MEDIUM EFFECTS IN THE PRODUCTION OF ω AND ϱ–RESONANCES IN PROTON–NUCLEUS AND ANTIPROTON–NUCLEUS INTERACTIONS*

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We calculate the forms of ω and ρ resonances produced in the reactions $pA \to VX \to e^+e^-X$ and $\bar{p}A \to VX \to e^+e^-X$ at rest. The mass distributions have two component structure which corresponds to the decay of resonance outside and inside nucleus. The latter component has the mass and width distorted by nuclear medium. We investigate also the role of the final state interaction of decay products in the reactions $\bar{p}A \to \rho X \to \pi^+\pi^-X$ and $\bar{p}A \to \omega X \to \pi^0\gamma X$.

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It is known (see, *e.g.* [1, 2]) that the nuclear matter modifies the properties of hadronic resonances. In particular, as it was shown in Ref. [2], the mass distribution of resonance created on nuclear target has two component structure. The first (narrow) component has the vacuum values of mass and width. It corresponds to the decay of resonance outside the nucleus. The second (broad) component corresponds to the resonance decay inside the nucleus. It can also be described by the Breit–Wigner formula with mass and width distorted by nuclear medium.

To describe this effect, it is convenient to consider the creation and decay of a fast resonance when its wave length is much smaller than nuclear radius. Then it is possible to use the eikonal approximation and to write the

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Green function of the resonance propagating through nuclear matter from the point $\vec{r} = (\vec{b}, z)$ to the point $\vec{r}' = (\vec{b}', z')$ in the following form [2]:

$$G_k(\vec{b}', z'; \vec{b}, z) = \frac{1}{2ik} \exp\left\{ i \int_z^{z'} [k + \frac{1}{2k}(\Delta + 4\pi f(0)\rho(\vec{b}, \zeta)] d\zeta \right\}$$
$$\times \ \delta(\vec{b} - \vec{b}')\Theta(z' - z)\,, \tag{1}$$

where z axis is directed along the resonance momentum $\vec{k}$, $\vec{b}$ is the impact parameter, $f(0)$ is the resonance-nucleon forward scattering amplitude, ρ is the nuclear density, Δ is the inverse resonance propagator

$$\Delta = P^2 - M_R^2 + iM_R\Gamma_R \tag{2}$$

with M_R, Γ_R and P being the mass, width and four momentum of the resonance. The latter can be defined through four momenta of its decay products

$$P = p_1 + p_2 + \dots . \tag{3}$$

Let us consider the production of the vector mesons ρ and ω on nuclear target and its decay into the lepton e^+e^- pair:

$$\bar{p}A \to RX \to e^+e^-X. \tag{4}$$

If the resonance R appears at the point $(\vec{b}, z)$ and decays in the point $(\vec{b}', z')$ then in the exponent of the Green function (1) we can separate the contributions from two different regions

1. $z \le z' \le z_s = \sqrt{R^2 - \vec{b}^2}$ and
2. $z' \ge z_s = \sqrt{R^2 - \vec{b}^2}$.

When resonance decays inside the nucleus only the first region contributes, and the inverse resonance propagator has the form

$$\Delta^* = \Delta + 4\pi f(0)\rho_0 = P^2 - M_R^{*2} + iM_R^*\Gamma_R^*\,, \tag{5}$$

where

$$M_R^{*2} = M_R^2 - 4\pi \mathrm{Re} f(0)\rho_0\,, \tag{6}$$
$$M_R^*\Gamma_R^* = M_R\Gamma_R + 4\pi \mathrm{Im} f(0)\rho_0\,. \tag{7}$$

When the resonance decays outside the nucleus both regions contribute, and the probability of production of the lepton pair with the total momentum $\vec{P}$ and the invariant mass squared P^2 can be written as

$$|M(\vec{P}, P^2)|^2 = N|f_{RX}|^2 \int d^2\vec{b}dz\rho(\vec{b}, z)|A_{\mathrm{in}}(\vec{P}, P^2; \vec{b}, z) + A_{\mathrm{out}}(\vec{P}, P^2; \vec{b}, z)|^2\,, \tag{8}$$

where the contributions from the first and second regions can be written as

$$A_{\rm in}(\vec{P}, P^2; \vec{b}, z) = \frac{1 - \exp[i(\Delta^*/2k)(z_s - z)]}{\Delta^*}, \tag{9}$$

$$A_{\rm out} = \frac{\exp[i(\Delta^*/2k)(z_s - z)]}{\Delta}. \tag{10}$$

Other notations in the Eqs (8)–(10) are following: f_{RX} is the amplitude of the inclusive resonance production, N is the normalization factor which contains also the branching ratio of $R \to e^+e^-$ decay.

Therefore when the resonance decays inside the nucleus, its form is described by the Breit–Wigner formula (9) which contains the effects of broadening

$$\Gamma_R^* = \Gamma_R + \delta\Gamma, \tag{11}$$

where

$$\delta\Gamma = \gamma v \sigma_{(RN)} \rho_0, \tag{12}$$

and mass shift

$$M_R^* = M_R + \delta M_R, \tag{13}$$

where

$$\delta M_R = -\gamma v \sigma_{(RN)} \rho_0 \alpha. \tag{14}$$

In Eqs (12) and (14) v is the resonance velocity, γ is the Lorentz factor, ρ_0 is the nuclear density, $\sigma_{(RN)}$ is the resonance-nucleon total cross section and $\alpha = +{\rm Re}f(0)/{\rm Im}f(0)$.

If α is small (as usually happens when there are many reaction channels) the broadening is the main effect.

We calculated the form of the ω – and ρ– peaks produced in the annihilation of antiprotons at rest on Au. The yields of ρ– and ω–mesons were calculated in the framework of intranuclear cascade model developed in ref. [3]. In order to take into account two component structure of resonance peak in e^+e^- decay mode, the intranuclear cascade model was modified. The contributions of broad and narrow components were calculated as follows. The mass of produced resonance was generated according to the Breit–Wigner distribution with the width $\Gamma_R^* = \Gamma_R + \delta\Gamma_R$. When resonance decays inside the nucleus, the event was added to the broad component. When resonance leaves the nucleus, its mass was redefined according to the narrow Breit–Wigner distribution with constraint imposed by energy conservation.

In Fig. 1 we presented the e^+e^- mass spectrum from ρ and ω decay. The dashed and dotted curves describe the contributions of narrow and broad component respectively. The solid curve describes the sum of them. We assume that $\sigma_{\rho N} \approx \sigma_{\pi N}$, and $\sigma_{\omega N}$ is taken as in Ref. [3]. The spectra of ω

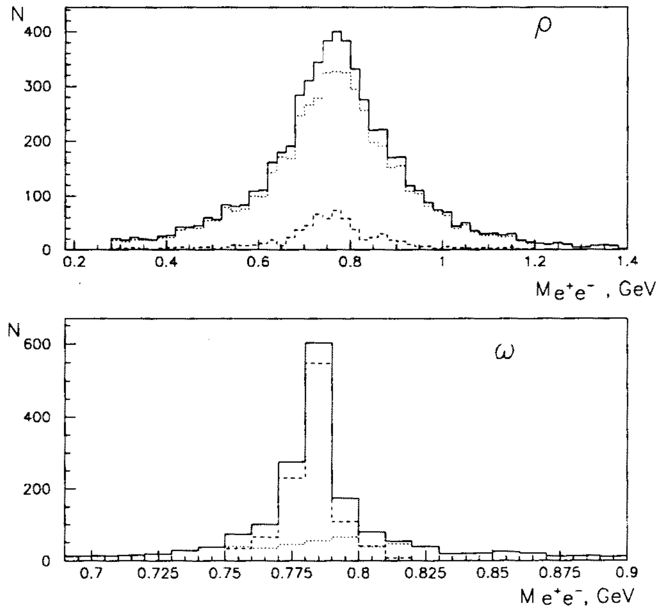

Fig. 1. Invariant mass spectrum of e^+e^--pairs produced in annihilation of stopped antiprotons on gold nucleus. Upper part — reaction $\bar{p}Au \to \rho X \to e^+e^-X$, lower part — reaction $\bar{p}Au \to \omega X \to e^+e^-X$. Dashed and dotted histograms describe the contributions from decay of resonance inside and outside the nucleus, respectively, solid histogram describes the sum of these contributions.

and ρ mesons in $\bar{p}p$-annihilation are presented in Ref. [3]. They are extended till 800 MeV/c with average momentum about 350 MeV/c.

As ρ– meson decays mainly inside the nucleus the broad component gives dominant contribution in Fig. 1 a. The width of the ρ-peak is about 220 MeV which is essentially larger than its vacuum width $\Gamma_\rho \approx 150 MeV$. In the case of ω–meson (Fig. 1b) the integrals under the dashed and dotted curves are comparable while the widths are quite different $\Gamma^*_\omega \gg \Gamma_\omega$.

If the resolution in M is good ($\delta M \sim 5$ MeV), then the narrow component can be simply separated from the broad background. If the resolution in M is bad ($\delta M \sim 50$ MeV), then the separation of two components is not trivial, and the two component structure of ω peak should be taken into account.

We have also calculated the forms of ρ and ω peaks in the reactions $\bar{p}$Au $\to \rho X \to \pi^+\pi^-X$ and $\bar{p}$Au $\to \omega X \to \pi^0\gamma X$ (see Fig. 2a and 2b respectively). The dashed curves in fig.2a and 2b describe the forms of ρ and ω peaks when the resonances decay inside the nucleus and the final state interaction (FSI) of pions is switched off. The solid curves were calculated taking into account rescattering of pions. FSI of the decay products shifts both resonance peaks to lower mass, and the magnitude of this shift is about 200 MeV. Moreover the form of the peaks becomes quite different from the Breit–Wigner one.

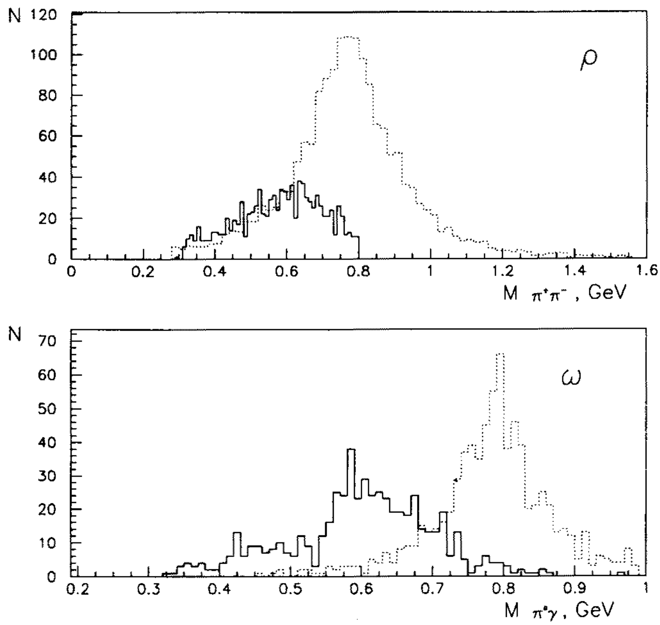

Fig. 2. Invariant mass spectrum of resonance decay products inside the nucleus before (dotted histograms) and after (solid histograms) rescattering. Upper part — reaction $\bar{p}Au \to \rho X \to \pi^+\pi^- X$, lower part — reaction $\bar{p}Au \to \omega X \to \pi^0\gamma X$.

We calculated also the form of ω peak in the reaction $pA \to VX \to e^+e^-X$ at proton energy $T_{\rm lab} = 2$ GeV. In this case, there are two main mechanisms of ω production [4]:

- direct $NN \to \omega NN$ and
- two-step process $NN \to \pi NN$ (1), $\pi N \to \omega N$ (2).

The ω spectrum is presented in Fig. 3. It is extended till 1.5 GeV/c with average momentum around 0.72 GeV/c. The dashed and dotted histograms in fig.4 describe the contribution of narrow and broad components of ω peak. The solid histogram is the total contribution. In this case, the width of ω peak is larger than in the reaction $\bar{p}A \to e^+e^-X$ at rest. The main reason is that the mean momentum of ω produced in the reaction pA at

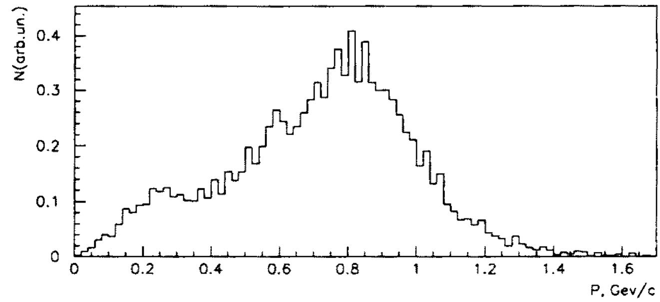

Fig. 3. Momentum distribution of ω mesons produced in p Au interaction at 2 GeV.

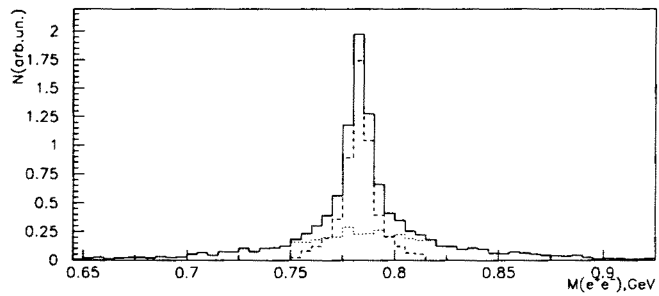

Fig. 4. Invariant mass spectrum of e^+e^--pairs produced in $p\text{Au} \to \omega X \to e^+e^-X$ reaction at 2 GeV. Dotted and dashed histograms describe the contributions from decay of resonance inside and outside the nucleus, respectively, solid histogram describes the sum of these contributions.

2 GeV is higher than in the reaction $\bar{p}A$ at rest. This leads to the larger collision broadening $\delta\Gamma$ as it is given by Eq. (12).

Conclusions

The shape of hadron resonance produced on nuclear targets is distorted by nuclear medium. For $kR \gg 1$ the main effect is the collision broadening $\delta\Gamma = \gamma v \sigma_{(RN)} \rho_0$. The resonance peak has two components: the narrow one from the decay outside nucleus, and the broad one from the decay inside nucleus.

Two component theory of resonance production [2] is incorporated into the intranuclear cascade model for pA, πA and $\bar{p}A$ collisions. This is a powerful tool to give quantitative support for experiments which investigate medium effects in the resonance production on nuclear targets.

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