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Yu.Kalashnikova, M.Shmatikov

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THE CASE OF *AX*: UNAMBIGIOUS SIGNATURE FOR MOLECULAR STRUCTURE

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THE CASE OF AX: UNAMBIGIOUS SIGNATURE FOR MOLECULAR STRUCTURE:
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Yu.Kalashnikova, M.Shmatikov*) - M., 1993 - 8p.

A wide-spread opinion exists, fortunately not shared by everybody, that numerous mesonic structures observed in the 1.5-2.0 GeV mass range are manifestations of multiquark/hybrid/quasinuclear exotics. However, there are a lot of facts indicating that at least some of these resonant states have the molecule-type nature. Here we show that their radiative decays, when measured experimentally, may provide a key to the solution of this challenging issue. The $AX/f2(1520)$ meson seems to be a testing ground best suited for this purpose.

Fig - 1, ref - 3

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*) Russian Research Center "Kurchatov Institute", 123182 Moscow, Russia

Mesonic multiquark state due to various dynamic mechanisms can acquire a molecular structure. One of such mechanisms are the long-range forces generated by π-meson exchange [1]. Besides, clusterization can occur due to proximity to the threshold: coupling of multiquark state possessing near-threshold S-matrix pole to open hadronic channels results in a molecular structure of this state [2], [3]. The AX-meson being a molecule implies that its wave function is dominated by $\rho - \rho$ and $\omega - \omega$ configurations with the relative weight controlled by underlying dynamics. Such a structure gives a unique opportunity to determine the mechanism for radiative decay and, thus, to predict the value of the corresponding branching ratio. Indeed, let us consider

$$AX(1520) \to l^+l^- + V \tag{1}$$

decay mode of the AX-meson, where V is a vector (ω or ρ) meson and l is a lepton ($l = \mu, e$). Denoting vertices of $AX \to V + V$ and $V \to l^+ + l^-$ processes as G_{AX} and G_V respectively one can write the amplitude M of the decay (1) in the form (see fig.1)

$$M = G_V \cdot D \cdot G_{AX}\,, \tag{2}$$

where D is the propagator of the vector meson (spin indeces are suppressed to make the result obtained more lucid). Then the differential width of the decay (1) reads

$$d\Gamma_{AX}(l^+l^-V) = \frac{1}{(2\pi)^9}\frac{1}{2m_{AX}}|M|^2\,dS_3\,, \tag{3}$$

where m_{AX} is the mass of the AX-meson and dS_3 is the three-particle phase-space volume. Let the l^+l^--pair (and decaying vector meson) have the invariant mass squared equal to Q^2. Then the three-particle phase-space volume dS_3 factorizes as follows

$$dS_3 = dQ^2 \cdot dS_2(m_{AX}; Q, m_V) \cdot dS_2(Q; m_l, m_l)\,, \tag{4}$$

where $dS_2(m; m_1, m_2)$ denotes a two-particle phase-space volume for the decay of the mass m particle into a pair of particles with masses m_1 and m_2.

Invariant mass Q of the l^+l^--pair determines the kinematics of the "two-particle" decay (1): e.g. c.m.s. momentum reads

$$k = \frac{\sqrt{\left[m_{AX}^2 - (m_V + Q)^2\right]\left[m_{AX}^2 - (m_V - Q)^2\right]}}{2m_{AX}} \tag{5}$$

Differential decay width (3) can be related to the wave function of the molecular state. Then one can check readily that the product of G_{AX} vertex and the propagator

$$D(Q^2) = \frac{1}{Q^2 - m_V^2}$$

is expressed in terms of two-vector-meson wave function χ

$$G_{AX} \cdot D(Q^2) = -(2\pi)^{3/2}\sqrt{2m_{AX}}\,\chi(\mathbf{k})\,, \tag{6}$$

where the χ wave function is normalized to the unity:

$$\int |\chi(\mathbf{k})|^2\, d\mathbf{k} = 1\,. \tag{7}$$

The G_V vertex is related in turn with the $V \to l^+l^-$ decay width $\Gamma_V(l^+l^-)$ reading:

$$\Gamma_V(l^+l^-) = \int \frac{1}{(2\pi)^2}\frac{1}{2m_V}|G_V(Q^2)|^2\, dS_2(Q,\, m_l, m_l) \tag{8}$$

Substituting (6) and (8) into (3) with the account of (4) we get

$$\frac{d\Gamma_{AX}(l^+l^-V)}{dQ^2} = 2\, m_V\, \Gamma_V(l^+l^-)\, |\chi(\mathbf{k})|^2 \cdot dS_2(m_{AX};,\, Q, m_V)\,. \tag{9}$$

For simplicity we neglect the spin structure of the $\chi(\mathbf{k})$ wave function. Then integrating two-particle phase-space volume over all but angular variables we get

$$\frac{d\Gamma_{AX}(l^+l^-V)}{dQ^2\, d\Omega_{\mathbf{k}}} = \frac{m_V}{2\, m_{AX}} \cdot \Gamma_V(l^+l^-) \cdot k\, |\chi(\mathbf{k})|^2 \tag{10}$$

This expression can be simplified further using relation between the c.m.s. momentum k and Q^2 (see (5)) to give:

$$d\Gamma_{AX}(l^+l^-V) = \frac{m_{AX}}{2\, E_V}\, |\chi(\mathbf{k})|^2\, \Gamma_V(l^+l^-)\, k^2\, dk\, d\Omega_{\mathbf{k}}\,, \tag{11}$$

where $E_V = \sqrt{k^2 + m_V^2}$ is the c.m.s. energy of the on-shell vector meson. Molecule-type structure of the AX-meson implies, in particular, that the binding energy of two vector mesons is small compared to the AX-meson mass:

$$(2m_V - m_{AX})/m_{AX} \ll 1$$

So, (11) can be transformed to yield

$$\frac{d\Gamma_{AX}(l^+l^-V)}{d\mathbf{k}} = \frac{m_V}{E_V}\, \Gamma_V\, |\chi(\mathbf{k})|^2 \tag{12}$$

Up to now we have neglected the isospin structure of the AX-meson state. Normalized wave function of two vector mesons accounting for isospin properties reads

$$\chi = \left\{ \frac{\boldsymbol{\rho}\cdot\boldsymbol{\rho}}{\sqrt{3}}\,\chi_{\rho\rho} + \omega\cdot\omega\,\chi_{\omega\omega} \right\} \tag{13}$$

implying that $\Gamma_V(l^+l^-)\,|\chi|^2$ in (12) is to be substituted by

$$\Gamma_V(l^+l^-)\,|\chi|^2 \to \left\{ \frac{1}{3}\Gamma_\rho(l^+l^-)\,|\chi_{\rho\rho}|^2 + \Gamma_\omega(l^+l^-)\,|\chi_{\omega\omega}|^2 \right\} \tag{14}$$

Note, however, that the wave function χ is normalized to unity (7) imposing normalization condition on $\chi_{\rho\rho}$ and $\chi_{\omega\omega}$ components:

$$\|\chi_{\rho\rho}\|^2 + \|\chi_{\omega\omega}\|^2 = 1 \tag{15}$$

Denoting for brevity $\|\chi_{\rho\rho}\| = \cos\phi$ (and $\|\chi_{\omega\omega}\| = \sin\phi$) one can rewrite (14) in the form

$$\Gamma_V(l^+l^-)\,|\chi|^2 \to \left\{ \frac{1}{3}\Gamma_\rho(l^+l^-)\cos^2\phi + \Gamma_\omega(l^+l^-)\sin^2\phi \right\} |\chi|^2 . \tag{16}$$

The value of ϕ angle controls relative contribution of $\rho-\rho$ and $\omega-\omega$ isotopic states to the AX-meson wave function. There are good reasons to believe that these states bring equal contributions. Indeed, arguments based on isospin and G-parity selection rules show that the long-range one-pion exchange is absent in diagonal (i.e. $\rho\rho \to \rho\rho$ and $\omega\omega \to \omega\omega$) channels being operative in the $\rho\rho \leftrightarrow \omega\omega$ transition only. It implies that up to very small distances where vector-meson exchanges come into play the $\chi_{\rho\rho}$ and $\chi_{\omega\omega}$ coincide with each other. Besides, AX is a loosely bound state of two vector mesons. This statement, translated in terms of normalization condition, implies that integral (7) is saturated by small k region (large intermeson distances) and insensitive to small-distance behavior of wave function. These arguments favor the conclusion that $\|\chi_{\rho\rho}\| = \|\chi_{\omega\omega}\|$ ($\phi = \pi/4$) entailing

$$\Gamma_V(l^+l^-)\,|\chi|^2 \to \frac{1}{2}\left\{ \frac{1}{3}\Gamma_\rho(l^+l^-) + \Gamma_\omega(l^+l^-) \right\} |\chi|^2 . \tag{17}$$

Note that these arguments hold true provided (small $\approx$ 20 MeV) mass difference between $\rho-\rho$ and $\omega-\omega$ components of the AX meson is neglected. In principle, the relative weight of these components due to proximity to the decay threshold might be affected by this mass difference. Then the full-scale

dynamics of meson coupling is required to determine the relative weight of $\rho-\rho$ and $\omega-\omega$ components. In estimates to follow we use (17) as a guide.
Finally, we get the expression for the differential width of the decay (1) reading

$$\frac{d\Gamma_{AX}(l^+l^-V)}{d\mathbf{k}} = \frac{m_V}{2E_V}\left\{\frac{1}{3}\Gamma_\rho(l^+l^-) + \Gamma_\omega(l^+l^-)\right\}|\chi(\mathbf{k})|^2 \qquad (18)$$

Note that $\Gamma_{\rho,\omega}(l^+l^-)$ in this equation are the decay widths of off-shell vector mesons (their effective mass is equal to Q) and thus, by virtue of (5), their values may depend on k. If in the vein of vector dominance model we make an additional assumption that they are insensitive to virtuality of the vector meson and, hence are independent of k, then (18) can be easily integrated with the account of (7) to yield

$$\Gamma_{AX}(l^+l^-V) = \frac{1}{2}\left\{\frac{1}{3}\Gamma_\rho(l^+l^-) + \Gamma_\omega(l^+l^-)\right\}. \qquad (19)$$

(When integrating over the c.m.s. momentum we, for simplicity, have neglected relativistic kinematics taking $E_V \simeq m_V$). Thus assuming that AX is a (loosely) bound state of two vector mesons we have obtained the unambigous predictions for its differential and total radiative decay widths (process (1)). Numerically, $AX \to e^+e^- + V$ decay width is rather small making $\simeq 1.43$ keV. However, investigation of this decay may be simplified by clear-cut signatures of events. Recoil of AX-meson produced in the $\bar{p}p$-annihilation being neglected, decay (1) will be observed for $Q \simeq m_V$ as a pair of leptons emitted in opposite directions with the momentum $\approx m_V/2$ with negligible background. Note also that the considered decay provides a unique possibility to probe the wave function of the two-vector-meson bound state (cf. (18)).
In conclusion we dwell upon decay rates for process (1) which are to be expected provided AX-meson has different (not molecular) nature. Molecule-type cluster structure of the meson implies that quarks and antiquarks are tightly packed in vector-meson states wherein their relative distances $r_{q\bar{q}}$ are small compared to the size of the AX-meson r_{AX}. Multiquark or quasinuclear exotics assumes that it has either $\bar{q}^2q^2$ or $\bar{N}N$ structure. In terms of spatial structure it implies that quarks and antiquarks are either homogeniously distributed over the AX-meson volume or quark and antiquarks are packed separately. In both cases $\bar{q}q$ annihilation into l^+l^- pair is hindered in comparison to tightly packed vector-meson state. Corresponding suppression factor equals to $r_{q\bar{q}}/r_{AX}$ in the first case and the same factor squared in the

second. Without knowledge of detailed and complicated dynamics of multi-quark states one can hardly get a quantitative estimate for these suppression factors, nevertheless one can make qualitative conclusion that if AX-meson is not a vector-meson molecule, its decay rate in the process (1) will be much smaller than (19).

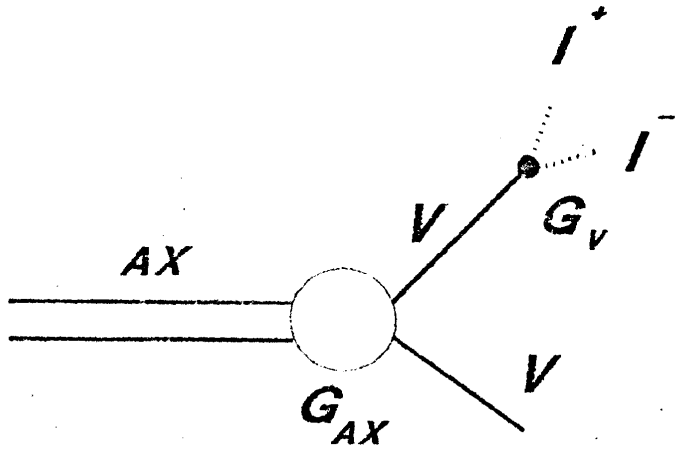

Fig.1. Diagram depicting radiative decay of the AX-meson: $AX \to l^+l^- + V$.

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