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POSSIBLE STUDY OF BOUND $\bar{p}n$ STATES IN EXPERIMENTS ON THE ANNIHILATION OF $\bar{p}$ ON d

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Submitted 18 May 1972
ZhETF Pis. Red. 15, No. 12, 748 - 751 (20 June 1972)

An earlier study [1] of the annihilation of stopped $\bar{p}$ in a deuterium bubble chamber has suggested that a bound state of n and $\bar{p}$ exists. A comparison of the experimental results with the theoretically expected spectrum of the recoil-nucleon momenta in the reaction

$$\bar{p} + d \to p + X, \tag{1}$$

where X is the bound $\bar{p}n$ state, was carried out in [2]. It was shown that, owing to the relatively large annihilation level widths, the form of this spectrum, and particularly the position and width of the maxima in it, are determined not only by the conservation laws and by the masses of the bound states, but also by their quantum numbers, and primarily by the orbital momenta. The maximum observed in [1] corresponded to an appreciable contribution of the d-state of the $\bar{p}n$ system. The maxima corresponding to the S- and p-waves of the relative motion of $\bar{p}$ and n, as noted in the analogous experiments at different energies of the incoming p, since in this case they turn out to be in the observable region of the recoil-proton spectrum (150 MeV/c < q < 800 MeV/c).

In this article we present the theoretically expected form of the momentum spectrum of the recoil protons in reaction (1) for different p energies. An analysis shows that a study of the spectra for different recoil-proton emission angles makes it possible to determine experimentally the nonzero orbital momenta of the bound states of $\bar{p}$ and n.

Just as in [2], we start out in the analysis of the reactions (1) from the pickup mechanism, which is well known in nuclear physics. We note that the choice of the concrete mechanism of the peripheral process is immaterial for the conclusions presented below, although the form of the spectrum can change in some way on going for example from pickup to the substitution reaction.

The differential cross section of reaction (1), corresponding to pickup, can be written in the form (we assume that $\hbar = c = 1$):

$$\frac{k}{m}\frac{d\sigma}{dq\,d\Omega} = \frac{2l+1}{2\pi}\,\frac{q^2(q^2+\alpha^2)^2\,F_d^2(q)\,F_{N\bar{N}}^2(s)\,\Gamma}{(q^2+\alpha^2-s^2-\kappa^2)^2+\Gamma^2m^2/4}. \tag{2}$$

Here $\vec{k}$ and $\vec{q}$ are the momenta of $\bar{p}$ and of the recoil proton, $d\Omega$ is the element of solid angle in the direction of $\vec{q}$, $\vec{s} = (\vec{k}+\vec{q})/2$, and I, κ^2/m, and Γ are respectively the total angular momentum, the binding energy, and the annihilation width of the considered state of the $N\bar{N}$ system, α^2/m is the deuteron binding energy, m is the mass of the nucleon, and F(a) are the Fourier components of the radial wave functions

$$F(a) = \int_0^\infty \chi_\ell(r)\,j_\ell(ar)\,r\,dr, \tag{3}$$

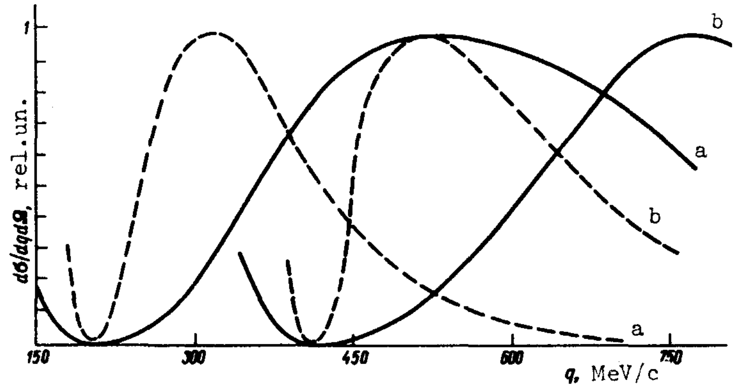


Fig. 1. Recoil-proton spectra in the reaction (1) at $\theta = 180°$ for different momenta of the incident antiproton: a) k = 200 MeV/c, b) k = 300 MeV/c. The solid curve corresponds to the $^3d_1$ (1855 MeV) state of the $\bar{p}n$ system and the dashed one to $^1p_1$ (1814 MeV).

(ℓ is the orbital momentum of relative motion of the particles).

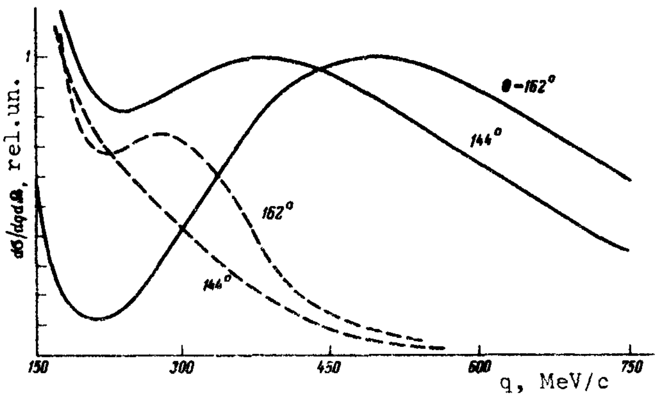
As follows from (2), the course of the cross section $d\sigma/dqd\Omega$ at sufficiently large level widths ($\Gamma \approx 100$ MeV) is determined, on the one hand, by the behavior of the form factor $F_{N\bar{N}}(s)$, and on the other hand by a monotonically decreasing function of q, which is determined by the mechanism of the reaction. Since $F_{N\bar{N}}(0) = 0$ for $\ell \neq 0$, it follows that in the backward spectra ($\theta = 180°$) the distributions with respect to the recoil-proton momenta will have minima at q values equal to the momenta of the incident antiproton, if higher orbital momenta take part in the $\bar{p}n$ annihilation.

In addition, $F^2_{N\bar{N}}(s)$ has in the region q > k a maximum at $s \approx \ell/R$ (R is the radius of the bound state). Taking into account the monotonic decrease with q in (2), we can expect maxima to appear in the spectrum at the angle $\theta = 180°$ in the section $k < q < 2\ell/R = k$, and their position is determined by the orbital momentum $\ell \neq 0$.

Figure 1 shows the recoil-proton spectra at $\theta = 180°$, calculated from formula (2). The deuteron form factor F_d was chosen in the Hulthen form. We used for $F_{N\bar{N}}(s)$ the form factors of the quasinuclear $N\bar{N}$ states considered in [3]. For the $\bar{p}n$ system (isospin I = 1) there was predicted the existence of seven bound states, three with positive G parity ($^3s_1$, $^1p_1$, $^3d_1$ - even pion decay modes), and four with negative G parity ($^1s_0$, $^3p_0$, $^3p_1$, $^3p_2$). Since the positions of the maxima in the spectrum are independent of the bound-state masses and are determined only by their orbital momenta, calculations were performed for two states, $^1p_1$ (1814 MeV) and $^3d_1$ (1855 MeV). Analogous spectra for the s states are monotonically decreasing functions of the recoil momenta, and their form depends little on the initial momentum of the antiproton. We note that the absolute normalization of the form factor $F_{N\bar{N}}$ depends strongly on the behavior of the $N\bar{N}$ wave function at small distances, which is not known with sufficient accuracy, and therefore we present in Fig. 1 only the forms of the spectra (arbitrary ordinates). As seen from Fig. 1, the spectra for the p and d states differ considerably in shape. The maxima corresponding to the p and d waves are shifted relatively to one another by an amount on the order of 150 - 200 MeV/c, and this shift depends little on the initial momentum of the antiproton.

Figure 2 shows the recoil-proton spectra in reaction [1] at different angles, for the p and d states.

Fig. 2. Recoil-proton spectra in the reaction (1) at different angles at an incident antiproton momentum k = 200 MeV/c. The solid lnd dashed curves represent the contributions of the d- and p-waves, respectively.



We see that the change of the relative momentum s of the nucleon and antinucleon with changing emission angle of the recoil proton has little effect on the form of the spectrum for the d-wave, for in this case we remain in the region where the form factor $F_{N\bar{N}}(s)$ increases. For the p-wave, the corresponding maximum vanishes with changing angle, for in this case the relative momentum falls in the region $s > 1/R$, where the form factor $F_{N\bar{N}}(s)$ decreases.

It follows thus from the analysis of Figs. 1 and 2 that a study of the recoil-proton spectra in reaction (1) at angles $90 \leq \theta \leq 180°$ and at different incident-antiproton energies makes it possible to separate the contributions of the bound-states in the $\bar{p}n$ system even if their widths are relatively large.

The foregoing calculations have shown that variation of the widths in a wide range (50 MeV $< \Gamma < 150$ MeV) does not change the qualitative form of the spectrum. At sufficiently small widths ($\Gamma \simeq 10$ MeV), the form of the spectrum is strongly affected by reasonance relations.

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