Photoproduction of ψ mesons

V. I. Zakharov, B. L. Ioffe, and L. B. Okun'

Institute of Theoretical and Experimental Physics
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Possible reasons for the smallness of the cross section for the photoproduction of ψ mesons are discussed. The causes of the decrease are: a) the cross section for the scattering of a real ψ meson is small because of the small residue of the Pomeranchuk trajectory; b) the virtual ψ meson does not have time due to the large mass m_ψ to develop during the time E_γ/m_ψ^2 a pomeron shower, and therefore the diffraction transition of a virtual ψ with $q^2=0$ into a real one with $q^2=m_\psi^2$ is small; c) the transition $\psi\to\gamma$ is weak, and the vertex $g_e\psi_\mu\bar{e}\gamma_\mu e$ is a primary one and is not due to the virtual photon. It is shown that it is possible to choose between these possibilities by an experimental investigation of processes of electric production of ψ mesons and of their photoproduction on nuclei.

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At the present time it seems most likely that the recently discovered ψ mesons—narrow resonances of masses 3.1 and 3.7 GeV[1-4]—are hadrons (for example, bound $c\bar{c}$ states of quarks). The known data agree not too badly with such a hypothesis, with the exception, possibly, of the data on the cross section for photoproduction[1)]

$$\sigma(\gamma N\to\psi X)\approx 20\ \text{nb}\quad (E_\gamma>70\ \text{GeV}), \tag{1}$$

which turned out to be anomalously small compared to the cross sections for the "elastic" photoproduction of ordinary vector mesons: ρ – 14000 nb, ω – 2000 nb, φ – 600 nb, ρ' – 1600 nb[5,6].

We discuss the following possibilities for explaining the smallness of the cross section for the photoproduction of ψ.

I. For ψ mesons the Pomeranchuk residue is small, i.e., the total cross section for the interaction of a real ψ meson with a nucleon is small.

II. The residue of the Pomeranchuk pole is small only for a virtual ψ meson with $q^2=0$, but is of the usual order of magnitude for real ψ mesons and other particles consisting of charmed quarks.

III. In contrast to ordinary hadrons ψ mesons have a direct interaction with electrons and muons and the transition $\gamma\to\psi$ is weak.

1. In discussing the possibility I we assume a naive vector dominance and estimate the ratio of cross sections for the strong interactions of ψ and other vector mesons. It turns out to be small. For example,

$$r_{\psi\rho}\equiv\frac{\sigma(\psi N\to\psi X)}{\sigma(\rho N\to\rho X)}=\frac{\Gamma_{\rho\to ee}}{\Gamma_{\psi\to ee}}\frac{m_\psi}{m_\rho}\frac{\sigma(\gamma N\to\psi X)}{\sigma(\gamma N\to\rho X)}\approx\frac{7\,\text{keV}}{6\,\text{keV}}\frac{3.1\,\text{GeV}}{0.77\,\text{GeV}}\frac{20\ \text{nb}}{1.4\ \mu\text{b}}\approx\frac{1}{150}, \tag{2}$$

where $\Gamma_{\rho\to ee}$, $\Gamma_{\psi\to ee}$ are the widths for the decay of ρ and ψ mesons into e^+e^-; m_ρ and m_ψ are the meson masses. Similar relations for other mesons are equal to:

$$r_{\rho'\rho}\approx 1.4,\quad r_{\omega\rho}\approx 1.2,\quad r_{\varphi\rho}\approx {}^1/_4. \tag{3}$$

Thus, starting with the hypothesis of naive vector dominance we arrive at the conclusion of the smallness of the residue of the Pomeranchuk pole for ψ mesons. Such smallness can be due to the fact that c quarks interact relatively weakly with ordinary hadrons. In such a case the small width for the radiation transitions $\psi\to$ hadrons + γ appears to be natural. As regards the decay $\psi(3.7)\to\psi(3.1)2\pi$, its observed width corresponds to an effective constant $\lambda\sim 5$ at the vertex $(4\pi)^{1/2}\lambda\psi\psi\pi\pi$, and such a value of λ also corresponds to a fairly weak interaction of ψ and π mesons, since it leads to a cross section for their low energy scattering $\sigma(\pi\psi'\to\pi\psi)\sim 1/m_\psi^2$, which is small compared to the unitary limit.

The smallness of the elastic cross section for ψN scattering means that although the total cross section for the ψN interaction with a nucleon is small, nevertheless it is considerably greater than the elastic cross section. Indeed, in virtue of the optical theorems

$$\sigma_{el}(\psi N)\approx\sigma_{tot}^2(\psi N)\,|t_{eff}|/16\pi. \tag{4}$$

Assuming that the effective value for the square of the transferred momentum t_{eff} for ψ is the same as for ρ mesons ($|t_{eff}|\sim\text{GeV}^2/6$) we obtain from (4) and (2)

$$\frac{\sigma_{tot}(\psi N)}{\sigma_{tot}(\rho N)}\approx\left[\frac{\sigma(\psi N\to\psi N)}{\sigma(\rho N\to\rho N)}\right]^{1/2}\approx\left[\frac{\sigma(\psi N\to\psi X)}{\sigma(\rho N\to\rho X)}\right]^{1/2}\approx\frac{1}{12}. \tag{5}$$

Taking into account the fact that for a ρ meson $\sigma_{el}\approx 4$ mb, $\sigma_{tot}\approx 22$ mb, $\sigma_{el}/\sigma_{tot}\sim {}^1/_5$, we obtain from (5) and (2)

$$\sigma_{tot}(\psi N)/\sigma_{el}(\psi N)\sim 50. \tag{6}$$

Starting with the premise that ψ is a bound $c\bar{c}$ state and taking the annihilation of $c\bar{c}$ into usual hadrons to be small, we arrive at the conclusion that in the total cross section for the interaction of ψ with nucleons the production of charmed particles must dominate. From this it follows that the total cross section for the photoproduction of pairs of charmed particles at energies considerably greater than threshold must also be considerably greater than the cross section for the photoproduction of ψ mesons:

$$\sigma(\gamma N\to\bar{D}DX)/\sigma(\gamma N\to\psi X)\sim 50, \tag{7}$$

where $D\bar{D}$ denotes a pair of charmed mesons.

One should make the reservation that in making the above estimates we assumed that the cross sections for the "elastic" photoproduction of ψ and for the diffraction excitation of ψ are of the same order of magnitude (cf., (5)). This is indeed true for ordinary vector particles. But if this is not so for ψ bosons, and in the experiment on photoproduction the cross section for diffraction excitation was observed to be considerably, say, by a factor of n greater than the cross section for elastic photoproduction, then the right hand side of relation (6) must be greater by a factor of $\sqrt{n}$, while the right hand side of (7) must be, roughly speaking, smaller by a factor of $\sqrt{n}$. Such a possibility can also be checked experimentally.

2. For ψ mesons, naive vector dominance and relations (2) and (7) following from it need not hold, owing to their large mass. The possibility II mentioned above consists of the supposition that for real ψ mesons the residue of the Pomeranchuk pole is of the usual order of magnitude, while it is small for virtual ones. The physical reason for the relative smallness of the cross section for the interaction of virtual ψ can be sought in the shortness of the time for a fluctuation in the course of which a photon exists in the form of ψ. This time in the laboratory system of coordinates is, evidently, of order E_γ/m_ψ^2, where E_γ is the photon energy. On the other hand, the time needed for the development of a pomeron shower is of order of magnitude of $E_\gamma/m_{char}m_\psi$, where m_{char} is a certain characteristic mass for strong interactions. If $m_{char} < m_\psi$, then an additional suppression of the cross section for the photoproduction of ψ arises. Such a space-time picture of the process of photoproduction of ψ arises naturally in the parton model[7]. In favor of such a picture we also have the circumstance that in the case of electroproduction of pions by a virtual photon of large mass Q^2 a similar discussion agrees with the behavior of the cross section for the photoproduction by a virtual photon on a nucleon $\sigma_\gamma(\nu, Q^2) \sim 1/Q^2$[8] and leads to a good description of the experimental data[9]. Since scaling in electroproduction occurs at not very great values of Q^2, one can suppose that $m_{char} \lesssim 1$ GeV.

We also call attention to a possible analogy between the photoproduction of ψ and the electroproduction of ρ mesons when $Q^2 + m_\rho^2 \sim m_\psi^2$. It is well known that both the total cross section and the fraction for the production of ρ mesons in the total cross section falls off with increasing Q^2.[2] It is therefore natural to assume that the photoproduction of ψ mesons is suppressed compared with ρ mesons and the suppression factor has the form $(m_\rho^2/m_\psi^2)^n$, where $n = 1 - 2$.[3]

If we introduce the factor m_ρ^2/m_ψ^2 into Eqs. (2) and (5), then we have

$$\sigma_{tot}(\psi N)/\sigma_{tot}(\rho N) \sim 1/3, \tag{8}$$

i.e., the cross sections for the interaction of real ψ mesons with nucleons will be of the order of hadron cross sections. In such a case relation (6) does not hold and the total cross section for the photoproduction of pairs of charmed particles must be of the order of (or several times larger than) the cross section for the photoproduction of ψ mesons.

It is possible to distinguish between possibilities I and II in experiments on photoproduction of ψ mesons on nuclei. In case I the nucleus is transparent for ψ mesons, remaining nontransparent for ρ mesons. Therefore for $E_\gamma < m_\psi^2 R_{nucl}$ the cross section for photoproduction of ψ must be proportional to A; at the same time the cross section for photoproduction of ρ is proportional to $A^{2/3}$. At an energy $E_\gamma \gg m_\psi^2 R_{nucl}$, when production of ψ mesons occurs in a region outside the nucleus, the cross section for photoproduction of ψ can also be proportional to $A^{2/3}$. In case II the nucleus is nontransparent for ψ mesons and therefore even for $E_\gamma < m_\psi^2 R_{nucl}$ the cross section for photoproduction of ψ must be proportional to $A^{2/3}$. In such a case ψ are created over the whole nuclear volume, but only those ψ mesons leave the nucleus without breaking up into pairs of charmed particles of type $D\bar{D}$ which were produced in a thin outer shell of the nucleus near its rear wall. Therefore one can expect that the ratio of cross sections for photoproduction of ψ and $D\bar{D}$ will in this case be proportional to $A^{1/3}$.

3. We now consider possibility III when the ψ meson has a direct interaction with electrons and hadrons with constants g_e and g_h, while the transition $\psi \to \gamma$ arises only in second order in e and g_e (or g_h). Then the ψ boson is a particle of the type of intermediate bosons that were discussed at one time[12-15], which had a semiweak (but parity-conserving) interaction linear in the ψ field, and a strong interaction with hadrons quadratic in ψ.

Such an intermediate boson (stenon, according to the terminology of Applequist and Bjorken[15]) in the majority of its interactions with ordinary hadrons and leptons is indistinguishable from a boson of hadron nature, which due to any kind of selection rules goes over weakly into ordinary hadrons. In particular, the processes of single and pair creation of ψ bosons in hadron collisions could have comparable cross sections in both cases. Further, the constant for the coupling of a stenon with leptons determined from the width of the decay $\psi \to e^+e^-$ is equal to $g_e \approx 2 \times 10^{-3}$ ($\Gamma_{\psi\to ee} = g_e^2 m_\psi/3$) and is of the same order of magnitude as for a hadron making a transition into leptons through a virtual photon $g_e \sim \alpha/\pi$. One might expect that due to the existence of a strong quadratic interaction of a stenon with hadrons the cross section for its elastic scattering by nucleons must be of the order of magnitude of ordinary hadron elastic cross sections, i.e., $\sim$ 5—10 mb, while the cross section for elastic photoproduction is

$$\sigma(\gamma N \to \psi N) \sim \alpha g_h^2 \sigma(\psi N \to \psi N) \sim 10 \text{ nb}$$

It is possible to check the hypothesis of the stenon nature of a ψ boson by investigating the process of electroproduction of ψ. Electroproduction of $c\bar{c}$ mesons on nucleons is described by the usual formulas:

$$\frac{d\sigma}{dQ^2\,d\nu} = \frac{\alpha}{\pi}\frac{1}{Q^2}\frac{1}{E}\left[\frac{mE-\nu}{\nu m} + \frac{\nu}{2Em^2}\right]\sigma_T(Q^2, \nu), \tag{9}$$

where $\sigma_\gamma(\nu, Q^2)$ is the cross section for photoproduction by a virtual photon, $\nu = m(E - E')$, E, E′ are the energies of the initial and the final electrons, m is the nucleon mass. (It is assumed that $\nu^2 \gg m^2Q^2$ and that the contribution of longitudinally polarized virtual photons has been neglected).

When $Q^2 \gg \alpha(g_h/g_e)m_\psi^2$ electroproduction of stenons is determined by the diagram of Fig. 1 and

$$\frac{d\sigma}{dQ^2\,d\nu} = \frac{g_e^2}{\pi}\frac{1}{(m_\psi^2+Q^2)^2}\frac{Q^2}{E}\left[\frac{mE-\nu}{\nu m} + \frac{\nu}{2Em^2}\right]\sigma_{scatt}(Q^2, \nu), \tag{10}$$

where $\sigma_{scatt}(Q^2, \nu)$ is the cross section for the scattering of a virtual ψ by a nucleon.

From a comparison of (9) and (10) it can be seen that the dependence of $d\sigma/dQ^2d\nu$ on Q^2 in the region

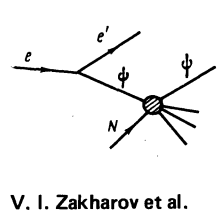

Diagram describing the electroproduction of ψ mesons in the case of their direct interaction with electrons ("stenon" hypothesis).

$\alpha m_\psi^2 \ll Q^2 \leq m_\psi^2$ differs considerably in the case of the two hypotheses under consideration. If one assumes that $\sigma_{scatt}(Q^2, \nu) = \sigma^0$ for $Q^2 < m_0^2$ and $\sigma_{scatt}(Q^2, \nu) = \sigma^0 m_0^2/Q^2$ for $Q^2 > m_0^2$, then for the total cross section for electroproduction according to the stenon hypothesis it follows from (10) that

$$\sigma(eN \to e\psi + \ldots) \sim \frac{g_e^2}{\pi}\frac{m_0^2}{m_\psi^2}\left(1+\frac{1}{2}\frac{m_0^2}{m_\psi^2}\right)\sigma^0\left[\ln\frac{mE}{\nu_m}-\frac{3}{4}+\frac{\nu_m}{mE}-\frac{1}{4}\frac{\nu_m^2}{m^2E^2}\right], \quad (11)$$

where $2\nu_m = m_\psi^2 + 2m_\psi m$. For $E = 20$ GeV, $m_0 = 1$ GeV, $\sigma^0 = 10$ mb, the cross section for electroproduction of ψ-meson is $\sigma(eN \to e\varphi + \ldots) \approx 0.5$ nb.

It is important to note that it is already now possible to exclude the possibility of a direct interaction of ψ with a neutrino with the constant $g_\nu \sim g_e$. Indeed, in the opposite case the cross section for the production of a stenon in a neutrino experiment would be of the same order of magnitude as the cross section for the electroproduction of ψ. In spite of the possible indefiniteness in the values of m_0 and σ^0, one can make an estimate that for $E_\nu \sim 100$ GeV $\sigma(\nu N \to \nu\psi + \ldots) \sim 10^{-34}$ cm^{-2} and the cross section for the production of muon pairs $\sigma(\nu N \to \mu^+\mu^-\nu + \ldots) \sim 10^{-35}$ cm^2. This value exceeds by several orders of magnitude the experimental upper limit for this quantity.

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1) Private communications from D. Bjorken on preliminary results obtained at the NAL [16].

2) In the case of electroproduction of ρ mesons $|t_{eff}|$ increases with increasing Q^2. Analogously one can expect that $|t_{eff}|$ for photoproduction of ψ is greater than in the case of ρ. One must keep this circumstance in mind in the reduction of experimental data.

3) The suppression factor under discussion here is of a different nature than the one which was considered in references [10,11].

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