Additional condition for a role of pion–nucleon rescattering in $\bar{p}d$ annihilation

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The distribution with respect to invariant mass of the πp system is studied as an additional condition on the reaction mechanism for the most interesting channel for the annihilation of stopped antiprotons with deuterium, namely, $\bar{p}d \to p_s 2\pi^+ 3\pi^-$. For events with momenta of the spectator proton above 200 MeV/c, a clearly defined Δ-resonance peak should be observed.

One of the most interesting processes in the physics of antinucleon–nucleus interactions is the capture of antiprotons at rest by deuterium, accompanied by the formation of five charged pions:

$$\bar{p}d \to p_s 2\pi^+ 3\pi^-. \qquad (1)$$

It was in this channel that a peak has been observed[1,2] in the mass spectrum of the $(2\pi^+ 2\pi^-)$ system. This peak corresponds to a $\zeta(1480)$ resonance, which appears to be a quasinuclear state of the $N\bar{N}$ system.[3,4] In addition, this peak turns out to have a totally unexpected property: It shifts and broadens[2] as we go to events with large momenta of the spectator protons, $p_s > 200$ MeV/c. It was shown in Ref. 5 that incorporating the rescatterings of pions by a proton in the final state explains the shift and broadening of the peak. It also explains the high-momentum tail in the proton spectrum. It was concluded in that paper that the changes in the parameters of the peak as we go from small to large spectator momenta in the case of reaction (1) should be taken as further evidence in favor of the existence of a $\zeta(1480)$ resonance.

Although this resonance was subsequently observed[6,7] directly in $\bar{p}p$ interactions (*AX*), attempts were made to find alternative explanations for the high-momentum tail of spectator protons. These attempts invoked both a mechanism of the capture of one of the pions produced in the first stage[8] and a mechanism of two-nucleon capture of an antiproton[9] (the shift and broadening of the resonance peak in the mass spectrum of the $2\pi^+ 2\pi^-$ system are not reproduced by these mechanisms). The mechanism for the $\bar{p}d$ interaction thus continues to attract interest.

In order to determine the mechanism for a direct reaction, it is necessary to make use of many criteria simultaneously.[10] A natural additional criterion for the role of πp rescattering (Fig. 1b) is the mass distribution of the πp system, which should have an isobar peak in the mass region 1100–1400 MeV. However, efforts to use this criterion are hindered by the following circumstances: (1) the momentum spectrum of pions from the reaction $\bar{p}n \to 2\pi^+ 3\pi^-$ has a peak[2,3] near 300 MeV/c. As a result, the distribution with respect to the mass spectrum of the pion and the spectator proton corresponding to the diagram of quasifree interaction in Fig. 1a has a peak near a Δ

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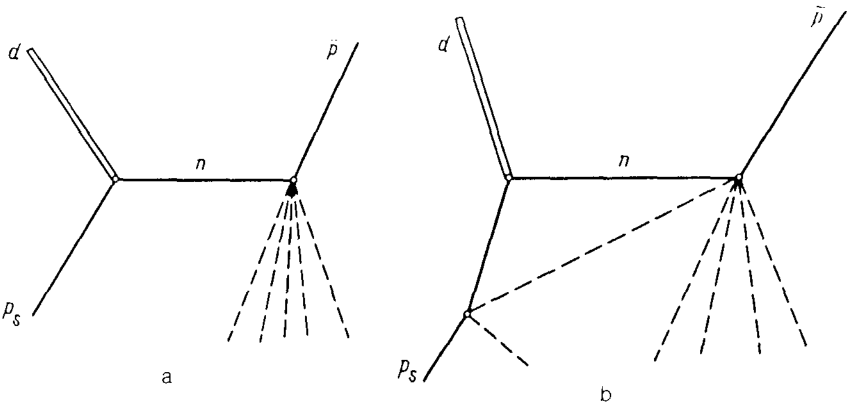

FIG. 1. Feynman diagrams for the process $\bar{p}d \to p_s 2\pi^+ 3\pi^-$.

resonance (we wish to stress that this circumstance is characteristic of specifically a channel with five final pions). (2) Experimentally, we do not know which of the final pions is rescattered by the proton. We are obliged to try all πp pairs. As a result, there is a strong nonresonance "substrate" which smears out the Δ peak. Accordingly, although there is no doubt that there could in principle be a Δ-resonance peak in the πp mass distribution, the question of whether it can be seen clearly in experiments is by no means obvious at the outset. A quantitative study is required.

A corresponding analysis has been carried out on the basis of the model of Ref. 5, i.e., through an examination of the diagrams in Fig. 1 which correspond to (a) a quasifree process at a neutron and (b) a process with a subsequent rescattering of one of the pions. The amplitude is the sum of terms corresponding to pole and triangle diagrams:

$$M = M_a + M_b, \tag{2a}$$

$$M_a = \varphi_d(p_s) M_1, \tag{2b}$$

$$M_b = \frac{E_p + E_1^*}{2\pi(m + E_1^*)} \int \frac{M_1 f_{\pi p}}{k'^2 - k^2 - i\eta} \varphi_d\left(\frac{1}{2}\mathbf{Q} + \mathbf{k}'\right) d\mathbf{k}'. \tag{2c}$$

Here $\varphi_d(\mathbf{p})$ is the wave function of the deuteron in the representation (a Bonn potential[11] was used as the wave function in the calculations), M_1 is the amplitude for $\bar{p}n$ annihilation in the $\bar{p}n \to 2\pi^+ 3\pi^-$ channel, p_s is the momentum of the spectator proton in the laboratory frame, E_1^* and E_p are the energies of the final pion and final proton, $\mathbf{k}'$ and $\mathbf{k}$ are the momentum of the pion before and after the scattering, and $\mathbf{Q}$ is the momentum of the deuteron. All these quantities are taken in the c.m. frame of the scattering pion and proton. The amplitude for πp scattering, $f_{\pi p}$, was used in Breit–Wigner form, corresponding to the isobar $\Delta(3/2, 3/2)$ with a suitable angular dependence, found through a convolution of Clebsch–Gordon coefficients with first-order spherical harmonics. Using the method of Ref. 12, we can reduce (2c) to a single integral in coordinate space. We can show that, after the squared modulus of the amplitude M_b is averaged over the spins of the initial deuteron and the final proton, the characteristic angular dependence for the πN scattering in the Δ-isobar region, $(1+3\cos^2\theta)$, leads to a factor of $(1+3\cos^2\alpha)$, where α is the angle between the momentum of the deuteron and that of the final pion in the pion–proton c.m. frame. The calculation formalism and the analytic results will be reported in more detail in a separate publication.

The further calculation of the distribution $dN/dm_{\pi p}$, with respect to the mass of the πp system, reduces to a double integration in a many-body phase space:

$$\frac{dN}{dm_{\pi p}} \propto \int dE_s dE_1 R_4(p_s,k_1)\,|M(p_s,k_1)|^2. \tag{3}$$

Here p_s (E_s) and k_1 (E_1) are the momenta (energies) of the final proton and the final pion in the laboratory frame, M is the amplitude in (2) expressed as a function of p_s and k_1, and R_4 is the invariant phase volume of the four unscattered pions, expressed as a function of p_s and k_1. The calculation of $dN/dm_{\pi p}$, where $m_{\pi p}$ is the mass of the rescattered pion and the rescattered proton, thus reduces to a triple integration along with a calculation of M_b. The integration in (3) was carried out numerically. Actually, the "substrate" also receives a contribution from those πp pairs in which the proton combines with a pion from the process in Fig. 1b, without undergoing a scattering. A rigorous calculation becomes complicated in this case, since the amplitude M_b and the reduced phase volume depend on different variables. The effect is to increase the multiplicity of the integration by a factor of 2. The contribution of the corresponding triangle diagrams was thus simulated by a pole diagram, but with the "true" distribution with respect to the momentum of the spectator proton.[5] This is a good approximation since the corresponding distribution is smooth.

Since the pole diagram is predominant at spectator–proton momenta up to 200 MeV/c, while the triangle diagram with rescattering is predominant at higher momenta,[5] we will look at the distribution with respect to the πp mass both for all possible spectator momenta and separately for the region $p_s > 200$ MeV/c. The results of these calculations are shown in Fig. 2. The dot-dashed curve shows the distribution given by the pole diagram in Fig. 1a. A calculation of the distribution given by the six-particle phase volume leads to a curve which is approximately the same as the dot-dashed curve but a bit broader. The dashed curve shows the distribution with respect to the πp mass for events with all spectator-proton momenta found when both diagrams in Fig. 1 are taken into account. The solid curve shows the same results, but for cases with spectator momenta $p_s > 200$ MeV/c. These curves have been normalized to an identical area. Shown for comparison by the dotted curve, in smaller scale, is the shape of the $\Delta(1232)$ resonance. We see that the difference between the dot-dashed and dashed curves is so great that it is difficult to detect a resonance amplification in the analysis of all events. This circumstance must of course be taken into account in an interpretation of experimental data. It was apparently because of this circumstance that no clearly defined peak was found in the πp mass spectrum in a preliminary analysis of the data in channel (1) (Ref. 13). On the other hand, the solid curve is fairly narrow, implying that it would be possible to observe the isobar peak if the

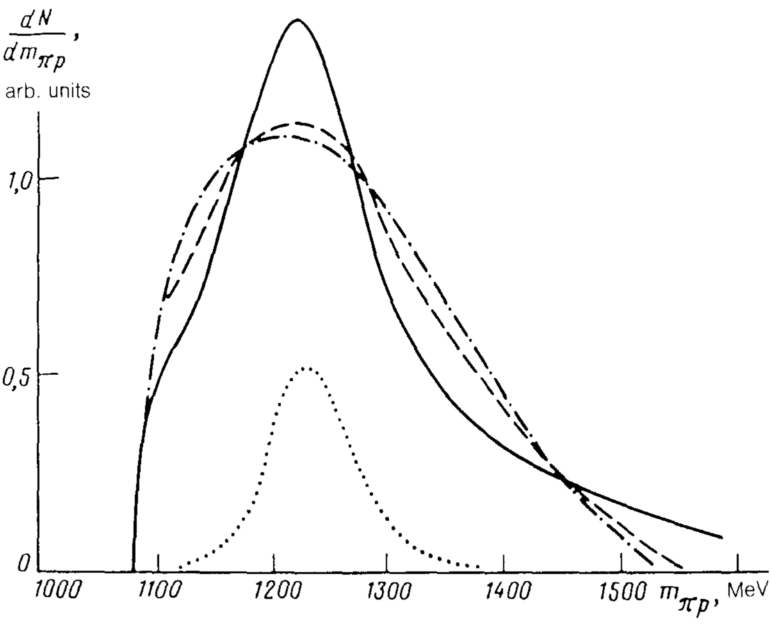

FIG. 2. Distributions with respect to the mass of the πp system. Dot-dashed curve—only the diagram in Fig. 1a is taken into account; dashed curve—overall distribution for all p_s; solid curve—overall distribution for $p_s > 200$ MeV/c; dotted curve—shape of the peak corresponding to the $\Delta(1232)$ isobar.

analysis were carried out separately for the cases with $p_s > 200$ MeV/c, for which the triangle diagrams are predominant (in this case the substrate associated with the incorporation of those πp pairs for which the proton combines with a pion which has not participated in a rescattering does not lead to any significant "smearing" of the Δ peak). These conclusions are supported by Fig. 3, which shows $W(m_{\pi p})$, the distributions with respect to the mass of the πp system divided by the distribution which is given by simply the six-particle phase volume. We see a narrow peak on the solid curve

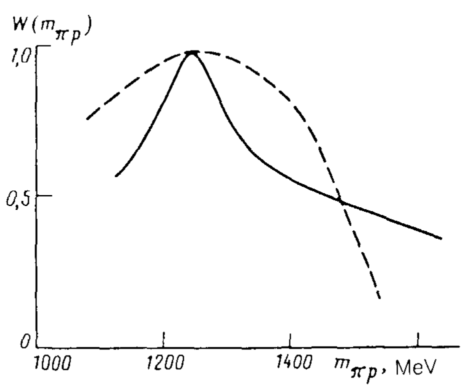

FIG. 3. Distribution with respect to the mass of the πp system, divided by the corresponding distribution given by a six-particle phase volume. Solid curve—$p_s > 200$ MeV/c; dashed curve—all p_s.

which corresponds to events with $p_s > 200$ MeV/c, along with a very broad distribution (the dashed curve) for events with all p_s. For convenience in comparing shapes, the two curves have been normalized to the same maximum value.

In summary, the Δ-resonance peak should be clearly observed in the distribution with respect to the mass of the πp system from process (1) if events with large spectator momenta are treated separately in the analysis of the experimental data. Such an analysis would be extremely desirable in view of the great interest in the physics of $\bar{N}N$ and $\bar{N}$-nucleus interactions.

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