Annihilation of $\bar{p}$ in tritium and bound states in the $\bar{p}n$ system

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(Submitted July 10, 1974)
ZhETF Pis. Red. **20**, No. 5, 341–345 (September 5, 1974)

It is shown that the spectrum of the recoil-deuteron momenta in the reaction of capture of stopped $\bar{p}$ in tritium, $\bar{p}+t\to d+(\bar{p}n)\to d+n\pi$, is sensitive to the contribution of higher partial waves ($l\geqslant 1$) in the ($\bar{p}n$) system. These spectra are compared with the experimentally investigated spectrum of the recoil-proton momenta in the reaction $\bar{p}+d\to p+(\bar{p}n)\to p+n\pi$.

In the experiments of Gray *et al.* [1] on annihilation of antiprotons in a deuterium bubble chamber, obtained an indication that a bound $\bar{p}n$ state exists. The authors have analyzed events of the type

$$\bar{p}+d\to p+(\bar{p}n)\to p+N_\pi, \tag{1}$$

where N_π are products of the pion decay of the ($\bar{p}n$) system, and obtained the momentum spectra of the recoil protons in the momentum interval 150 MeV/$c\leqslant q\leqslant$ 800 MeV/c for the decays of the ($\bar{p}n$) system into an even (4 or 6) or odd (3 or 5) number of pions. The peak in the spectrum for the channel with $G=+1$ at a recoil-proton momentum $q=300$ MeV/c was interpreted by the authors as a Breit-Wigner resonance in the ($\bar{p}n$) system with mass $M=1794.5=1.14$ MeV and width $\Gamma=15\pm 2$ MeV.

A comparison of the experimental results with the theoretically expected spectrum of the recoil-proton momenta was carried out in[2]. The reaction (1) was examined by starting from the pickup mechanism, which is well known in nuclear physics (diagram of Fig. 1a). It was shown that in the case when the annihilation widths of the levels in the ($\bar{p}n$) system are large enough ($\Gamma\gtrsim 50$ MeV), the form of the recoil-proton momentum spectrum in reaction (1) and, in particular, the positions and widths of the maxima in this spectrum, are determined not only by the conservation laws and by the masses of the bound states, but also by the quantum numbers and, in particular, by the orbital angular momentum of the ($\bar{p}n$) system. The observed maximum has in this case a kinematic character and is attributed to the appreciable contribution of the d state in the ($\bar{p}n$) system. The maxima corresponding to the s and p waves of the relative motion of $\bar{p}$ and n can be observed in analogous experiments at different energies of the incident $\bar{p}$, since they fall in this case in the observable part of the recoil-proton spectrum (100 MeV/$c\leqslant q\leqslant$ 800 MeV/c). [3]

In this paper, to explain the true origin of the maximum observed in the effective mass of the ($\bar{p}n$) system as in the reaction (1), we propose to investigate the recoil-deuteron momentum spectrum in the annihilation of stopped $\bar{p}$ in tritium, i. e., in a reaction of the type

$$\bar{p}+t\to d+(\bar{p}n)\to d+N_\pi. \tag{2}$$

It will be shown below that the position of the kinematic maxima in the recoil-deuteron momentum spectrum in reaction (2), corresponding to large annihilation widths of the levels in the ($\bar{p}n$) system ($\Gamma\gtrsim 50$ MeV) is shifted towards smaller recoil momenta q by an amount $\Delta q\approx 100$ MeV/c. In the case of small widths ($\Gamma\lesssim 10$ MeV), the position of the maxima in the spectrum of the recoil-deuteron momenta is determined only by the conservation laws and by the mass of the bound state in the ($\bar{p}n$) system.

The differential cross section of reaction (2), corresponding to the pickup mechanism (diagram of Fig. 1b), can be directly expressed in terms of the differential cross section of the reaction (1), given by diagram 1a, with the aid of the following formula ($\hbar=c=1$):

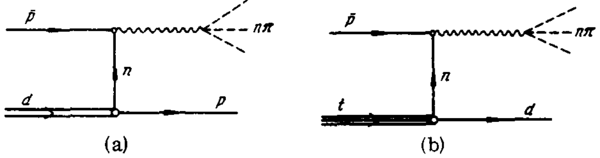

FIG. 1. Pickup mechamism for the reactions $\bar{p}+d\to p+N_\pi$ (a) and $\bar{p}+t\to d+N_\pi$ (b).

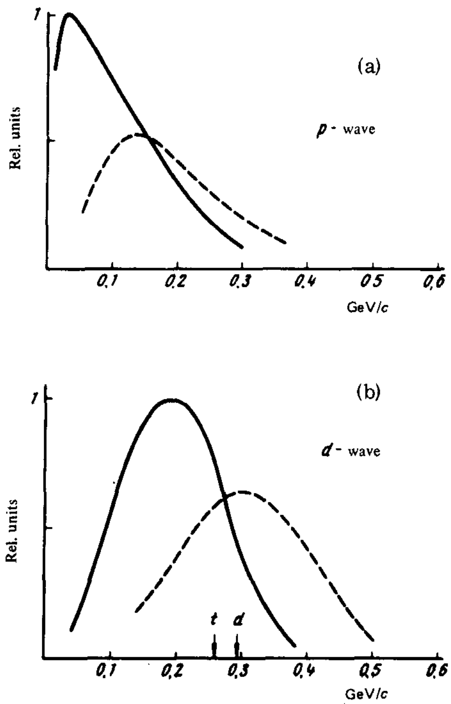

FIG. 2. Distribution with respect to the recoil-proton momenta in the reaction 1 (dashed curve) and of the recoil-deuteron momenta in the reaction 2 (solid curve), for the p-wave (a) and the d-wave (b) in the $\bar{p}n$ relative motion.

$$\left(\frac{d\sigma}{dq}\right)_t = \frac{3}{4}\,\frac{(3q^2 + 4\kappa_d^2 - 4\kappa_x^2)^2 + 4m^2\Gamma^2}{(q^2 + 2\kappa_{t,d}^2 - 2\kappa_x^2)^2 + m^2\Gamma^2}\,\frac{|F_t(q)|^2}{|F_d(q)|^2}\left(\frac{d\sigma}{dq}\right)_d. \qquad (3)$$

Here q is respectively the recoil-deuteron momentum in the lab. frame for the reaction (2) and of the recoil proton in the case of reaction (1): $\kappa d^2 = m\epsilon_d$, $\kappa_{t,d}^2 = m(\epsilon_t - \epsilon_d)$; $\kappa_x^2 = m\epsilon_x$, where ϵ_d, ϵ_t, and ϵ_x are the binding energies of the deuteron, tritium, and of the $(\bar{p}n)$ system, m is the annihilation width of the bound $(\bar{p}n)$ state, m is the nucleon mass, $F_d(q)$ is the Fourier component of the radial wave function of the deuteron, normalized by the condition $\int F_d^2(q)\, d^3q = (2\pi)^3$

$$F_t(q) = -[\sqrt{3\pi}(3/2m)(q^2 + \kappa^2)]^{-1} W(q, 0), \qquad (4)$$

where $\kappa^2 = (4/3)m(\epsilon_t - \epsilon_d)$, $W(q, 0)$ is the vertex function for the $t \to d + n$ decay (see, e. g., [4]).

To find the $d \to pn$ and $t \to dn$ vertex functions it is necessary to know the wave functions of t and d. By now, appreciable progress was made in the solution of the three-nucleon problem by solving the Faddeev equations for realistic NN potentials (with allowance for repulsion at short distances). Calculations of $F_t(q)$, carried out in[4,5] for the realistic Malfliet-Tjon potential[6] and for the modified Bressel-Kerman-Ruben potential[7] yielded vertex functions that practically coincided in the physical region ($q^2 > 0$) (there is a difference near $q = 0$, but this difference is immaterial for the purposes of the present paper). These potentials account for the deuteron binding energy and for the phase shift of the NN scattering in $^1S_0$ and $^3S_1$ states up to 360 MeV, and give an energy ϵ_t close to the experimental value. The corresponding $t \to dn$ vertex functions for a real deuteron was substituted in formula (3). The results of the calculations for $(d\sigma/dq)_t$ (solid curve) and $(d\sigma/dq)_d$ (dashed curve) are shown in Fig. 2. The maxima corresponding to the contribution of the p-wave in the relative motion of $(\bar{p}n)$ system (Fig. 2a) and of the d-wave (Fig. 2b) turn out to be shifted by an amount on the order of $\Delta q \approx 100$ MeV/c on going from reaction (1) to reaction (2).

The position of the Breit-Wigner resonance in the effective mass of the $\bar{p}n$ system for the reactions (1) and (2) is shown by the arrow in Fig. 2b.

The authors are sincerely grateful to I. S. Shapiro for useful discussions.

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