Quasi-tritium state in the $\bar{p}d$ system

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A nuclear-like bound state with a binding energy close to the tritium binding energy and with quantum numbers $I(J^p) = 1/2(1/2^-)$ was obtained for the $\bar{p}pn$ system by using the Fadeev equations. A search for the predicted quasi-tritium state was concentrated in experiments on the annihilation of stopped antiprotons in deuterium with the emission of monoenergetic γ quanta that correspond to radiation transitions from the states of the $\bar{p}d$ atom to the examined quasi-tritium state with a relative intensity $\gtrsim 10^{-3}$.

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An investigation of the possibility for the existence of near-threshold states with a small binding energy (of the order of a few MeV) in a system of two nucleons and one antinucleon is of interest for several reasons. First, a spectrum of three-particle states $2N\bar{N}$ of the quasi-nuclear type has been predicted theoretically.[1,2] Second, the nuclear scattering lengths a for each pair of particles can be much greater than the force radius in the $\bar{p}pn$ system near the threshold. This conclusion for the scattering length $a_{\bar{p}p}$ follows from a measurement of the nuclear shift of the $1S$ level of the $\bar{p}p$ atom.[3] The value of $a_{\bar{p}p}$ determined from these data was equal to $a_{\bar{p}p} = 6.66 - i0.37$F.[4] Such a large value of $a_{\bar{p}p}$ is attributable to a close-to-threshold level in the $\bar{p}p$ system with a binding energy $\epsilon \approx 0.87$ MeV and a width $\Gamma \approx 150$ keV. Asympototic estimates of the number of levels in the $\bar{p}pn$ system in this case indicate that a close-to-threshold level can exist (the number of levels was estimated to be $N \sim k \ln(a/r_0) \sim 1$, where $1/\pi \leqslant k \leqslant \frac{1}{2} \ln^2 3$, a is the nuclear scattering length, and r_0 is the force radius[5]). Finally, a detailed investigation of the near-threshold region in the $\bar{p}d$ interaction, which takes into account the capabilities of the slow-antiproton storage ring under construction at CERN, has been planned.

Since the measurement of the shift of the $1S$ level of the $\bar{p}p$ atom gives information about the length $a_{\bar{p}p}$ of nuclear scattering of an antiproton by a proton and, consequently, about the corresponding amplitude or the t matrix, we can use the Fadeev integral equations to describe the near-threshold bound states of the $2N\bar{N}$ system. In fact, the information about two-particle interaction is taken into account in the Fadeev equations by means of the pair t matrix, and the problem reduces to the selection of a model to describe it. We can use for the close-to-threshold baryonium level the effective-radius approximation, which gives simple analytical expressions corresponding to the one-term Yamaguchi potential for the t matrix outside the energy surface. The necessary formulas are given in Ref. 2, where

$$g(k) = \text{const}/(k^2 + \beta^2) \tag{1}$$

was used as the form factor of the virtual decay (fusion) $(N\bar{N})^* \to N + \bar{N}$. We investigated the case of two channels in the specific calculations of the three-particle $\bar{p}pn$ system: $\bar{p} + d\ (\alpha = 1)$ and $n + (\bar{p}p)^*$ [or $p + (\bar{p}n)^*$] $(\alpha = 2)$. Because of the use of isospin formalism in the latter case, the $(\bar{p}p)^*$ and $(\bar{p}n)^*$ states cannot be distinguished if the isospin $I = 1$ is assigned to the $N\bar{N}$ pair. Since both levels [d and $(\bar{p}p)^*$] appear in the S wave, we can restrict ourselves to the orbital angular momentum $L_\alpha = 0$. The spin of the $(\bar{p}p)^*$ system was also assumed to be equal to 0.[1)] The orbital momentum of the spectator for the $J^P = \frac{1}{2}^-$ state uniquely defined as $l_\alpha = 0$. Thus, in terms of quantum numbers the situation is analogous to tritium, but n in this case is replaced by $\bar{p}$. The dynamics of the $\bar{p}pn$ system are also basically similar to those of ^3H or ^3He in terms of the location of the levels of the particle pairs near the corresponding thresholds. Finally, the Pauli principle (the actual nonidentity of n and $\bar{p}$) in this case does not lead to significant differences, i. e., the geometrical coefficients of the Fadeev equations for the $\bar{p}pn$ system turn out to be similar to the corresponding coefficients of ^3H (or ^3He). We obtained the following values for the coefficients $\Gamma^{\alpha\alpha 2}$ [see Eq. (18) in Ref. 2]: $\Gamma^{11} = -0.194$, $\Gamma^{12} = \Gamma^{21} = -0.712$, and $\Gamma^{22} = -0.291$. Therefore, we can expect the appearance of a level in the $\bar{p}pn$ system with a binding energy close to that of tritium. We call this state a quasi-tritium state.

We used the value $a_{N\bar{N}} = 6.6$ F for the $N\bar{N}$-scattering length in the numerical calculations of the determinant $\Delta(E)$ of the homogeneous system of algebraic equations, which determines the binding energy when it is equated to zero. In this case, the parameter β in Eq. (1), which determines the radius of the $N\bar{N}$ interaction, was varied (see Table I) as a function of the effective radius r_0 in accordance with the known relation,

$$\beta = \frac{3}{2} r_0 (1 + \sqrt{1 - 16 r_0 / 9a}). \tag{2}$$

We can see in Table I that as a result of variation of r_0 (and hence of β) within a

TABLE I

r_0, F	β, F^{-1}	$\epsilon_{\bar{p}pn}$, MeV
0.6	4.7	- 10.1
0.8	3.7	- 7.7
1.0	2.7	- 6.1

broad range, the binding energy of the $\bar{p}pn$ system with the quantum numbers $I(J^P) = \frac{1}{2}(\frac{1}{2}^-)$ varies moderately and remains close to the tritium binding energy (8.48 MeV). Similar calculations with allowance for five channels, including the $\bar{p}+d^s$ (d^s is a "singlet deuteron") and $N+(N\bar{N})^*$ channels with baryonium parameters corresponding to certain theoretically predicted states in the $N\bar{N}$ system, gave the value $\epsilon_{\bar{p}pn} = -4$ MeV, in reasonable agreement with the results in Table I. In addition, we note that allowance for the possible annihilation of $\bar{p}$ results in the appearance of an annihilation width Γ_a in the predicted quasi-tritium state, which is close to the width of the near-threshold level of baryonium, i. e., $\Gamma_a \approx 0.2$ MeV, and in the appropriate change in the binding energy $\Delta\epsilon_{\bar{p}pn} \approx 0.2$ MeV, which is unimportant in our calculations.

The predicted quasi-tritium state can be observed by analyzing the γ-ray spectrum that accompanies the annihilation of the stopped antiprotons in a deuterium target. This spectrum must contain a γ-ray line with an energy $\epsilon_\gamma = \epsilon_{\bar{p}pn}$ (within an accuracy equal to the Coulomb binding energy of the $\bar{p}d$ atom), which corresponds to the $E1$ radiative transitions from the P states of a $\bar{p}d$ atom to the predicted quasi-tritium state. The relative intensity $P_\gamma(E1)$ of the γ-ray line can be estimated by comparing it with an analogous quantity $P_x(E1)$ for the x-ray K_α line in the $\bar{p}d$ atom. We use the following estimate for this relation:

$$\frac{P_\gamma(E1)}{P_x(E1)} \approx \eta\left(\frac{\epsilon_\gamma}{\epsilon_x}\right)^3\left(\frac{R}{a_B}\right)^7, \quad (3)$$

where a_B is the Bohr radius of the $\bar{p}d$ atom, R is the radius of the quasi-tritium state, ϵ_x is the energy of the K_α line, and the numerical coefficient $\eta = 1.8$. Assuming that $\epsilon_x = 6$ keV, $\epsilon_\gamma = 6$ MeV, $R \approx (m\epsilon_\gamma)^{1/2} = 2.6$ F, and $a_B = 38$ F, we obtain $P_\gamma(E1)/P_x(E1) = 12$ for the ratio. This means that the relative intensity of the γ-ray line with such energy must be greater than the value of the x-ray K_α line of the $\bar{p}d$ atom by more than an order of magnitude (the measured intensity of the γ-ray line in the $\bar{p}p$ atom, according to the data of Ref. 3, is 2×10^{-4}). We also point out that we used in the estimate the unperturbed Coulomb energy of the $1S$ level of the $\bar{p}d$ atom. The quasi-tritium state can facilitate a rearrangement of the atomic spectrum, i. e., decrease the Coulomb binding energy ϵ_x and, consequently, increase the intensity ratio.

[1]The spin $S=1$ is not very probable for the following reason: the near-threshold $(\bar{p}p)^*$ level in this case is a vector state $J^P=1^-$. Thus, by using the branching measured experimentally

$B(\bar{p}p \to e^+e^-) = (3.2 \pm 0.9) \times 10^{-7}$ (Ref. 6) and the value $v\sigma_a = 19.5$ mb obtained in Ref. 4 from the width of the atomic level, we obtain the electromagnetic form factor $G(q^2 = 4m^2) = 0.19$, which is almost one-third of the measured value in the immediate vicinity of the threshold. Since it is reasonable to assume that the form factor G is an increasing function,[7] these data are incompatible with the hypothesis $S = 1$. Note that this argument leads to a definite prediction for the width of the triplet $1S$ level of the $\bar{p}p$ atom, i. e., $\Gamma(S=1) \gtrsim 3\Gamma(S=0)$.

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