Two-pion decay of a narrow nuclear resonance

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Experimental data on pion production in collisions of protons with nuclei at an energy of about 350 MeV are explained in terms of the formation of a resonance with a spin and parity of 2^+ and a width of about 7 MeV, accompanied by the emission of two pions. This resonance could result from the excitation of $\Delta\Delta$ states in nuclei.

Experiments on pion production in the collisions of protons with copper nuclei in the energy range 240–500 MeV have revealed an anomaly at a proton energy of 350 MeV in the spectrum in pions emitted at an angle of 90° (Ref. 1). The pion spectrum measured in the pion energy range 30–110 MeV has been found to be rich in low-energy pions. These measurements were carried out at the phasotron of the Laboratory of Nuclear Problems by researchers from the Institute of Nuclear Research and the Joint Institute for Nuclear Research. The measurements were subsequently repeated under similar conditions at the Saturn synchrotron at the Nuclear Research Center at Saclay, and the presence of an anomaly was confirmed.[2] Measurements have shown that the anomalous increase in the yield of low-energy pions is observed up to pion energies of about 70 MeV. Subsequent measurements with a good proton-beam energy resolution yielded an estimate of about 5 MeV for the width of the appearance of the anomaly along the proton-energy scale.[3] Some new measurements were recently carried out in the Laboratory of Nuclear Problems of the Joint Institute for Nuclear Research for several pion emission angles. It was found that the nature of the anomaly

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as a function of the proton energy differs for pion emission angles of 90°, 115°, and 125° (Ref. 4).

In the present letter we offer an explanation for the observed anomalous production of pions, in terms of a resonant intensification of the yield of two pions at a proton energy of about 350 MeV. In the case of the decay of an excited nuclear state with an energy of 350 MeV, in a process accompanied by the emission of two pions, the maximum energy of the pion in the case of a fairly heavy nucleus will not exceed 350 MeV $- 2m_\pi \approx 70$ MeV. This is what is observed experimentally.[1-4]

At the proton energies under consideration, above the threshold for the production of two pions in a collision with a heavy nucleus, there could evidently be a nonresonant production of two pions in nucleon-nucleon collisions because of the Fermi motion of the nucleons in the nucleus and nucleon correlations or in successive collisions. The amplitude for the $(p,2\pi)$ reaction is thus written as the sum of resonant and nonresonant parts:

$$F = A + B. \tag{1}$$

It can be assumed that in a sufficiently narrow energy interval the amplitude B will be independent of the energy and that in general, the resonant amplitude will be expressed in terms of the difference between the total and resonant proton energies, $E - E_r$, the total width Γ, and the widths of the entrance and exit channels, Γ_p and $\Gamma_{2\pi}$:

$$A = \frac{\sqrt{\pi}}{k_0} \sum_\lambda C_\lambda Y_{\lambda 0}(\cos\theta) \sqrt{\Gamma_p \Gamma_{2\pi}} (E - E_r + i \frac{\Gamma}{2})^{-1}, \tag{2}$$

where θ is the production angle, k_0 is the wave number of the incident proton, λ is the orbital angular momentum in the exit channel, and the constants C_λ depend on the spin variables and their projections, including the spin of the resonance, J. Numerical calculations have shown that it is sufficient to consider the orbital angular momentum $\lambda = 2$ in order to describe the experimental data at the various angles. The expression for the reaction cross section then takes the form

$$\frac{d\sigma}{d\Omega} = \Big[(E - E_r)^2 + \frac{\Gamma^2}{4}\Big]^{-1} \Big[\frac{5C_2^2}{16k_0^2} \Gamma_p \Gamma_{2\pi} (3\cos^2\theta - 1)^2 + \frac{\sqrt{5} C_2 B}{2k_0} (E - E_r) \sqrt{\Gamma_p \Gamma_{2\pi}} (3\cos^2\theta - 1)\Big] + B^2. \tag{3}$$

The normalization in (3) has been carried out on the basis of the maximum cross section at the resonance at an angle of 90° (Ref. 2), of about 40 μb. From the total width found from the shape of the curve, $\Gamma \approx 7$ MeV, we find $\Gamma_p \Gamma_{2\pi} \sim 3$ MeV^2.

The partial widths cannot be determined from the experimental data available. Figure 1 shows results calculated for $\Gamma_{2\pi} = \Gamma/2 = 3.5$ MeV. We then find $\Gamma_p = 0.84$ MeV and $\Gamma_p/\Gamma = 0.12$. In order to obtain a qualitative description of the experimental data, we must introduce the extremely small nonresonant amplitude $B = 0.35$

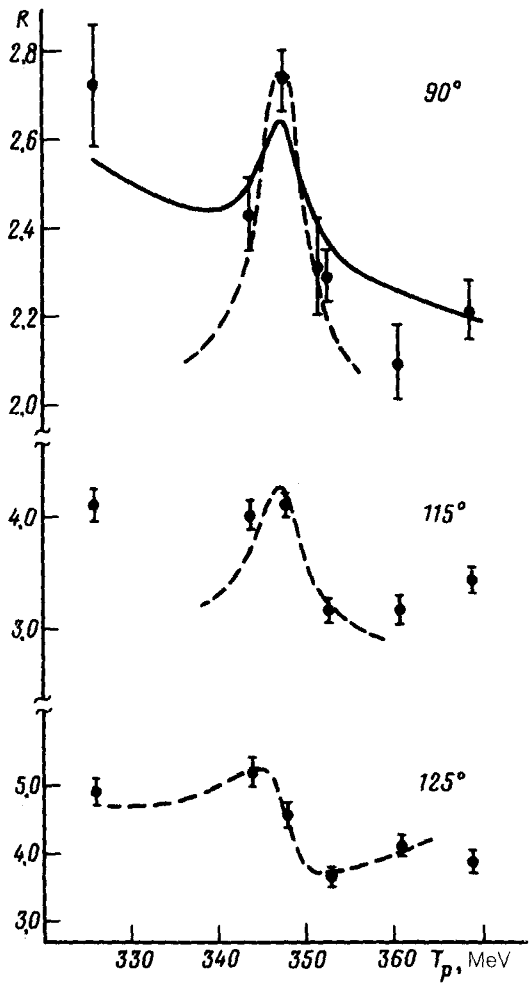

FIG. 1. Comparison of the experimental ratio of the yields of pions with energies below and above 60 MeV with the results calculated for the cross sections from expression (3). Dashed lines—In arbitrary units, versus the proton kinetic energy for a copper target; solid lines—calculated with allowance for the production of single pions. The production angles are given in the figure.

$\mu b^{1/2}$. The corresponding correction to the cross section at the resonance in the 90° case is only about 0.3%. At $\theta = 125°$, however, the nature of the resonant dependence changes because the Legendre polynominal $P_2(\cos\theta)$ is close to zero.

Figure 1 shows the experimental data as a plot of the ratio (R) of the yields of low-energy pions, with 20–60 MeV, to the yield of pions with energies above 60 MeV versus the proton energy. As we have already stated, the higher-energy pions do not exhibit a resonant dependence on the proton energy near 350 MeV.

Since inclusive pion spectra were measured in the experiments, we also need to consider the incoherent background from the production of single pions, which is particularly important at the smaller angles, at which we observe a strong but smooth dependence of R on the proton energy. Figure 1 makes a comparison with the experimental data for an angle of 90°; the incoherent background was added on the basis of experimental data far from the resonance.

The determination of the spin and parity of the resonance is obviously influenced by the spin state of the two pions which are emitted. Analysis of the data on the pion-pion interaction at energies up to 70 MeV leads to the conclusion that the s-wave interaction is nearly an order of magnitude stronger than the p-wave interaction in the amplitude.[5] The same conclusion is implied by the fact that there is no decay of the $\Delta(1232)$ isobar into two pions and a nucleon. With a copper target in the final state, an even-even nucleus is formed, probably with spin zero, so we find the spin and parity of the resonance to be 2^+.

A spin of this magnitude and the two-pion decay of the resonance suggest that the structure of the resonance is a consequence of the excitation of two $\Delta(1232)$ isobars in the nuclei. Brown *et al.*[6] have pointed out the possibility of an increased role of $\Delta\Delta$ states during the absorption of pions in nuclei. In this case the Δ isobars form under the influence of fairly high-energy protons in the nuclear matter. In addition to their decay, with a width Γ_π, they can undergo an interaction with nucleons of the nucleus, $\Delta N \to NN$, with a width Γ_{NN}. Under the condition that the total width $\Gamma \approx \Delta_{NN} + \Gamma_\pi$ is basically determined by the absorption width, we find the following result from the dispersion relation for the refractive index of a pion, n:

$$n^2 - 1 = -\delta(\omega - \omega_r + \delta + i\frac{\Gamma}{2})^{-1}, \qquad (4)$$

where $\delta = (16\pi/3)\rho f^2 (\omega_r/\omega)$, $\rho = 0.48 m_\pi^{-3}$ is the nuclear density, $f^2 = 0.08$ is the pion-nucleon interaction constant, and ω and ω_r are the total and resonant energies of the pion.

An estimate of the shift of the resonance yields $\delta \approx 140$ MeV, which leads to the following resonant energy for the excitation of two Δ isobars: $E_r = 2(1232-140)$ MeV $= 308$ MeV $+ 2m_p$. This result is extremely close to the resonant energy observed experimentally; 350 MeV $+ 2m_p$. Because of the p-wave penetrability factor, the decay width is smaller than that of a free Δ resonance, $\Gamma_\pi(\omega_r) \sim 120$ MeV:

$$\Gamma_\pi(\omega) = (\frac{k}{k_r})^3 \frac{\omega_r}{\omega} \Gamma_\pi(\omega_r), \qquad (5)$$

where k and k_r are the pion wave numbers corresponding to the energies ω and ω_r. At a pion emission energy of 20 MeV, the decay width is estimated to be about 7 MeV. This figure can explain the small width of the observed resonance.

It would be worthwhile to carry out correlation measurements and to determine the isospin of the resonance on the basis of the yields of pairs of pions with charges of different sign.

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