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Antiproton-Neutron Bound State*

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We discuss the possibility of an antiproton-neutron bound state for explaining a narrow peak which was found recently in the experiment $\bar{p}+n\to 4\pi$ and 6π. It is pointed out that the state is likely to be a ${}^1P_1$ state or a higher angular momentum state.

A recent experiment[1] of antiproton-neutron annihilation at rest has shown a narrow peak in positive G-parity states, and $\bar{p}$-n bound-state formation was suggested for its explanation. Although the possibility of a nonrelativistic bound state of the $\bar{p}$-n system has already been studied by several authors,[2,3] none of these predictions could account for the reported narrow width (≤ 8 MeV) at the binding energy 83.3 ± 1.4 MeV. In this note, we point out that the observed state should correspond to a higher angular momentum state, possibly a p state. Let us simplify the problem by assuming a central square-well potential for the antinucleon-nucleon force. (Let the potential depth be $-V$, and the range R.) Certainly we are aware of the fact that the nuclear force depends on the spin, isospin, and velocity of the nucleons through a complicated exchange mechanism. However, the essential part of the discussion will not depend on the detailed form of the potential, as can be seen by comparing our result with some of the more elaborate calculations.[3] Since we have the narrow peak only in the positive G-parity state, we are dealing with ${}^3S_1$, ${}^1P_1$, ${}^3D_{1,2,3}\cdots$ states for the $I=1$ NN system and have to assume its potential for negative G-parity states to be very different from that of positive G-parity states. (The latter should be more attractive than the former.) Such a difference in the potentials for both G-parity states may be partly due to an L-S coupling force and partly due to a short-range force which results from more complicated t-channel exchange and s-channel annihilation diagrams. Whether this is true or not is to be seen by a further investigation.

The formula for computing the width Γ_l of annihilation from a $\bar{p}$-n bound state with orbital angular momentum l may be given by

$$\Gamma_l=\sigma_l v\rho_l\,, \tag{1}$$

where σ_l designates the lth partial cross section for $\bar{p}$-n annihilation and the densities of states are expressed as

$$\rho_s=\frac{1}{\frac{4}{3}\pi R'^3}\int_0^{R'}\!\!\int|\psi_0|^2r^2drd\Omega \qquad \text{for } s \text{ state} \tag{2}$$

and

$$\rho_p=\frac{1}{\frac{4}{3}\pi R'^3}\int_0^{R'}\!\!\int\frac{|\nabla\psi_1|^2}{k_1^{\,2}}\,r^2drd\Omega \qquad \text{for } p \text{ state}\,. \tag{3a}$$

Here R' stands for the annihilation radius, which is assumed to be smaller than R, and

$$k_1=[2\mu(V-|E|)]^{1/2}\,, \tag{4}$$

μ and E being the reduced mass and the binding energy, respectively. The formulas (1) and (3a) for the p wave reduce to those given by Jackson *et al.*,[4] when $R'\to 0$, i.e.,

$$\rho_p\to\frac{1}{k_1^{\,2}}|\nabla\psi_1(0)|^2\,.$$

We might as well use the density for the p state,

$$\rho_p=\frac{1}{\frac{4}{3}\pi R'^3}\int_0^{R'}\!\!\int|\psi_1|^2r^2drd\Omega\,, \tag{3b}$$

which vanishes in the limit $R'\to 0$. As will be seen later (Table I), the formulas (3a) and (3b) lead to similar results as long as $R'=0.5$–1.2 F. (For definiteness, we have fixed the value of R to be 1.2 F.)

Using the boundary condition at $r=R$

$$\frac{k_1j_l{}'(k_1R)}{j_l(k_1R)}=\frac{ik_2h_l^{(1)\prime}(ik_2R)}{h_l^{(1)}(ik_2R)}\,, \tag{5}$$

with

$$k_2=(2\mu|E|)^{1/2}\,, \tag{6}$$

we obtain the depth of the potential:

$$V=226\text{ MeV}\quad\text{for } s\text{-wave bound state,} \tag{7a}$$

$$V=420\text{ MeV}\quad\text{for } p\text{-wave bound state} \tag{7b}$$

for the observed binding energy $E = -83.3$ MeV.

From Eqs. (1)–(6), it follows that[5]

$$\Gamma_s = (\sigma v)_s \frac{|A_0|^2}{3\pi} \tfrac{3}{2}\left[j_0^{\,2}(k_1R') + n_0(k_1R')\,j_1(k_1R')\right] \tag{8}$$

and

$$\Gamma_p = (\sigma v)_p \frac{|A_1|^2}{3\pi}\; 9\left\{\tfrac{1}{2}\left[j_1^{\,2}(k_1R') - j_0(k_1R')\,j_2(k_1R')\right] + \frac{j_1(k_1R')}{k_1R'}\left[j_0(k_1R') - \frac{2}{k_1R'}\,j_1(k_1R')\right]\right\} \tag{9a}$$

or

$$\Gamma_p = (\sigma v)_p \frac{3}{2\pi}\,|A_1|^2\left[j_1^{\,2}(k_1R') - j_0(k_1R')\,j_2(k_1R')\right] , \tag{9b}$$

where A_0 and A_1 are the normalization constants for the s wave and the p wave, respectively, given by

$$|A_0|^2 = \frac{1}{\frac{1}{2}R^3\left[j_0^{\,2}(k_1R)\;(1 + 1/k_2R) + n_0(k_1R)\,j_1(k_1R)\right]} ,$$

$$|A_1|^2 = \frac{-1}{\frac{1}{2}R^3\,(1 + k_1^{\,2}/k_2^{\,2})\,j_0(k_1R)\,j_2(k_1R)} .$$

As for the estimate of the partial annihilation cross section, we make an assumption that

$$(\sigma)_s \approx a ,\qquad (\sigma v)_p \approx b k^2 , \tag{10}$$

where a, b are constants.

Although no direct beam experiments are available up to now, an early indirect determination of $\sigma(\bar{p}n)$ by subtracting $\bar{p}p$ cross sections from those of $\bar{p}d$, coupled with the Glauber shadow-effect correction, seems to indicate that $\sigma(\bar{p}p) \approx \sigma(\bar{p}n)$ within the experimental error.[6–8] Therefore, assuming the same cross sections for both antiproton-nucleon annihilations, and from the data of $\bar{p}p \to$ even number of pions, we get

$$(\sigma v)_s \approx 10.2 \text{ mb},\qquad (\sigma v)_p \approx 0.67 \text{ mb} \tag{11}$$

for a positive G-parity state, the latter being the value at the momentum 0.66 GeV/c, which is the c.m. momentum of the antiproton-neutron bound system in the p state. Since we have neglected the k-dependent term of the s-wave cross section which would give an ambiguity in the determination of the p-wave cross section, Eq. (11), the value quoted above for the p-wave cross section must be taken as an indication of the order of magnitude.

The result of numerical computation of the decay widths, using Eqs. (1)–(11), is given in Table I. Notations a and b for the p wave refer to the adopted formulas, (9a) and (9b). From the table, one can immediately notice that the s-wave annihilation gives too large a decay width, while the p-wave annihilation is consistent with the observed width ≤ 8 MeV. (We note, however, that in a recent work,[9] some questions are raised about the estimate of the width of the peak in the experiment.) As we mentioned earlier, formulas (9a) and (9b) give approximately equal widths except for a small annihilation radius.

Accepting the premise that the observed narrow peak is due to a p-wave bound state of the $\bar{p}$-n sys-

TABLE I. Densities and decay widths of the $\bar{p}n$ bound states with positive G parity. [a and b for the p-wave width refer to Eqs. (9a) and (9b) in the text.]

State \ Annihilation radius (R')		1.2 F a	1.2 F b	0.5 F a	0.5 F b	0.1 F a	0.1 F b	Zero a	Zero b
$L=1$ ($^1P_1$)	4ρ (MeV/mb)	9.5	8.0	5.6	5.9	18.96	0.31	19.45	0
	Γ (MeV)	6.4	5.3	3.8	4.0	12.7	0.21	13.0	0
$L=0$ ($^3S_1$)	$\frac{4}{3}\rho$ (MeV/mb)	2.8		6.4		7.5		7.55	
	Γ (MeV)	28.4		64.8		76.5		77.0	

tem ($^1P_1$), one encounters a question regarding why the ground s-wave bound state has not been observed in the experiment. In order to answer this question, we estimate the binding energy of the s-state using the potential (7b), obtaining

$$E_{\text{ground state}} = -248 \text{ MeV} .$$

Since both states are positive G-parity states, and

$$E_{p \text{ state}} - E_{\text{ground state}} = 165 \text{ MeV} < 2\, m_\pi ,$$

the transition $(^1P_1) \to (^3S_1)$ by strong interaction is forbidden. The transition by electromagnetic interaction, $(^1P_1) \to (^3S_1) + \gamma$, has a small width ($\approx 0.28$ MeV.) Thus the $^3S_1$ ground state is difficult to observe, unless it is formed directly from $\bar{p}$ in an outer orbit. Finally, it should be pointed out that our argument is merely of a qualitative nature, since the obtained potential (7b) is so deep that a nonrelativistic treatment may not be warranted.

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