal to

$$\Gamma_{st}(n) \sim \frac{1}{n} vN\pi a_0^2 \sim \frac{2\cdot 10^{-3}}{n} \text{ eV}, \quad (4)$$

where $v \sim 10^6$ cm/sec is the velocity of the $p\bar{p}$ atom and $N = 4\times 10^{22}$ cm^{-3} is the density of the hydrogen atoms.

The annihilation width $\Gamma_a(n, l)$ of the atomic level of the $p\bar{p}$ system with principal quantum number n and orbital angular momentum l can be estimated from the formula

$$\Gamma_a(n, l) = v\sigma_a \rho(n, l), \quad (5)$$

where $\sigma_a \sim 50$ mb is the experimental annihilation cross section, $\rho(n, l)$ is the average particle density in the annihilation region $\rho(n, l) = |\Psi_{nl}(0)|^2$. Let us find $\Gamma_a(n, l)$ for the S and P levels, using the asymptotic form of the wave functions at short distances. For the S level we have

$$\Gamma_a(n, S) \approx \Gamma_a(1, S)\frac{\rho(1, S)}{\rho(1, S)} \sim \frac{\Gamma_a(1, S)}{n^3}. \quad (6)$$

For the P level we can write analogously

$$\Gamma_a(n, p) \approx \Gamma_a(2, P)\frac{\rho(n, P)}{\rho(2, P)} \sim \Gamma_a(2, P)\frac{32}{3}\,\frac{n^2-1}{n^5} \sim \frac{10\Gamma_a(2, P)}{n^3}. \quad (7)$$

Furthermore, $\Gamma_a(1, S)$ and $\Gamma_a(2, P)$ can be expressed in terms of the annihilation widths $\Gamma_a^N(S)$ and $\Gamma_a^N(P)$ of the quasinuclear S and P levels of the $N\bar{N}$ system in the following manner:

$$\Gamma_a(1, S) \approx \Gamma_a^N(S)\frac{\rho(1, S)}{\rho^N(S)} \sim \Gamma_a^N(S)\left(\frac{a_S^N}{a_{1S}}\right)^3 \quad (8)$$

and

$$\Gamma_a(2, P) \approx \Gamma_a^N(P)\frac{\rho(2, P)}{\rho^N(P)} \sim \Gamma_a^N(P)\left(\frac{a_P^N}{a_{2P}}\right)^5, \quad (9)$$

where $\rho^N(l)$ is the mean value of the particle density in the annihilation region for the quasinuclear bound state of the $N\bar{N}$ system, $a_{1S} = 57$ F is the radius of the Coulomb 1S orbit, $a_S^N \approx 1$ F is the effective radius of the quasinuclear S state, $a_{2P} = 114$ F and $a_P^N \approx 1$ F, are the same quantities for the 2P-atomic and P-quasinuclear states. The annihilation widths $\Gamma_a^N(S)$ and $\Gamma_a^N(P)$ are of the order of 100 MeV and 10 MeV, respectively. Thus, we have for $\Gamma_a(n, S)$ and $\Gamma_a(n, P)$

$$\Gamma_a(n, S) \sim \frac{500}{n^3}\text{eV}, \quad \Gamma_a(n, P) \sim \frac{5\cdot 10^{-3}}{n^3} \text{ eV}. \quad (10)$$

Relation (10) shows that for $n \gtrsim 4$ the annihilation width $\Gamma_a(n, P)$ of the P state is much smaller than the width $\Gamma_{St}(n)$ of the Stark mixing, namely, $\Gamma_a(n, P)/\Gamma_{St}(n) \sim 2/n^2$.

It is seen from the estimates (4) and (10) that the effective width for the annihilation of a $p\bar{p}$ atom from the S state is determined by the width $\Gamma_{St}(n)$, since $\Gamma_{St}(n) \ll (1/n)\Gamma_a(n, S)$ at $n \leqslant 30$. Thus, the rate of annihilation from the S state is equal to the rate of Stark mixing:

$$\Gamma_{eff}(n, S) \approx \Gamma_{St}(n) \sim \frac{2\cdot 10^{-3}}{n} \text{ eV}. \quad (11)$$

The rate of the annihilation of the $p\bar{p}$ atom from the P state is proportional to the annihilation width $\Gamma_a(n, P)$ and to the statistical weight of the P state with the projection of the orbital angular momentum $m = \pm 1$ (antiprotons with $m=0$ are absorbed via the S state as a result of Stark mixing). Assuming that antiprotons with given n are distributed over the levels with different l in proportion to $(2l+1)$, we have

$$\Gamma_{eff}(n, p) = \frac{2}{n^2}\Gamma_a(n, P) \sim \frac{10^{-2}}{n^5} \text{ eV}. \quad (12)$$

For the sought ratio $\Gamma_{eff}(n, P)/\Gamma_{eff}(n, S)$ we obtain

$$R \equiv \frac{\Gamma_{eff}(n, P)}{\Gamma_{eff}(n, S)} \sim \frac{5}{n^4}. \quad (13)$$

The determination of the range of values of n at which the greater part of the antiproton is absorbed calls for complicated cascade calculations. Such calculations were performed in[6] for K^- mesons. It turned out that more than half of the K^- are absorbed at $n > 10$, and only less than 4% of the particles reach the level with $n = 4$. It is natural to assume that the antiprotons are also absorbed in the main from levels with $n > 4$. We thus obtain $R < 2\%$ in the case of annihilation of antiprotons from atomic levels.

The experimentally observed $R \approx 40\%$ can therefore be attributed to the fact that near the threshold there exists a quasinuclear p state with large radius ($a_p^N \approx 3-5$ F). This radius is responsible for the states with low binding energy (~1 MeV). Assuming that $a_p^N = 4$ F, we obtain in analogy with (13) the following estimate of R

$$R = \frac{\Gamma_{eff}\ (n, P)}{\Gamma_{eff}\ (n, S)} \sim \frac{5 \cdot 10^3}{n^4}. \quad (14)$$

The absorption from the P states then becomes predominant at $n \leqslant 10$ ($R \geqslant 1/2$).

The radiative transitions decrease the value of R, but for levels with $n > 3$ these transitions can be neglected. The radiative width of the $2P$ level is equal to

$$\Gamma_\gamma(2P) = 0.37 \cdot 10^{-3}\ \text{eV}$$

With increasing n, the radiative width $\Gamma_\gamma(n, P)$ decreases in proportion to n^{-3}. It should be noted that in order for the Stark mixing to take place, the shift of the atomic levels due to the strong interaction $\Delta E \sim \Gamma$ should be much smaller than the distance between the two outermost components of the level that is being split. This distance is equal to $3Fn(n-1) \sim 3(e^2/a_0^2)n^2$. For the S levels we have

$$\gamma = \frac{\Delta E}{3Fn^2} \sim \frac{10}{n^5}.$$

Thus, $\gamma \ll 1$ already at $n \gtrsim 2$.

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[1] D. R. Desai, Phys. Rev. **119**, 1385 (1960); R. Bizzarri *et al.*, Nucl. Phys. **B69**, 298 (1974).

[2] I. S. Shapiro, Usp. Fiz. Nauk **109**, 431 (1973) [Sov. Phys.-Uspekhi **16**, 173 (1973)]; L. N. Bogdanova, O. D. Dalkarov, and I. S. Shapiro, Ann. of Phys. **84**, 261 (1974).

[3] T. E. Kalogeropoulos, Direct Channel NN Phenomena, in: Vzaimodeĭstvie chastits Vysokoĭ energii s yadrami i novye yadernopodobnye sistemy. Trudy mezhdynarodnogo seminara (Interaction of High-Energy Particles with Nuclei and New Nucleuslike Systems. Proc. of Internat. Seminar), No. 4, Moscow, Atomizdat (1974), p. 23.

[4] S. Devons *et al.*, Phys. Rev. Lett. **27**, 1614 (1971).

[5] B. Day, G. A. Snow, and J. Sucher, Phys. Rev. Lett. **3**, 61 (1959).

[6] M. Leon and H. A. Bethe, Phys. Rev. **127**, 636 (1962).