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PARITY DETERMINATION FOR THE NEW GENERATION OF HEAVY NEUTRAL MESONS

by

Ngee-Pong Chang

Physics Department
City College of the City University of New York
New York, New York 10031

C. A. Nelson

Deutsches Elektronen-Synchrotron DESY, Hamburg
and
Department of Physics
State University of New York at Binghamton
Binghamton, New York 13901

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Ngee-Pong Chang
Physics Department
City College of the City University of New York
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and

C. A. Nelson
Deutsches Elektronen-Synchrotron DESY, Hamburg
and
Department of Physics [+]
State University of New York at Binghamton
Binghamton, New York 13901

Abstract

We consider how best to experimentally determine the parity quantum number of a new heavy neutral meson, including the possibility of exotic J^{PC}. Multiquark and gluonium states can have exotic J^{PC} quantum numbers forbidden to the non-relativistic $q\bar{q}$ system. If only the existence of easily identifiable two-body hadronic modes is known, it is not possible to establish the parity so an "exotic" meson, $J > 0$, could be mis-identified as a "normal" meson. Direction-linear polarization coefficients, which would identify the parity, are also found to be small for $e\bar{e} \to 1^{--} \to 1^{\pm+}\gamma$, $0^{\pm+}\gamma$ with the high energy photon externally converting into an $e\bar{e}$ pair. However, important parity tests do exist, independent of the polarization state of the decaying particle, which can be used to settle the confusion. These are listed in Part III of this paper.

[+] Permanent address

I. DIFFICULTIES IN ESTABLISHING PARITIES BY EXISTENCE OF HADRONIC DECAY MODES

The rich structure of states in the psion family suggests a whole new generation of heavy neutral mesons, made presumably out of a new heavy quark-antiquark pair, and possibly of gluon and/or multi-quark bound states. These new heavy mesons are generally expected to be ordinary isotopic-spin singlets, with J^{PC} quantum numbers being those allowed for a non-relativistic $q\bar{q}$ system, viz 0^{-+}, 0^{++}, 1^{++}, 1^{--}, 1^{+-}, 2^{++}, 2^{--}, 2^{-+}, ... Mesons with J^{PC} that are not found in a non-relativistic $q\bar{q}$ system are, by definition, exotic. Their quantum numbers are given by 0^{--}, 0^{+-}, 1^{-+}, 2^{+-}, ... Among the well-known low energy resonances, no exotic mesons have to date been confirmed. The treatment of parity determination given below applies, of course, both to new generations of heavy neutral mesons in a non-relativistic $q\bar{q}$ system and also to the general case which includes exotic J^{PC} mesons.

Among the recently discovered new heavy mesons, it is reasonable to expect, based on ideas of QCD and bag model, the formation of multiquark-antiquark states such as the baryonium ($qq\bar{q}\bar{q}$) and higher multiquark states ($qqq\bar{q}\bar{q}\bar{q}$, etc.).[1] These multiquark states will in general have J^{PC} quantum numbers that include those forbidden to the non-relativistic $q\bar{q}$ system. Thus "exotic" mesons are likely to exist, as a corollary to any discovery of baryonium states[2], and should be experimentally looked for and distinguished from the "normal" mesons. Similarly, gluonium[3] has exotic J^{PC} (see Eq. (2) below).

Exotic mesons, assuming they can be found, can also be interpreted[4] as a signal for relativistic bound state $q\bar{q}$ systems.

In this paper we address ourselves to the question of how one can decide experimentally that a given new heavy neutral meson is "exotic". Apart from the exception of a spin-*0* exotic meson, for it has odd charge-conjugation quantum number, we can point out some "confusion" theorems. They emphasize the fact that without a determination of its intrinsic parity an exotic meson could be easily mis-identified as a "normal" meson. So then in part II of this paper, because of the potential application in $e\bar{e}$ colliding beam processes, we discuss parity determination by γ cascade. The direction-linear polarization coefficients are found to be small for $e\bar{e} \to 1^{--} \to 1^{\pm +}\gamma$, $0^{\pm +}\gamma$ with the photon converting externally. In part III of our paper we give a list of important parity tests that can be made to settle the confusion.

To keep our discussion simple and for convenience in reference to experiments, we shall limit our attention to the easily identifiable two body decay modes [5] $P\bar{P}$, $V\bar{V}$, $B\bar{B}$, PV and list the allowed J^{PC} quantum numbers if a given heavy neutral isotopic-spin singlet meson has been seen in that channel:
(exotic J^{PC} quantum numbers are in italic's)

$$P\bar{P} \text{ seen: } J^{PC} = 0^{++},\ 1^{--},\ 2^{++},\ \ldots$$
$$P\bar{P} \text{ absent: } J^{PC} = \mathit{0}^{+-},\ \mathit{1}^{-+},\ \mathit{2}^{+-},\ \ldots;\ \mathit{0}^{--};\ 0^{-+};\ 1^{+\pm},\ 2^{-\mp},\ \ldots \tag{1}$$

$$V\bar{V} \text{ seen: } J^{PC} = 0^{++};\ 1^{\mp\mp},\ 2^{\pm\pm},\ \ldots;\ 0^{-+};\ 1^{+-},\ 2^{-+},\ \ldots;\ \mathit{1}^{-+},\ \mathit{2}^{+-},\ \ldots$$
$$V\bar{V} \text{ absent: } J^{PC} = \mathit{0}^{--},\ \mathit{0}^{+-} \tag{2}$$

$$B\bar{B} \text{ seen: } J^{PC} = 0^{++};\ 1^{\pm\pm},\ 2^{\mp\mp},\ \ldots;\ 0^{-+},\ 1^{+-},\ \ldots$$
$$B\bar{B} \text{ absent: } J^{PC} = \mathit{0}^{--};\ \mathit{0}^{+-},\ \mathit{1}^{-+},\ \ldots \tag{3}$$

And

$$\text{PV seen: } J^{PC} = \underset{\sim}{0}^{--};\ 1^{--},\ 2^{--},\ \ldots;\ 1^{+-},\ \underset{\sim}{2}^{+-},\ 3^{+-};\ \ldots$$
$$\text{PV absent: } J^{PC} = \underset{\sim}{0}^{+-};\ 0^{++},\ 1^{++},\ \ldots;\ 0^{-+},\ \underset{\sim}{1}^{-+},\ 2^{-+};\ \ldots \qquad (4)$$

In Eq.(4) G parity (i.e. isotopic spin and charge conjugation) has been used, e.g. $0^{-+}(I=0) \not\to 0^{-+}(I=1) + 1^{--}(I=1)$. For PV modes involving strange particles, SU(3) has been assumed to be good in the hadronic decay.

Inspection of this list [6] easily shows the following: The presence or absence of any set of these modes cannot be used to establish an exotic spin-J meson with $J > 0$, but only that the observation of the $B\bar{B}$ mode can be used to exclude it. Such an exotic meson can appear in the $V\bar{V}$ channel and if J is even, it can appear in the PV channel. For J = 0 meson, observation of a PV decay mode would directly establish its exoticity, whereas observation of $P\bar{P}$, $V\bar{V}$, $B\bar{B}$ modes would imply that its J^{PC} quantum number is not exotic. 0^{+-}, however, cannot be established directly through these hadronic modes.

Both 0^{+-} and 0^{--} exotic mesons have negative charge conjugation, and with 0 spin might on dynamical grounds be expected to be among the lowest lying exotic states of a new generation of heavy neutral mesons. Thus the above list very clearly emphasizes the simplicity and importance of a search via a γ cascade chain for a spin 0, iso-singlet, neutral meson state with negative C.

If SU(3) is not assumed to be good for the hadronic PV decay channel of the heavy neutral SU(3) singlet meson, only $J^P = 0^+$ is forbidden for PV mode involving strange particles.

II. PARITY DETERMINATION BY γ CASCADES

Because it is necessary to measure a small direction-polarization correlation of a linearly polarized photon having an energy of the order of a hundred MeV, we find that it would be difficult, though in principle possible, to determine relative parities of states in a new generation of heavy neutral mesons by study of γ cascades. The alignment of an initial 1^{--} state, such as the ψ', is a consequence of its formation by $e\bar{e}$ colliding beams.

This technique for measuring the relative parity has been used extensively, of course, in nuclear physics [7] so we will only briefly review what it is necessary to measure in the relativistic case [8].

To show the confusion theorem that exists even for relativistic systems, unless there is a measurement of the dependence of the decay distribution on the linear polarization of the photon, we recall Zwanziger's decomposition of three- and four-particle scattering amplitudes involving massless particles into a minimum number of linearly independent invariant amplitudes that are free of kinematic singularities [9]. For the electromagnetic vertex function, gauge invariance and Lorentz invariance imply the invariant decay amplitudes for a right circularly polarized photon and those for a left circularly polarized photon are related by (suppressing angular momentum indices)

$$A_+ = \eta A_- ,$$

where η is the relative parity of the other two particles. Because of this simple proportionality [9] which involves the relative parity, there is a confusion about the relative parity unless there is a direction-polarization correlation measurement. To be able to eliminate the confusion, such a measurement must involve linear, not circular, photon polarization.

Assuming a photon energy of the order of a hundred MeV, we consider measurement of photon linear polarization by pair production. Indeed, the absolute rate is small for a high energy γ to convert into $e\bar{e}$ in the presence of the external high Z nucleus; however, it is still worthwhile to calculate the range of allowed values for the resulting correlation coefficients. We follow the Maximon-Olsen treatment of γ linear polarization measurement by pair production [10,11] and obtain the range of allowed values for the correlation coefficients in the two simplest cases

$$e\bar{e} \rightarrow 1^{--} \rightarrow 1^{\pm +}\gamma$$

and

$$e\bar{e} \rightarrow 1^{--} \rightarrow 0^{\pm +}\gamma \, .$$

We consider $e\bar{e} \rightarrow 1^{--} \rightarrow 1^{\pm +}\gamma$ for the case in which the photon and $e\bar{e}$ pair are nearly coplanar. In the 1^{--} rest frame with the γ momentum chosen along the z axis, the resulting direction-polarization distribution $W(\theta,\chi)$ is a function of the polar angle θ of the initial electron beam and of the opening angle χ measured from the initial electron beam to the conversion produced, final, positron momentum direction. For 1^{++} we find

$$W(\theta,\chi) = 1 - (\tfrac{1}{2} - \tfrac{a}{b}) \sin^2\theta + \tfrac{1}{2}(1 + 2\tfrac{M}{N})^{-1} \sin^2\theta \cos 2\chi \tag{5}$$

with a, b $\gtrsim$ 0, and for 1^{-+}

$$W(\theta,\chi) = 1 - (\tfrac{1}{2} - \tfrac{c}{d}) \sin^2\theta - \tfrac{1}{2}(1 + 2\tfrac{M}{N})^{-1} \sin^2\theta \cos 2\chi \tag{6}$$

with c, d $\gtrsim$ 0, where the quantities M and N describe the density matrix for the γ conversion into $e\bar{e}$ in the case of complete screening, which is what is appropriate for a high Z nucleus. These quantities, M and N, are given explicitly in the appendix and are functions of the photon energy k, the final positron energy ϵ_1, the final electron energy ϵ_2, and a parameter α which is needed to correctly analyze [10,11] the conversion density matrix.

This parameter $\alpha = \Delta\phi/\beta$, where $\beta^{-1} = 111/Z^{1/3}$ is the screening radius of the atom in Compton wavelengths. In terms of α the conversion density matrix is found to be

$$\rho_{ij} = \begin{pmatrix} M + N\cos^2\phi_1 & L\sin 2\phi_1 \\ L\sin 2\phi_1 & M + N\sin^2\phi_1 \end{pmatrix} \tag{7}$$

where L = 1/2 N. This, indeed, gives det ρ independent of ϕ_1. The positron azimuthal angle ϕ_1 is measured from the direction of the photon polarization vector to the positron momentum. The elements of this conversion density matrix have been integrated over the polar angles θ_1 (and θ_2) between the momentum of the photon and that of the conversion produced positron (and electron), and have also been integrated over a small range of the azimuthal angle ϕ,

$$[\pi - \Delta\phi] \leq [\phi = \phi_1 - \phi_2] \leq [\pi + \Delta\phi], \quad \Delta\phi << 1,$$

between the $e\bar{e}$ pair which is nearly coplanar with the converting photon.

This latter integration is essential [10,11] since any experiment will average over a small range of ϕ close to π and the elements of the conversion density matrix are very sensitive to ϕ near π.

If data with associated acceptances existed, the full direction-polarization distribution $W(\theta, \chi)$ given above would probably be the quantity to use for making a maximum-likelihood fit by letting a/b (similarly c/d) be a free non-negative parameter. However, to assess the possible magnitude of this parity signature, it is simpler to integrate over the angle θ and consider the case of an equal energy pair, $\epsilon_1 = \epsilon_2 = k/2$ so then for 1^{++}

$$W(\chi) = 1 + \frac{1}{2}\left(1 + \frac{a}{b}\right)^{-1}\left[\frac{R-1}{R+1}\right]\cos 2\chi \tag{8}$$

and for 1^{-+}

$$W(\chi) = 1 - \frac{1}{2}\left(1 + \frac{c}{d}\right)^{-1}\left[\frac{R-1}{R+1}\right]\cos 2\chi \tag{9}$$

where N/M has been replaced by $R = 1 + N/M$, $R \geq 0$.

A plot of R versus α is given in Reference 11) in Fig. 4. In the α range of interest, R increases monotonically with α with a flattening trend for larger α. In particular, for $\alpha = 0$, $R = 0.5$ but this point is $\Delta\phi = 0$ and so it is not relevant to experiment as we discussed above; near $\alpha \simeq 1$, $R = 1$ so here the $W(\chi) = 1$ for both 1^{++} and 1^{-+}; and then at $\alpha = 8$, $R \simeq 1.316$. Assuming, then, a favorable value of $\alpha = 8$ (but still $\Delta\phi \ll 1$), we find for 1^{++}

$$W(\chi) = 1 + \left(1 + \frac{a}{b}\right)^{-1}(0.0682)\cos 2\chi \tag{10}$$

.

with a,b $\geq$ 0, and for 1^{-+}

$$W(\chi) = 1 - \left(1 + \frac{c}{d}\right)^{-1} (0.0682) \cos 2\chi \tag{11}$$

with c,d $\geq$ 0. So, the direction-polarization coefficient cannot be large in this case.

For $e\bar{e} \to 1^{--} \to \bar{0}^{++}\gamma$ the expressions given above hold, but now the coefficients are unique with a = 0 (for 0^{-+}) and c = 0 (for 0^{++}) respectively. The direction-polarization distributions, then, have the coefficients $\pm$ (R-1)/(R + 1) which equal $\pm$ 0.0682 for α = 8.

Our purpose in this calculation was to very simply assess the possible magnitude of this parity signature. The specific choice of α = 8 (but still $\Delta\phi \ll 1$) was made because it is not unrealistic experimentally and because it does enhance the effect, versus a smaller choice of α. Again, if actual data existed, one might be able to enhance the effect somewhat further by cuts in α(Comparison with a similar proposal in Reference 11 indicates that an effective R $\lesssim$ 1.5 in this way might be possible, depending in part on the nucleus chosen, so 0.0682 might be replaced by a number $\lesssim$ 0.2 .).

III. PARITY DETERMINATIONS FOR THE NEW GENERATION OF HEAVY NEUTRAL MESONS

From the preceeding discussion the simplest tests to establish an "exotic" J^{PC} meson, and to determine its parity, are:

(i) For spin 0, if C is odd, then the meson is exotic. Such states can be searched for and established via γ cascade chains. Since $0^{--} \rightarrow$ PV, observation of its PV mode would uniquely establish its parity. For 0^{+-}, however, no easily identifiable hadronic modes exist and so unlike for the case of even charge conjugation, $\phi\phi$ decay[12] cannot be used as a parity test. Other hadronic decay channels can couple to 0^{+-}. In SU(3) limit, both 0^{+-} and 0^{--} can be coupled to AV channel and $0^{+-} \rightarrow$ SV whereas $0^{--} \not\rightarrow$ SV (forbidden by parity conservation). The latter mode would probably be difficult to identify but in principle it is a definitive parity signature for 0^{+-}.

(ii) For spin J, $J > 0$, the simplest test is based on the fact that both the exotic and normal J^{PC} meson can couple to $V\bar{V}$ channel, e.g. $\phi\phi$, so the parity can be determined, if such a decay mode is observed, by a study of the dependence of the decay distribution on the azimuthal angle between the two $V \rightarrow PP'$ decay planes. This method, which is independent of the polarization state of the particle, is discussed in Trueman's recent article [13,12]. For example, consider the choice of 1^{-+} (exotic) versus 1^{++} (normal). Then $\phi\phi \rightarrow 2K2\bar{K}$ or $K^*\bar{K}^* \rightarrow 2K2\pi$ would have a decay distribution $(1 + \frac{1}{2}\cos\phi)$ for $J^{PC} = 1^{-+}$ and $(1 - \frac{1}{2}\cos\phi)$ for $J^{PC} = 1^{++}$. The azimuthal angle between two $V \rightarrow PP'$ decay planes is denoted by ϕ , and the K^+ ... acceptances are $\pi/2$ in the V rest frame (for $\phi \rightarrow K^+K^-$, the angle ϕ is specified by the two K^+ momenta).

Obviously, the parity of new heavy neutral mesons with J^{PC} quantum numbers as allowed by the non-relativistic $q\bar{q}$ system can also be determined. Since $(0^{++}, 1^{--}, 2^{++}, \ldots) \rightarrow P\bar{P}$ but $(0^{-+}, 1^{+-}, 2^{-+}, \ldots) \not\rightarrow P\bar{P}$, observation of $P\bar{P}$ mode will, of course, establish states of the former series. The 1^{--} has quantum numbers of the photon and so could be formed in $e\bar{e}$ colliding beams. Since mesons of both series can couple to $V\bar{V}$, the dependence of the decay distribution on the azimuthal angle of the $V \rightarrow PP'$ decay planes can again be used to establish the parity for states of either series for any spin.

APPENDIX: EXPRESSIONS USED FOR STUDYING MEASUREMENT OF LINEAR γ POLARIZATION BY PAIR PRODUCTION

For completeness we list those expressions which we used in the calculation discussed in Section II. The γ conversion into $e\bar{e}$ density matrix, Eq. (7), we expressed in terms of

$$M(\alpha)=(\alpha^2-1)^{-2}\Big\{\tfrac{1}{2}k^2(\alpha^2-1)\left[-\alpha^2+\alpha(2\alpha^2-1)f(\alpha)\right] - 2\epsilon_1\epsilon_2(\alpha^2-1)\left[-\alpha^2+\alpha^3 f(\alpha)\right]\Big\} \tag{A1}$$

$$N(\alpha)=(\alpha^2-1)^{-2}\Big\{-2\epsilon_1\epsilon_2(\alpha^2-3/2)\left[\alpha^2-\tfrac{1}{3}\alpha(2\alpha^2+1)f(\alpha)\right]\Big\} \tag{A2}$$

where $f(\alpha)=\cosh^{-1}\alpha/(\alpha^2-1)^{1/2}$, $\alpha>1$; 1, $\alpha=1$; $\cos^{-1}\alpha/(1-\alpha^2)^{1/2}$, $\alpha<1$.

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