New Excitation Mode of the Nucleon?

A.P. Kobushkin

Laboratoire National Saturne, CEA/DSM CNRS/IN2P3, F-91191 Gif-sur-Yvette Cedex, France

and

Bogolyubov Institute for Theoretical Physics, National Academy of Sciences of Ukraine

252143, Kiev, Ukraine

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We consider properties of narrow baryon states observed recently in reaction \( pp \to p\pi^+X \). Two lowest of them (with mass 1004 and 1044 MeV, respectively) are stable against strong decay. Moreover we conclude that they cannot decay to \( \gamma N \) and thus this states are a kind of metastable levels in quark system. The simplest decay channel is assumed to be \( 2\gamma N \) and possible quark configuration with such properties is discussed. New experiment for verification of status of this states in \( \gamma N \) collision is proposed.

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Recently three narrow bumps in missing mass spectra of the reaction \( pp \to p\pi^+X \) with \( m_X = 1004, 1044 \) and 1094 MeV have been observed with good statistics by Tatischeff, Yonnet et al. \cite{1,2}. The bump widths are probably in the range 4–15 MeV and are determined by experimental resolution. The masses \( m_X = 1004 \) and 1044 MeV are below \( m_N + m_\pi \) threshold and allows an interpretation as a possible cusp effect. In this paper we will denote the possible new states with the property of the constituent quark model there is a room for 3-quark states with the flavor-spin of their wave function corresponds to 20-plet of the SU(6)\(_{\text{SF}}\). Feynman \cite{4} mentioned that such states cannot be transformed into a nucleon by operator acting on one quark (\( \text{e.g. electromagnetic current} \)). Indeed the 20-plet is totally antisymmetric representation of the SU(6)\(_{\text{SF}}\), \([1^3]_{\text{SF}}\), and one has to act on two different quarks of it to create totally symmetrical representation \([3]_{\text{SF}}\) which includes the nucleon (Figure 1).

FIG. 1. The quark diagram for \( N' \to 2\gamma N \) decay. The first photon changes the spin-flavor symmetry from \([1^3]_{\text{SF}}\) to \([21]_{\text{SF}}\); the second photon changes it as \([21]_{\text{SF}} \to [3]_{\text{SF}}\).

To excite such objects from the nucleon one needs (at least) two steps for changing the spin-flavor symmetry. For example, in the experiment \cite{3} it was made as follows: at the first step a resonance with mixed spin-flavor symmetry, \([21]_{\text{SF}}\), is produced in \( pp \to pN^* \) collision. At the second step the \( N^* \) decays on the narrow state and the pion, \( N^* \to N\pi \) (Figure 2 a). This model predicts that production cross section for the \( N'(1004), N'(1044) \) must increase when the 4-momenta \( p_1, p_2 \) and \( p_3 \) of the target, beam and final protons, respectively, are constrained by

\[
\sqrt{(p_1 + p_2 - p_3)^2} \approx M_R
\]

where \( M_R \) is energy of one of resonances with \([21]_{\text{SF}}\) spin-flavor wave function. The lowest of them are the negative parity resonances \( D_{13} \) and \( S_{11} \) with average energy near 1520 MeV and a number of resonances between 1600 and 1700 MeV.


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The two step mechanism of the $N'$ excitation is very similar to laser pumping: first a level with energy higher that energy of appropriate metastable state is excited and then quantum system transits to the metastable state.

From their symmetry properties the $N'$ states cannot be excited at intermediate state of the Compton scattering $\gamma N \to \gamma N$ at $E_\gamma = 68, 112$ MeV. In turn, the two steps production mechanism takes place in an “inelastic Compton” scattering $\gamma N \to \gamma N'$ which is described by the same quark diagram as the $N' \to 2\gamma N$ decay, but with inverse direction of quark lines and a line of one of the photons (Figure 2 b). The appropriate photon energy must be $E_\gamma = 774$ MeV (which corresponds to $\sqrt{s} = 1520$) or higher.

The 20-plet consists of flavor octet and singlet with $\frac{1}{2}^-$ and $\frac{3}{2}^-$ spin, respectively. The singlet has nonzero strangeness and thus is excluded from our consideration. To characterize an orbital wave function we will use the notations of the translationally invariant shell model (3).

$$\Psi(\vec{r}_{12}, \vec{r}) = |N(\lambda, \mu)| f_X |LY_X\rangle,$$  \hspace{1cm} (2)

where $N$ is the number of excitation quanta, $\langle \lambda, \mu \rangle$ is the Elliot symbol determining the $SU(3)$ harmonic oscillator multiplet, $|f_X\rangle$ is the Young diagram for the spatial permutation symmetry, $L$ is the total orbital momentum, $Y_X$ is the Yamamichi symbol specifying the basis vector of the representation $[f_X]$ of the permutation group $S_3$, and $\vec{r}_{12}$ and $\vec{r}$ are Jacobi coordinates. For a totally symmetrical spin-flavor state the Pauli principle requires wave function $|2(01)[1^3]1(123)\rangle$, i.e., the second excitation, $N = 2$, with total orbital momentum $L = 1$. So one gets two desirable states with spin-parity-isospin $J^P T = \frac{1}{2}^{-} \frac{1}{2}$, $\frac{3}{2}^{-} \frac{1}{2}$, respectively. In this case one of the bumps, say the 1094 MeV bump (which is observed with less confidence), should have another nature.

An important question of our model is how energy of 1600-1700 MeV (typical mass of nucleon resonances from the second excitation) is reduced to the energy of 1100 MeV and less. Of course it cannot be related to a mechanism of a chiral constituent quark model by Glozman and Riska (4) which explains low mass of the Roper resonance and in any case it cannot be treated by perturbative calculation. For example, naive application of the model (4) to our object gives

$$m_{N'} = 3V_0 + 5\hbar \omega + 10P_{11},$$  \hspace{1cm} (3)

where $V_0 = 296.3$ MeV and $\hbar \omega = 157.4$ MeV are parameters of confining oscillator potential. The expectation value of pion exchange potential $P_{11}$ was fitted to be positive, 45.2 MeV and the masses of this states become very high. Nevertheless one can assume existence of $LL$-coupling potential in three quark system

$$V_{LL} = \tilde{L}^{(12)} \tilde{L}^{(\rho)} v_{LL} (\vec{r}_{12}, \rho),$$  \hspace{1cm} (4)

where $\tilde{L}^{(12)}$ and $\tilde{L}^{(\rho)}$ are angular momentum operators corresponding to appropriate Jacobi coordinate. It does not contribute to the energy of baryons with $N = 0$ and 1, as well as to the well established resonances with $N = 2$ and the spatial permutation symmetry [3]X (for example to the Roper resonance). So the most important part of the baryon spectroscopy (4) is not changed. In turn for the $N'$ states the angular momenta are $L = L^{(12)} = L^{(\rho)} = 1$; so

$$<2(01)[1^3]1(123)| \tilde{L}^{(12)} \tilde{L}^{(\rho)} |2(01)[1^3]1(123)\rangle = \frac{1}{2} \left[ L(L + 1) - L^{(12)} (L^{(12)} + 1) - L^{(\rho)} (L^{(\rho)} + 1) \right] = -1$$  \hspace{1cm} (5)

and the potential (4) could strongly affect effective potential for orbital motion of the quarks. At the moment one can say nothing about the form of the potential $v_{LL} (\vec{r}_{12}, \rho)$.

The 40 MeV splitting between the two states may be explained by spin-orbit interaction similar to that for usual baryons.

In conclusion, we propose a model for narrow states observed in (2). According to their symmetry properties they cannot be exited as intermediate state in Compton scattering on the nucleon but can be produced in inelastic Compton scattering $\gamma N \to \gamma N'$. Of course the $N'$ states can be also exited in a reaction where one of photons (or both photons) in the inelastic Compton scattering is (are) replaced by a pion (pions) at appropriate kinematic conditions.

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FIG. 2. Examples of the $N'$ excitation by the two step mechanism: $pp \to p\pi + X$ (upper diagram) and inelastic Compton scattering (lower diagram).
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