Production and Decay of Normal and Exotic Mesons in GlueX

GlueX-doc-4788.v10

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December 11, 2020

Abstract

This document summarizes the possible photoproduction mechanisms for both normal and exotic-hybrid mesons in GlueX. It then looks at the allowed possible decay modes for the exotic mesons, and summarizes what the detected final states would be. For the normal mesons, the possible photoproduction mechanisms are summarized. Of particular interest is the differences in photoproduction mechanisms for the $L = 2$ vector mesons.

Mesons in The Quark Model

In the quark model, mesons are bound states of quarks and antiquarks ($q\bar{q}$). The quantum numbers of such fermion-antifermion systems are functions of the total spin, S, of the quark-antiquark system, and the relative orbital angular momentum, L, between them. The spin S and angular momentum L combine to yield the total spin

$$J \quad = \quad L \oplus S \,, \tag{1}$$

where L and S add as two angular momentums.

Parity is the result of a mirror reflection of the wave function, taking $\vec{r}$ into $-\vec{r}$. It can be written as

$$P\left[\psi(\vec{r})\right] \quad = \psi(-\vec{r}) \quad = \eta_P \psi(\vec{r})\,, \tag{2}$$

where η_P is the eigenvalue of parity. As application of parity twice must return the original state, $\eta_P = \pm 1$. In spherical coordinates, the parity operation reduces to the reflection of a Y_{lm} function,

$$Y_{lm}(\pi-\theta, \pi+\phi) \quad = \quad (-1)^l Y_{lm}(\theta,\phi)\,. \tag{3}$$

From this, we conclude that $\eta_P = (-1)^l$.

For a $q\bar{q}$ system, the intrinsic parity of the antiquark is opposite to that of the quark, which yields the total parity of a $q\bar{q}$ system as

$$P(q\bar{q}) \quad = \quad -(-1)^L\,. \tag{4}$$

Charge conjugation, C, is the result of a transformation that takes a particle into its antiparticle. For a $q\bar{q}$ system, only electrically-neutral states can be eigenstates of C. In order to determine the eigenvalues of C (η_C), we need to consider a wave function that includes both spatial and spin information

$$\Psi(\vec{r},\vec{s}) \quad = \quad R(r) Y_{lm}(\theta,\phi)\chi(\vec{s})\,. \tag{5}$$

As an example, we consider a $u\bar{u}$ system, the C operator acting on this reverses the meaning of u and $\bar{u}$. This has the effect of mapping the vector $\vec{r}$ to the u quark into $-\vec{r}$. Thus, following the arguments for parity, the spatial part of C yields a factor of $(-1)^L$. This exchange also flips the spin wave functions, and requires separate analysis for fermions and bosons, although they both reach the same result. For bosons, we get a factor of $(+1)$ for $S = 0$ and (-1) for the $S = 1$ state, resulting in a $(-1)^S$. For fermions, we obtain a factor of (-1) for the $S = 0$ case and a factor of $(+1)$ for the $S = 1$ yielding $(-1)^{S+1}$. However, interchanging fermion and anti-fermion adds an additional factor of (-1), so the end result is also $(-1)^S$. When combined with the L factor, we get the same result for both fermions and bosons. Combining all of this, we find that the C-parity of (a neutral) $q\bar{q}$ system is

$$C(q\bar{q}) \quad = \quad (-1)^{L+S} . \tag{6}$$

Because C-parity is only defined for neutral states, it is useful to extend this to the more general G-parity which can be used to describe all $q\bar{q}$ states, independent of charge. For isovector states ($I = 1$), C would transform a charged member into the oppositely charged state (*e.g.* $\pi^+ \to \pi^-$). In order to transform this back to the original charge, we would need to perform a rotation in isospin ($\pi^- \to \pi^+$). For a state of whose neutral member has C-parity C, and whose total isospin is I, the G-parity is defined to be

$$G \quad = \quad C \cdot (-1)^I , \tag{7}$$

which can be generalized to

$$G(q\bar{q}) \quad = \quad (-1)^{L+S+I} . \tag{8}$$

The latter is valid for all of the $I = 0$ and $I = 1$ members of a nonet. This leads to mesons having well defined quantum numbers: total angular momentum, J, isospin, I, parity P, C-parity, C, and G-parity, G. These are represented as $(I^G)J^{PC}$, or simply J^{PC} for short. For the case of $L = 0$ and $S = 0$, we have $J^{PC} = 0^{-+}$, while for $L = 0$ and $S = 1$, $J^{PC} = 1^{--}$. The allowed quantum numbers for L smaller than 5 are given in Table 1.

QNs					Names				
L	S	J^{PC}	(I^G)		(I^G)			(I)	
0	0	0^{-+}	(1^-)	π	(0^+)	η	η'	$(\frac{1}{2})$	$\mathbf{K}$
0	1	1^{--}	(1^+)	ρ	(0^-)	ω	ϕ	$(\frac{1}{2})$	$\mathbf{K}^*$
1	0	1^{+-}	(1^+)	$\mathbf{b_1}$	(0^-)	$\mathbf{h_1}$	$\mathbf{h_1'}$	$(\frac{1}{2})$	$\mathbf{K_1}$
1	1	0^{++}	(1^-)	$\mathbf{a_0}$	(0^+)	$\mathbf{f_0}$	$\mathbf{f_0'}$	$(\frac{1}{2})$	$\mathbf{K_0^*}$
1	1	1^{++}	(1^-)	$\mathbf{a_1}$	(0^+)	$\mathbf{f_1}$	$\mathbf{f_1'}$	$(\frac{1}{2})$	$\mathbf{K_1}$
1	1	2^{++}	(1^-)	$\mathbf{a_2}$	(0^+)	$\mathbf{f_2}$	$\mathbf{f_2'}$	$(\frac{1}{2})$	$\mathbf{K_2^*}$
2	0	2^{-+}	(1^-)	$\pi_\mathbf{2}$	(0^+)	$\eta_\mathbf{2}$	$\eta_\mathbf{2}'$	$(\frac{1}{2})$	$\mathbf{K_2}$
2	1	1^{--}	(1^+)	$\rho_\mathbf{1}$	(0^-)	$\omega_\mathbf{1}$	$\phi_\mathbf{1}$	$(\frac{1}{2})$	$\mathbf{K_1^*}$
2	1	2^{--}	(1^+)	$\rho_\mathbf{2}$	(0^-)	$\omega_\mathbf{2}$	$\phi_\mathbf{2}$	$(\frac{1}{2})$	$\mathbf{K_2}$
2	1	3^{--}	(1^+)	$\rho_\mathbf{3}$	(0^-)	$\omega_\mathbf{3}$	$\phi_\mathbf{3}$	$(\frac{1}{2})$	$\mathbf{K_3^*}$
3	0	3^{+-}	(1^+)	$\mathbf{b_3}$	(0^-)	$\mathbf{h_3}$	$\mathbf{h_3'}$	$(\frac{1}{2})$	$\mathbf{K_3}$
3	1	2^{++}	(1^-)	$\mathbf{a_2}$	(0^+)	$\mathbf{f_2}$	$\mathbf{f_2'}$	$(\frac{1}{2})$	$\mathbf{K_2^*}$
3	1	3^{++}	(1^-)	$\mathbf{a_3}$	(0^+)	$\mathbf{f_3}$	$\mathbf{f_3'}$	$(\frac{1}{2})$	$\mathbf{K_3}$
3	1	4^{++}	(1^-)	$\mathbf{a_4}$	(0^+)	$\mathbf{f_4}$	$\mathbf{f_4'}$	$(\frac{1}{2})$	$\mathbf{K_4^*}$
4	0	4^{-+}	(1^-)	$\pi_\mathbf{4}$	(0^+)	$\eta_\mathbf{4}$	$\eta_\mathbf{4}'$	$(\frac{1}{2})$	$\mathbf{K_4}$
4	1	3^{--}	(1^+)	$\rho_\mathbf{3}$	(0^-)	$\omega_\mathbf{3}$	$\phi_\mathbf{3}$	$(\frac{1}{2})$	$\mathbf{K_3^*}$
4	1	4^{--}	(1^+)	$\rho_\mathbf{4}$	(0^-)	$\omega_\mathbf{4}$	$\phi_\mathbf{4}$	$(\frac{1}{2})$	$\mathbf{K_4}$
4	1	5^{--}	(1^+)	$\rho_\mathbf{5}$	(0^-)	$\omega_\mathbf{5}$	$\phi_\mathbf{5}$	$(\frac{1}{2})$	$\mathbf{K_5^*}$

Table 1: The naming scheme for normal $q\bar{q}$ mesons in the quark model. The first state listed for a given quantum number is the isospin one state. The second state is the isospin zero state that is mostly u and d quarks ($n\bar{n}$), while the third name is for the mostly $s\bar{s}$ isospin zero state. Note that for the kaons, the C- and G-parity are not defined.

Similarly, in table 2 are given the quantum numbers and names of the exotic mesons. Lattice QCD predicts a nonet of 0^{+-} hybrids, two nonets of 1^{-+} hybrids and two nonets of 2^{+-} hybrids. For completeness, the quantum numbers 0^{--} and 3^{-+} are also exotic, so we include them in the following table as well.

QNs			Names				
J^{PC}	(I^G)		(I^G)			(I)	
$\mathbf{0^{--}}$	$(\mathbf{1^+})$	$\rho_\mathbf{0}$	$(\mathbf{0^-})$	$\omega_\mathbf{0}$	$\phi_\mathbf{0}$	$(\frac{1}{2})$	K_0^*
$\mathbf{0^{+-}}$	$(\mathbf{1^+})$	$\mathbf{b_0}$	$(\mathbf{0^-})$	$\mathbf{h_0}$	$\mathbf{h_0'}$	$(\frac{1}{2})$	K_0^*
$\mathbf{1^{-+}}$	$(\mathbf{1^-})$	$\pi_\mathbf{1}$	$(\mathbf{0^+})$	$\eta_\mathbf{1}$	$\eta_\mathbf{1}'$	$(\frac{1}{2})$	K_1^*
$\mathbf{2^{+-}}$	$(\mathbf{1^+})$	$\mathbf{b_2}$	$(\mathbf{0^-})$	$\mathbf{h_2}$	$\mathbf{h_2'}$	$(\frac{1}{2})$	K_2^*
$\mathbf{3^{-+}}$	$(\mathbf{1^-})$	$\pi_\mathbf{3}$	$(\mathbf{0^+})$	$\eta_\mathbf{3}$	$\eta_\mathbf{3}'$	$(\frac{1}{2})$	K_3^*

Table 2: The naming scheme for hybrid mesons. The first state listed for a given quantum number is the isospin one state. The second state is the isospin zero state that is mostly u and d quarks ($n\bar{n}$), while the third name is for the mostly $s\bar{s}$ isospin zero state. Note that for the kaons, the C- and G-parity are not defined. Kaons cannot not have manifestly exotic quantum numbers.

Isospin Relations

Important in both the production and decay of mesons are the isospin Clebsch-Gordan coefficients. In particular, we want to look at neutral isospin 0 and 1 states decaying to pairs of isospin 1 states. For an isospin 0 particle connecting to two isospin 1 states,

$$\begin{aligned}
< 0\,0\,|\,1\,+1\,;\,1\,-1 > &= \sqrt{\frac{1}{3}} \\
< 0\,0\,|\,1\,0\,;\,1\,0 > &= -\sqrt{\frac{1}{3}} \\
< 0\,0\,|\,1\,-1\,;\,1\,+1 > &= \sqrt{\frac{1}{3}}\,.
\end{aligned}$$

There are non-zero clebsch-gordan coefficients to all three possible charged states: $+-$, 00 and $-+$. For the case of isospin 1 connecting to two isospin 1 states,

$$\begin{aligned}
< 1\,0\,|\,1\,+1\,;\,1\,-1 > &= \sqrt{\frac{1}{2}} \\
< 1\,0\,|\,1\,0\,;\,1\,0 > &= 0 \\
< 1\,0\,|\,1\,-1\,;\,1\,+1 > &= \sqrt{\frac{1}{2}}\,.
\end{aligned}$$

Thus, we can only couple to the $+-$ and $-+$ states.

In photoproduction, this means production processes that involve both an incoming ρ mesons and an exchanged isospin 1 state can only couple to isospin 0 produced mesons.

Identical Bosons

Identical Bosons must be in a symmetrical state. This means that the relative orbital angular momentum, L, between such particles must be even. Thus, odd angular momentum are not allowed. In terms of photoproduction, and incoming photon that fluctuates into a ρ^0 can only exchange a ρ^0 in the t channel in $L = 0$ or $L = 2$; $L = 1$ is forbidden. Similarly, an incoming ω and only exchange an ω and an incoming ϕ can only exchange a ϕ under similar restrictions.

Photoproduction of Exotic Hybrid Mesons

In the photoproduction of mesons, the usual assumption is to assume vector meson dominance (VMD) where the incident photon fluctuates into a vector meson (ρ, ω or ϕ), which then undergoes a t-channel exchange with the proton target to produce the outgoing meson. For production to happen, the reaction must conserve J, P, C, G and I. In the following tables, exotic quantum number states are shown in blue, the the allowed normal meson states are shown in black.

π^0 Exchange

Incident	exchange	$(I)^G$	L	J^{PC}			Exotics
ρ	π^0	$(0)^-$	$L=0$	1^{+-}			h_1 , h_1'
			$L=1$	$\mathbf{0^{--}}$	1^{--}	2^{--}	ω_0 , ϕ_0 , ω_1 , ϕ_1 , ω_2 , ϕ_2
			$L=2$	1^{+-}	$\mathbf{2^{+-}}$	3^{+-}	h_1 , h_1' , h_2 , h_2' , h_3 , h_3'
ω,ϕ	π^0	$(1)^+$	$L=0$	1^{+-}			b_1^0
			$L=1$	$\mathbf{0^{--}}$	1^{--}	2^{--}	ρ_0^0 , ρ_1^0 , ρ_2^0
			$L=2$	1^{+-}	$\mathbf{2^{+-}}$	3^{+-}	b_1^0 , $\mathbf{b_2^0}$, b_3^0

$\pi^\pm$ Exchange

Incident	exchange	$(I)^G$	L	J^P			Exotics
ρ	$\pi^\pm$	$(1)^-$	$L=0$	1^+			$a_1^\pm$
			$L=1$	0^-	$\mathbf{1^-}$	2^-	$\pi^\pm$, $\pi_1^\pm$, $\pi_2^\pm$
			$L=2$	1^+	2^+	3^+	$a_1^\pm$, $a_2^\pm$, $a_3^\pm$
ω,ϕ	$\pi^\pm$	$(1)^+$	$L=0$	1^+			$b_1^\pm$
			$L=1$	$\mathbf{0^-}$	1^-	2^-	$\rho_0^\pm$, $\rho_1^\pm$, $\rho_2^\pm$
			$L=2$	1^+	$\mathbf{2^+}$	3^+	$b_1^\pm$, $b_2^\pm$, $b_3^\pm$

η and η' Exchange

Incident	exchange	$(I)^G$	L	J^{PC}			Exotics
ρ	η, η'	$(1)^+$	$L=0$	1^{+-}			b_1^0
			$L=1$	$\mathbf{0^{--}}$	1^{--}	2^{--}	ρ_0^0 , ρ_1^0 , ρ_2^0
			$L=2$	1^{+-}	$\mathbf{2^{+-}}$	3^{+-}	b_1^0 , $\mathbf{b_2^0}$, b_3^0
ω,ϕ	η, η'	$(0)^-$	$L=0$	1^{+-}			h_1 , h_1'
			$L=1$	$\mathbf{0^{--}}$	1^{--}	2^{--}	ω_0 , ϕ_0 , ω_1 , ϕ_1 , ω_2 , ϕ_2
			$L=2$	1^{+-}	$\mathbf{2^{+-}}$	3^{+-}	h_1 , h_1' , $\mathbf{h_2}$, $\mathbf{h_2'}$, h_3 , h_3'

Pomeron Exchange

Incident	exchange	$(I)^G$	L	J^{PC}			Exotics
ρ	$\mathcal{P}$	$(1)^+$	$L=0$	1^{--}			ρ_1^0
			$L=1$	$\mathbf{0^{+-}}$	1^{+-}	$\mathbf{2^{+-}}$	$\mathbf{b_0^0}$, b_1^0 , $\mathbf{b_2^0}$
			$L=2$	1^{--}	2^{--}	3^{--}	ρ_1^0 , ρ_2^0 , ρ_3^0
ω,ϕ	$\mathcal{P}$	$(0)^-$	$L=0$	1^{--}			ω_1 , ϕ_1
			$L=1$	$\mathbf{0^{+-}}$	1^{+-}	$\mathbf{2^{+-}}$	$\mathbf{h_0}$, $\mathbf{h_0'}$, h_1 , h_1' , $\mathbf{h_2}$, $\mathbf{h_2'}$
			$L=2$	1^{--}	2^{--}	3^{--}	ω_1 , ϕ_1 , ω_2 , ϕ_2 , ω_3 , ϕ_3

ρ^0 Exchange

Note that two identical bosons ($\rho\rho$) need to be in a symmetric state. This means that the $L = 1$ $\rho\rho$ production of η_1 and η_3 is forbidden.

Incident	exchange	$(I)^G$	L	J^{PC}				Exotics
ρ	ρ^0	$(0)^+$	$L=0$	0^{++}	1^{++}	2^{++}		f_0 , f_0' , f_1 , f_1' , f_2 , f_2'
			$L=2$	0^{++}	1^{++}	2^{++}	3^{++}	f_1 , f_1' , f_2 , f_2' , f_3 , f_3'
ω,ϕ	ρ^0	$(1)^-$	$L=0$	0^{++}	1^{++}	2^{++}		a_0^0 , a_1^0 , a_2^0
			$L=1$	0^{-+}	$\mathbf{1^{-+}}$	2^{-+}	$\mathbf{3^{-+}}$	π^0 , $\boldsymbol{\pi_1^0}$, π_2^0 , $\boldsymbol{\pi_3^0}$
			$L=2$	0^{++}	1^{++}	2^{++}	3^{++}	a_0^0 , a_1^0 , a_2^0 , a_3^0

$\rho^\pm$ Exchange

Incident	exchange	$(I)^G$	L	J^{PC}				Exotics
ρ	$\rho^\pm$	$(1)^+$	$L=0$	$\mathbf{0^+}$	1^+	$\mathbf{2^+}$		$\mathbf{b_0^\pm}$, $b_1^\pm$, $\mathbf{b_2^\pm}$
			$L=1$	$\mathbf{0^-}$	1^-	2^-	3^-	$\boldsymbol{\rho_0^\pm}$, $\rho_1^\pm$, $\rho_2^\pm$, $\rho_3^\pm$
			$L=2$	$\mathbf{0^+}$	1^+	$\mathbf{2^+}$	3^+	$\mathbf{b_0^\pm}$, $b_1^\pm$, $\mathbf{b_2^\pm}$, $b_3^\pm$
ω,ϕ	$\rho^\pm$	$(1)^-$	$L=0$	0^+	1^+	2^+		$a_0^\pm$, $a_1^\pm$, $a_2^\pm$
			$L=1$	0^-	$\mathbf{1^-}$	2^-	$\mathbf{3^-}$	$\pi^\pm$, $\boldsymbol{\pi_1^\pm}$, $\pi_2^\pm$, $\boldsymbol{\pi_3^\pm}$
			$L=2$	0^+	1^+	2^+	3^+	$a_0^\pm$, $a_1^\pm$, $a_2^\pm$, $a_3^\pm$

ω and ϕ Exchange

Note that two identical bosons ($\omega\omega$ and $\phi\phi$) need to be in a symmetric state. This means that $\omega\phi$ and $\phi\omega$ will be the allowed mechanism in the $L = 1$ production.

Incident	exchange	$(I)^G$	L	J^{PC}				Exotics
ρ	ω,ϕ	$(1)^-$	$L=0$	0^{++}	1^{++}	2^{++}		a_0^0 , a_1^0 , a_2^0
			$L=1$	0^{-+}	$\mathbf{1^{-+}}$	2^{-+}	$\mathbf{3^{-+}}$	π^0 , $\boldsymbol{\pi_1^0}$, π_2^0 , $\boldsymbol{\pi_3^0}$
			$L=2$	0^{++}	1^{++}	2^{++}	3^{++}	a_0^0 , a_1^0 , a_2^0 , a_3^0
ω,ϕ	ω, ϕ	$(0)^+$	$L=0$	0^{++}	1^{++}	2^{++}		f_0 , f_0' , f_1 , f_1' , f_2 , f_2'
			$L=1$	0^{-+}	$\mathbf{1^{-+}}$	2^{-+}	$\mathbf{3^{-+}}$	η , η' , $\boldsymbol{\eta_1}$, $\boldsymbol{\eta_1'}$, η_2 , η_2' , $\boldsymbol{\eta_3}$, $\boldsymbol{\eta_3'}$
			$L=2$	0^{++}	1^{++}	2^{++}	3^{++}	f_0 , f_0' , f_1 , f_1' , f_2 , f_2' , f_3 , f_3'

b_1^0 Exchange

Incident	exchange	$(I)^G$	L	J^{PC}				Exotics
ρ	b_1^0	$(0)^+$	$L=0$	0^{-+}	$\mathbf{1^{-+}}$	2^{-+}		η , η' , $\boldsymbol{\eta_1}$, $\boldsymbol{\eta_1'}$, η_2 , η_2'
			$L=1$	0^{++}	1^{++}	2^{++}	3^{++}	f_0 , f_0' , f_1 , f_1' , f_2 , f_2' , f_3 , f_3'
			$L=2$	0^{-+}	$\mathbf{1^{-+}}$	2^{-+}	$\mathbf{3^{-+}}$	η , η' , $\boldsymbol{\eta_1}$, $\boldsymbol{\eta_1'}$, η_2 , η_2' , $\boldsymbol{\eta_3}$, $\boldsymbol{\eta_3'}$
ω,ϕ	b_1^0	$(1)^-$	$L=0$	0^{-+}	$\mathbf{1^{-+}}$	2^{-+}		π^0 , $\boldsymbol{\pi_1^0}$, π_2^0
			$L=1$	0^{++}	1^{++}	2^{++}	3^{++}	a_0^0 , a_1^0 , a_2^0 , a_3^0
			$L=2$	0^{-+}	$\mathbf{1^{-+}}$	2^{-+}	$\mathbf{3^{-+}}$	π^0 , $\boldsymbol{\pi_1^0}$, π_2^0 , $\boldsymbol{\pi_3^0}$

$b_1^{\pm}$ Exchange

Incident	exchange	$(I)^G$	L	J^P				Exotics
ρ	$b_1^{\pm}$	$(1)^+$	$L=0$	$\mathbf{0^-}$	1^-	2^-		$\boldsymbol{\rho_0^{\pm}}$, $\rho_1^{\pm}$, $\rho_2^{\pm}$
			$L=1$	$\mathbf{0^+}$	1^+	$\mathbf{2^+}$	3^+	$\mathbf{b_0^{\pm}}$, $b_1^{\pm}$, $\mathbf{b_2^{\pm}}$, $b_3^{\pm}$
			$L=2$	$\mathbf{0^-}$	1^-	2^-	3^-	$\boldsymbol{\rho_0^{\pm}}$, $\rho_1^{\pm}$, $\rho_2^{\pm}$, $\rho_3^{\pm}$
ω,ϕ	$b_1^{\pm}$	$(1)^-$	$L=0$	0^-	$\mathbf{1^-}$	2^-		$\pi^{\pm}$, $\boldsymbol{\pi_1^{\pm}}$, $\pi_2^{\pm}$
			$L=1$	0^+	1^+	2^+	3^+	$a_0^{\pm}$, $a_1^{\pm}$, $a_3^{\pm}$, $a_3^{\pm}$
			$L=2$	0^-	$\mathbf{1^-}$	2^-	$\mathbf{3^-}$	$\pi^{\pm}$, $\boldsymbol{\pi_1^{\pm}}$, $\pi_2^{\pm}$, $\boldsymbol{\pi_3^{\pm}}$

h_1 and h_1' Exchange

Incident	exchange	$(I)^G$	L	J^{PC}				Exotics
ρ	h_1,h_1'	$(1)^-$	$L=0$	0^{-+}	$\mathbf{1^{-+}}$	2^{-+}		π^0 , $\boldsymbol{\pi_1^0}$, π_2^0
			$L=1$	0^{++}	1^{++}	2^{++}	3^{++}	a_0^0 , a_1^0 , a_2^0 , a_3^0
			$L=2$	0^{-+}	$\mathbf{1^{-+}}$	2^{-+}	$\mathbf{3^{-+}}$	π^0 , $\boldsymbol{\pi_1^0}$, π_2^0 , $\boldsymbol{\pi_3^0}$
ω,ϕ	h_1,h_1'	$(0)^+$	$L=0$	0^{-+}	$\mathbf{1^{-+}}$	2^{-+}		η , η' , $\boldsymbol{\eta_1}$, $\boldsymbol{\eta_1'}$, η_2 , η_2'
			$L=1$	0^{++}	1^{++}	2^{++}	3^{++}	f_0 , f_0' , f_1 , f_1' , f_2 , f_2' , f_3 , f_3'
			$L=2$	0^{-+}	$\mathbf{1^{-+}}$	2^{-+}	$\mathbf{3^{-+}}$	η , η' , $\boldsymbol{\eta_1}$, $\boldsymbol{\eta_1'}$, η_2 , η_2' , $\boldsymbol{\eta_3}$, $\boldsymbol{\eta_3'}$

Summary of Production Mechanisms

Exotic	Beam	Exchange	L
π_1^0	ρ^0	ω,ϕ	1
	ρ^0	h_1,h_1'	0, 2
	ω,ϕ	ρ^0	1
	ω,ϕ	b_1^0	0, 2
$\pi_1^{\pm}$	ρ^0	$\pi^{\pm}$	1
	ω,ϕ	$\rho^{\pm}$	1
	ω,ϕ	$b_1^{\pm}$	0, 2

Exotic	Beam	Exchange	L
η_1,η_1'	ρ^0	b_1^0	0, 2
	ω	ϕ	1
	ϕ	ω	1
	ω,ϕ	h_1, h_1'	0, 2

Exotic	Beam	Exchange	L
b_2^0	ρ^0	η, η'	2
	ρ^0	$\mathcal{P}$	1
	ω, ϕ	π^0	2
$b_2^{\pm}$	ρ^0	$\rho^{\pm}$	0, 2
	ω,ϕ	$\pi^{\pm}$	2

Exotic	Beam	Exchange	L
h_2, h_2'	ω, ϕ	η, η'	2
	ω, ϕ	$\mathcal{P}$	1

Exotic	Beam	Exchange	L
b_0^0	ρ^0	$\mathcal{P}$	1
$b_0^\pm$	ρ^0	$\rho^\pm$	0, 2
	ρ^0	$b_1^\pm$	1

Exotic	Beam	Exchange	L
h_0, h_0'	ω, ϕ	$\mathcal{P}$	1

Exotic	Beam	Exchange	L
ρ_0^0	ρ^0	η, η'	1
	ω, ϕ	π^0	1
$\rho_0^\pm$	ρ^0	$\rho^\pm$	1
	ρ^0	$b_1^\pm$	0, 2
	ω, ϕ	$\pi^\pm$	1

Exotic	Beam	Exchange	L
ω_0, ϕ_0	ρ	π^0	1
	ω, ϕ	η, η'	1

Exotic	Beam	Exchange	L
π_3^0	ρ^0	ω, ϕ	1
	ρ^0	h_1, h'	2
	ω, ϕ	ρ^0	1
	ω, ϕ	b_1^0	2
$\pi_3^\pm$	ρ^0	$\pi^\pm$	1
	ρ^0	$b_1^\pm$	0, 2
	ω, ϕ	$\rho^\pm$	1
	ρ^0	$b_1^\pm$	0, 2
	ω, ϕ	$b_1^\pm$	2

Exotic	Beam	Exchange	L
η_3, η_3'	ρ^0	b_1^0	2
	ω, ϕ	ϕ, ω	1
	ω, ϕ	h_1, h_1'	2

The Decays of Exotic Hybrid Mesons

Please note that this is not a complete list of all possible decays. In particular, the listed decays for the ρ_0^0, $\rho_0^\pm$, ω_0, ϕ_0, π_3^0, $\pi_3^\pm$, η_3 and the η_3' are a very limited subset of the possible decays.

π_1^0 Decays

Exotic	$(I)^G J^{PC}$	Daughters		L	Final States	
π_1^0	$(1)^- 1^{-+}$	$\rho^\pm$	$\pi^\mp$	1	$\pi^+\pi^-\pi^0$	
		η'	π^0	1	$\eta\pi^+\pi^-\pi^0$	$\eta\pi^0\pi^0\pi^0$
		f_1	π^0	0	$\eta\pi^+\pi^-\pi^0$	$\eta\pi^0\pi^0\pi^0$
		$b_1^\pm$	$\pi^\mp$	1	$\omega\pi^+\pi^-$	
		ρ^0	ω	1	$\omega\pi^+\pi^-$	
		a_1^0	η	1	$\eta\pi^+\pi^-\pi^0$	
		b_1^0	ω	0	$\omega\omega\pi^0$	

$\pi_1^\pm$ Decays

Exotic	$(I)^G J^P$	Daughters		L	Final States	
$\pi_1^\pm$	$(1)^- 1^-$	$\rho^\pm$	π^0	1	$\pi^\pm\pi^0\pi^0$	
		ρ^0	$\pi^\pm$	1	$\pi^\pm\pi^+\pi^-$	
		η'	$\pi^\pm$	1	$\eta\pi^+\pi^-\pi^\pm$	$\eta\pi^0\pi^0\pi^\pm$
		f_1	$\pi^\pm$	0	$\eta\pi^+\pi^-\pi^\pm$	$\eta\pi^0\pi^0\pi^\pm$
		$b_1^\pm$	π^0	1	$\omega\pi^\pm\pi^0$	
		b_1^0	$\pi^\pm$	1	$\omega\pi^0\pi^\pm$	
		$b_1^\pm$	ω	0	$\omega\omega\pi^\pm$	
		$\rho^\pm$	ω	1	$\omega\pi^\pm\pi^0$	
		$a_1^\pm$	η	0	$\eta\pi^\pm\pi^+\pi^-$	$\eta\pi^\pm\pi^0\pi^0$

η_1 and η_1' Decays

Exotic	$(I)^G J^{PC}$	Daughters		L	Final States		
η_1	$(0)^+ 1^{-+}$	η'	η	1	$\eta\eta\pi^+\pi^-$	$\eta\eta\pi^0\pi^0$	
		f_1	η	0	$\eta\eta\pi^+\pi^-$	$\eta\eta\pi^0\pi^0$	
		f_2	η	2	$\eta\pi^+\pi^-$	$\eta\pi^0\pi^0$	
		$a_2^\pm$	$\pi^\mp$	2	$\eta\pi^+\pi^-$	$\pi^+\pi^-\pi^+\pi^-$	$\pi^+\pi^-\pi^0\pi^0$
		a_2^0	π^0	2	$\eta\pi^0\pi^0$	$\pi^+\pi^-\pi^0\pi^0$	
		a_1^0	π^0	0	$\eta\pi^0\pi^0$	$\pi^+\pi^-\pi^0\pi^0$	
		b_1^0	ρ^0	0	$\omega\pi^+\pi^-\pi^0$		
η_1'	$(0)^+ 1^{-+}$	ω	ϕ	1	$\omega\phi$		
		$(K^*)^\pm$	$K^\mp$	1	$K^+K^-\pi^0$		
		$(K^*)^0$	K_S	0	$K^+K_S\pi^-$	$K^-K_S\pi^+$	
		$K_1^\pm$	$K^\mp$	0	$K^+K^-\pi^+\pi^-$		
		K_1^0	K_S	1	$K^+K_S\pi^-\pi^0$	$K^-K_S\pi^+\pi^0$	

b_2^0 Decays

Exotic	$(I)^G J^{PC}$	Daughters		L	Final States		
b_2^0	$(1)^+2^{+-}$	ω	π^0	2	$\omega\pi^0$		
		ρ^0	η	2	$\eta\pi^+\pi^-$		
		$a_2^\pm$	$\pi^\mp$	1	$\eta\pi^+\pi^-$	$\pi^+\pi^-\pi^+\pi^-$	$\pi^+\pi^-\pi^0\pi^0$
		b_1^0	η	1	$\omega\eta\pi^0$		
		f_1	ρ^0	1	$\eta\pi^+\pi^-\pi^+\pi^-$	$\eta\pi^+\pi^-\pi^0\pi^0$	
		$a_1^\pm$	$\pi^\mp$	1	$\pi^+\pi^-\pi^+\pi^-$	$\pi^+\pi^-\pi^0\pi^0$	

$b_2^\pm$ Decays

Exotic	$(I)^G J^P$	Daughters		L	Final States		
$b_2^\pm$	$(1)^+2^+$	ω	$\pi^\pm$	2	$\omega\pi^\pm$		
		$\rho^\pm$	η	2	$\eta\pi^\pm\pi^0$		
		$a_2^\pm$	π^0	1	$\eta\pi^\pm\pi^0$	$\pi^\pm\pi^+\pi^-\pi^0$	$\pi^\pm\pi^0\pi^0\pi^0$
		a_2^0	$\pi^\pm$	1	$\pi^\pm\pi^+\pi^-\pi^0$		
		$b_1^\pm$	η	1	$\omega\eta\pi^\pm$		
		b_1^0	$\rho^\pm$	1	$\omega\pi^0\pi^0\pi^\pm$		
		$b_1^\pm$	ρ^0	1	$\omega\pi^+\pi^-\pi^\pm$		
		f_1	$\rho^\pm$	1	$\eta\pi^+\pi^-\pi^0\pi^\pm$	$\eta\pi^0\pi^0\pi^0\pi^\pm$	
		$a_1^\pm$	π^0	1	$\pi^\pm\pi^+\pi^-\pi^0$	$\pi^\pm\pi^0\pi^0\pi^0$	
		a_1^0	$\pi^\mp$	1	$\pi^\pm\pi^+\pi^-\pi^0$		

h_2 and h_2' Decays

Exotic	$(I)^G J^{PC}$	Daughters		L	Final States	
h_2	$(0)^-2^{+-}$	ρ^0	π^0	2	$\pi^+\pi^-\pi^0$	
		ω	η	2	$\omega\eta$	
		$b_1^\pm$	$\pi^\mp$	1	$\omega\pi^+\pi^-$	
		b_1^0	π^0	1	$\omega\pi^0\pi^0$	
		f_1	ω	1	$\omega\eta\pi^+\pi^-$	$\omega\eta\pi^0\pi^0$
h_2'	$(0)^-2^{+-}$	ϕ	η	2	$\phi\eta$	
		f_1	ϕ	1	$\phi\eta\pi^+\pi^-$	$\phi\eta\pi^0\pi^0$
		$K_1^\pm$	$K^\mp$	1	$K^+K^-\pi^+\pi^-$	
		K_1^0	K_S	2	$K^+K_S\pi^-$	$K^-K_S\pi^+$
		$(K_2^*)^\pm$	$K^\mp$	1	$K^+K^-\pi^0$	$K^+K^-\pi^+\pi^-$
		$(K_2^*)^0$	K_S	$0,2$	$K^\pm K_S\pi^\mp$	$K^\pm K_S\pi^\mp\pi^0$

b_0^0 Decays

Exotic	$(I)^G J^{PC}$	Daughters		L	Final States	
b_0^0	$(1)^+0^{+-}$	f_1	ρ^0	1	$\eta\pi^+\pi^-\pi^+\pi^-$	$\eta\pi^+\pi^-\pi^0\pi^0$
		b_1^0	η	1	$\omega\eta\pi^0$	
		h_1	π^0	1	$\pi^+\pi^-\pi^0\pi^0$	

$b_0^\pm$ Decays

Exotic	$(I)^G J^P$	Daughters		L	Final States	
$b_0^\pm$	$(1)^+0^+$	f_1	$\rho^\pm$	1	$\eta\pi^+\pi^-\pi^0\pi^\pm$	$\eta\pi^0\pi^0\pi^0\pi^\pm$
		$b_1^\pm$	η	1	$\omega\eta\pi^\pm$	
		b_1^0	$\rho^\pm$	1	$\omega\pi^0\pi^0\pi^\pm$	
		$b_1^\pm$	ρ^0	1	$\omega\pi^+\pi^-\pi^\pm$	
		h_1	$\pi^\pm$	1	$\pi^+\pi^-\pi^0\pi^\pm$	

h_0 and h_0' Decays

Exotic	$(I)^G J^{PC}$	Daughters		L	Final States	
h_0	$(0)^-0^{+-}$	$b_1^\pm$	$\pi^\mp$	1	$\omega\pi^+\pi^-$	
		b_1^0	π^0	1	$\omega\pi^0\pi^0$	
		h_1	η	1	$\eta\pi^+\pi^-\pi^0$	
h_0'	$(0)^-0^{+-}$	$K_1^\pm$	$K^\mp$	1	$K^+K^-\pi^+\pi^-$	
		$K(1460)^\pm$	$K^\mp$	0	$K^+K^-\pi^+\pi^-$	$K^+K^-\pi^0\pi^0$

ρ_0^0 Decays

Exotic	$(I)^G J^P$	Daughters		L	Final States	
ρ_0^0	$(1)^+0^{--}$	ω	π^0	1	$\omega\pi^0$	
		ϕ	π^0	1	$\phi\pi^0$	
		ρ^0	η	1	$\eta\pi^+\pi^-$	
		ρ^0	η'	1	$\eta\pi^+\pi^-\pi^+\pi^-$	$\eta\pi^0\pi^0\pi^+\pi^-$
		ρ^0	f_1	0	$\eta\pi^+\pi^-\pi^+\pi^-$	$\eta\pi^0\pi^0\pi^+\pi^-$
		ρ^0	f_2	2	$pi^+\pi^-\pi^+\pi^-$	$\pi^+\pi^-\pi^0\pi^0$
		$K^{*\pm}$	$K^\mp$	1	$K^+K^-\pi^0$	$K^\pm K_S\pi^\pm$

$\rho_0^{\pm}$ Decays

Exotic	$(I)^G J^P$	Daughters		L	Final States	
$\rho_0^{\pm}$	$(1)^+0^-$	ρ^0	$\rho^{\pm}$	1	$\pi^{\pm}\pi^+\pi^-\pi^0$	
		ρ^0	$b_1^{\pm}$	0, 2	$\omega\pi^{\pm}\pi^+\pi^-$	
		$\rho^{\pm}$	b_1^0	0, 2	$\omega\pi^{\pm}\pi^0\pi^0$	
		ω	$\pi^{\pm}$	1	$\omega\pi^{\pm}$	
		ϕ	$\pi^{\pm}$	1	$\phi\pi^{\pm}$	
		$\rho^{\pm}$	η	1	$\eta\pi^{\pm}\pi^0$	
		$\rho^{\pm}$	η'	1	$\eta\pi^+\pi^-\pi^{\pm}\pi^0$	$\eta\pi^0\pi^0\pi^{\pm}\pi^0$
		$\rho^{\pm}$	f_1	0	$\eta\pi^+\pi^-\pi^{\pm}\pi^0$	$\eta\pi^0\pi^0\pi^{\pm}\pi^0$
		$\rho^{\pm}$	f_2	2	$pi^{\pm}\pi^0\pi^+\pi^-$	$\pi^{\pm}\pi^0\pi^0\pi^0$

ω_0 and ϕ_0 Decays

Exotic	$(I)^G J^P$	Daughters		L	Final States	
ω_0^0	$(0)^-0^{--}$	ρ^0	π^0	1	$\pi^+\pi^-\pi^0$	
		ω	η	1	$\omega\eta$	
ϕ_0	$(0^-)0^{--}$	ϕ	η	$\phi\eta$		
		ω	$\eta\prime$	$\omega\eta\pi^+\pi^-$	$\omega\eta\pi^0\pi^0$	
		ϕ	$\eta\prime$	$\phi\eta\pi^+\pi^-$	$\phi\eta\pi^0\pi^0$	
		ρ^0	a_1^0	0	$\pi^+\pi^-\pi^+\pi^-\pi^0$	
		ρ^0	a_2^0	2	$\pi^+\pi^-\pi^+\pi^-\pi^0$	$\eta\pi^+\pi^-\pi^0$
		$K^{*\pm}$	$K^{\mp}$	1	$K^+K^-\pi^0$	$K^{\pm}K_S\pi^{\pm}$

π_3^0 Decays

Exotic	$(I)^G J^P$	Daughters		L	Final States
π_3^0	$(1^-)3^{-+}$	ρ^0	ω	1	$\omega\pi^+\pi^-$
		ρ^0	ϕ	1	$\phi\pi^+\pi^-$
		ρ^0	h_1	2	$\pi^+\pi^-\pi^+\pi^-\pi^0$
		ω	b_1^0	2	$\omega\omega\pi^0$
		ϕ	b_1^0	2	$\phi\omega\pi^0$

$\pi_3^{\pm}$ Decays

Exotic	$(I)^G J^P$	Daughters		L	Final States
$\pi_3^{\pm}$	$(1^-)3^{-+}$	$\rho^{\pm}$	ω	1	$\omega\pi^{\pm}\pi^0$
		$\rho^{\pm}$	ϕ	1	$\phi\pi^{\pm}\pi^0$
		$\rho^{\pm}$	h_1	2	$\pi^{\pm}\pi^0\pi^+\pi^-\pi^0$
		ω	$b_1^{\pm}$	2	$\omega\omega\pi^{\pm}$
		ϕ	$b_1^{\pm}$	2	$\phi\omega\pi^{\pm}$

η_3 and η_3' Decays

Exotic	$(I)^G J^P$	Daughters		L	Final States
η_3	$(0^+)3^{-+}$	ω	ϕ	1	$\omega\phi$
		ρ^0	b_1^0	2	$\omega\pi^0\pi^+\pi^-$
		ω	h_1	2	$\omega\pi^+\pi^-\pi^0$
η_3'	$(0^+)3^{-+}$	ϕ	h_1	1	$\phi\pi^+\pi^-\pi^0$

Photoproduction of Normal Mesons

From the photoproduction tables above, it appears that there are photoproduction mechanisms that, in principle, could produce all normal mesons up to $L = 2$ in Table 1. In this section, we summarize those mechanisms. It is interesting to note that for the $L = 2$ vector mesons, the 3^{--} states have a much more limited set of production mechanisms compared to the 1^{--} and 2^{--} states.

Meson	Beam	Exchange	L	Meson	Beam	Exchange	L
π^0	ρ^0	ω	1	η, η'	ω	ϕ	1
	ω	ρ^0	1		ϕ	ω	1
	ρ^0	h_1	0, 2		ρ^0	b_1^0	0, 2
	ω	b_1^0	0, 2		ω	h_1	0, 2

Meson	Beam	Exchange	L	Meson	Beam	Exchange	L
ρ^0	ρ^0	η	1	ω	ρ^0	π^0	1
	ρ^0	$\mathcal{P}$	0, 2		ω	η	1
	ω	π^0	1		ω	$\mathcal{P}$	0, 2
				ϕ	ρ	π^0	1
					ϕ	η	1
					ϕ	$\mathcal{P}$	0, 2

Meson	Beam	Exchange	L	Meson	Beam	Exchange	L
$\pi^\pm$	ρ^0	$\pi^\pm$	1	$\rho^\pm$	ρ^0	$\rho^\pm$	1
	ω	$\rho^\pm$	1		ρ^0	$b_1^\pm$	0, 2
	ω	$b_1^\pm$	0, 2		ω	$\pi^\pm$	1

Meson	Beam	Exchange	L	Meson	Beam	Exchange	L
b_1^0	ρ^0	η	0, 2	h_1	ρ^0	π^0	0, 2
	ρ^0	$\mathcal{P}$	0, 2		ω	η	0, 2
	ω	π^0	0, 2		ω	$\mathcal{P}$	1
				h_1'	ϕ	η	0, 2
					ϕ	$\mathcal{P}$	1

Meson	Beam	Exchange	L	Meson	Beam	Exchange	L
a_0^0, a_1^0, a_2^0	ρ^0	ω	0, 2	f_0, f_1, f_2	ρ^0	ρ^0	0, 2
	ω	ρ^0	0, 2		ω	ω	0, 2
	ρ^0	h_1	1		ρ	b_1^0	1
	ω	b_1^0	1		ω	h_1	1
				f_0', f_1', f_2'	ω	ϕ	0, 2
					ϕ	ϕ	0, 2

Meson	Beam	Exchange	L	Meson	Beam	Exchange	L
$b_1^{\pm}$	ρ^0	$\rho^{\pm}$	0, 2	$a_0^{\pm}$	ω	$\rho^{\pm}$	0, 2
	ρ^0	$b_1^{\pm}$	1		ω	$b_1^{\pm}$	1
	ω	$\pi^{\pm}$	0, 2				

Meson	Beam	Exchange	L	Meson	Beam	Exchange	L
$a_1^{\pm}$	ρ^0	$\pi^{\pm}$	0, 2	$a_2^{\pm}$	ρ^0	$\pi^{\pm}$	2
	ω	$\rho^{\pm}$	0, 2		ω	$rho^{\pm}$	0, 2
	ω	$b_1^{\pm}$	1		ω	$b_1^{\pm}$	1

Meson	Beam	Exchange	L	Meson	Beam	Exchange	L
π_2^0	ρ^0	ω	1	η_2, η_2'	ω	ϕ	1
	ω	ρ^0	1		ϕ	ω	1
	ρ^0	h_1	0, 2		ρ^0	b_1^0	0, 2
	ω	b_1^0	0, 2		ω	h_1	0, 2

Meson	Beam	Exchange	L	Meson	Beam	Exchange	L
ρ_2^0	ρ^0	η	1	ω_2	ρ^0	π^0	1
	ρ^0	$\mathcal{P}$	2		ω	η	1
	ω	π^0	1		ω	$\mathcal{P}$	2
				ϕ_2	ω	η'	1
					ϕ	η	1
					ϕ	$\mathcal{P}$	2

Meson	Beam	Exchange	L	Meson	Beam	Exchange	L
ρ_3^0	ρ^0	$\mathcal{P}$	2	ω_3	ω^0	$\mathcal{P}$	2
				ϕ_3	ϕ	$\mathcal{P}$	2

Meson	Beam	Exchange	L	Meson	Beam	Exchange	L
$\rho_2^{\pm}$	ρ^0	$\rho^{\pm}$	1	$\rho_3^{\pm}$	ρ^0	$\rho^{\pm}$	1
	ρ^0	$b_1^{\pm}$	0, 2		ρ^0	$b_1^{\pm}$	2
	ω	$\pi^{\pm}$	1				