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$N+\omega$ decay of baryons in a flux-tube-breaking mechanism

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We present a calculation of the $N+\omega$ decay widths of the $N=2$ band baryon resonances using a flux-tube-breaking mechanism and treating the emitted meson as a finite size particle. The results are compared with those derived by Koniuk from a pointlike vector emission model.

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The motivation for the present work lies in the CEBAF project [1] to study the vector-meson decay of nonstrange baryons through photoproduction reactions. By the analysis of such data, one aims at identifying new but predicted resonances as well as checking various quark-model predictions. Theoretical models presently predict many more resonances than those discovered in πN scattering or pion photoproduction experiments. One reason for not observing some of the predicted resonances may be that they have too small a πN branching ratio. If they have large couplings to the vector-meson ρN and ωN channels, then they have a chance to be identified in the corresponding decays. Calculation of the decay widths for vector-meson decays is therefore highly desirable both for giving an orientation in the experimental search and for testing quark models.

At present there are very few theoretical studies [2–4] of the $N+\rho$ decay and only one of the $N+\omega$ decay [3]. In Ref. [3], Koniuk assumed that the baryon emits a pointlike meson and defined transition matrix elements through a nonrelativistic reduction of the most-general quark vector current, in analogy to the pseudoscalar emission model [5]. The transition operator contains two elementary amplitudes which play the role of free parameters. In our analysis of the $N+\rho$ decay [4] we used a flux-tube-breaking mechanism motivated by QCD which has been previously tested on $N+\pi$ decays [6,7]. The only parameter in our calculations, the strength of the breaking amplitude, has been adjusted to describe the decay of the $\Delta(1232)$ into $N+\pi$. A major difference with the model proposed by Koniuk is that in our calculations the meson is treated as a finite size particle. This leads to a nonlocal emission operator [8].

The present work extends the study of the $N\rho$ decays to $N\omega$ decays. The ρ and ω mesons have identical coordinate space wave functions. However, because of the difference in their flavor content, the decay amplitudes are different. In particular, the Δ^* resonances cannot decay into $N+\omega$ due to the isospin conservation, while they do decay into $N+\rho$ channels.

The baryon eigenstates used in these calculations result from the diagonalization [9,10] of a Hamiltonian, containing a linear confinement potential and a hyperfine interaction, in a space spanned by the $\mathbf{56}(0^+,2^+)$, $\mathbf{56}'(0^+)$, $\mathbf{70}(0^+,2^+)$, and $\mathbf{20}(1^+)$ SU(6) multiplets. These are all positive parity states. In the present calculations we use the same set of mixing angles and eigenvalues as those used in the analysis of $N+\pi$ [7] and $n+\rho$ [4] decays.

The calculations of the decay widths have been performed within a flux-tube-breaking mechanism, as in Ref. [4]. The limit of an infinite extension flux tube has been used. It has been shown both for mesons [11] and $N+\pi$ baryon decays [7] that this limit, besides being simpler, provides a very good approximation to a finite-extension, QCD-inspired, flux-tube breaking [11]. In this limit, commonly called the $^3P_0$ quark pair creation model [12], the $R\rightarrow N+M$ transition amplitude is given by

$$\langle NM|T|R\rangle^{J_R}_{m_N m_M}=\sum_m \langle 11m-m|00\rangle\langle\phi_N^{m_N}\phi_M^{m_M}|\phi_R\phi_{\rm vac}^{-m}\rangle \times I_m(R;N,M)\ , \tag{1}$$

where the notation is the same as in Ref. [4], i.e., J_R, m_N, and m_M are the total angular momentum of the resonance, and the projection of the nucleon and the meson spins, respectively. The matrix element $\langle\phi_N^{m_N}\phi_M^{m_M}|\phi_R\phi_{\rm vac}^{-m}\rangle$ contains the spin-flavor part of the wave functions and I_m is the nine-dimensional integral:

$$I_m(R;N,M)=-\left[\frac{3}{4\pi}\right]^{1/2}\frac{2^3}{(2\pi)^{3/2}}\delta(\mathbf{k}_M+\mathbf{k}_N)\gamma_0 \times\int d^3\rho\, d^3\lambda\, d^3x\,\psi_R[\boldsymbol{\rho},\boldsymbol{\lambda}+(\tfrac{8}{3})^{1/2}\mathbf{x}]\psi_N(\boldsymbol{\rho},\boldsymbol{\lambda})\exp\{i\mathbf{k}_M\cdot[(\tfrac{2}{3})^{1/2}\boldsymbol{\lambda}+\mathbf{x}]\}\boldsymbol{\varepsilon}_m\cdot(\mathbf{k}_M+i\boldsymbol{\nabla}_x)\psi_M(2\mathbf{x})\ , \tag{2}$$

where γ_0 is the strength of the breaking amplitude. Its value has been fixed to reproduce the $N\pi$ decay of $\Delta(1232)$. For details, see Ref. [6]. The integral (2) has been calculated with a Monte Carlo method. Since ω is a spin-1 meson, two (for $J_R=\frac{1}{2}$ baryons) or three (for $J_R\geq\frac{3}{2}$ baryons) different $N+\omega$ partial waves can be observed. The corresponding amplitudes are then connected to the helicity amplitude (1) by the Jacob-Wick formula [13]

$$M_{1s}^{J_R} = \left[\frac{2l+1}{2J_R+1}\right]^{1/2} \sum_{m_N m_N} \langle 1s0m|J_R m\rangle \times \langle s_N s_M m_N - m_M|sm\rangle \times \langle NM|T|R\rangle_{m_N m_M}^{J_R}, \quad (3)$$

where l and s are the relative orbital momentum and total spin of the outgoing particles. s_N and s_M stand for the nucleon and the meson spin, respectively.

As one deals with a decaying meson, an appropriate calculation of the baryon width would require, in principle, an integration of the $\Gamma_{N\omega}$ width derived from (3) over a weighted Breit-Wigner mass distribution of the decaying meson [4]. But because of the fact that $\Gamma_\omega = 8.5$ MeV is much smaller than $\Gamma_\rho = 153$ MeV [14], the situation is much simpler here, as compared to the treatment of the $N\rho$ decay. First, the integration is not necessary for resonances well above the threshold. This is certainly the case of resonances having a mass $m_R > m_N + m_\omega + 2\Gamma_\omega \cong 1740$ MeV, i.e., most of the resonances under consideration. Second, the resonance $N(1680)$ is located five times Γ_ω below the threshold. Hence one can safely assume that its decay width into $N+\omega$ is negligible. Therefore, we exclude it from our calculations, as well as any other resonance lighter than it, and in particular all of the $N=1$ band negative parity resonances.

We are left with the resonances $P_{13}(1720)$ and $P_{11}(1710)$ located in the vicinity of the threshold. There is a caveat here. The result is quite sensitive to the value of m_R, and both the theoretical and experimental uncertainties on m_R are large as compared to Γ_ω. A problem in the theoretical description of mass spectra [9,10,15] is that the coupling of baryons to baryon-meson channels, which may produce important mass shifts [16–18] has not yet been included. Because of this situation, we use the experimental mass instead of the theoretical value [9] both for $P_{13}(1720)$ and $P_{11}(1710)$ resonances.

In Table I our results for the partial wave amplitudes (MeV$^{1/2}$) and the total widths (MeV) are exhibited in the first row attached to each resonance. The second row represents Koniuk's results. Each amplitude $\Gamma_{1s}^{1/2}$ carries a phase defined by the product $\sigma_{\text{in}}\sigma_{\text{out}}$, where σ_{in} is the sign of the ingoing $R \to N+\pi$ amplitude determined as in Ref. [6] and σ_{out} is the phase of the presently calculated amplitude.

There are both similarities and differences between our results and those of Koniuk. About half of our phases are the same as those of Koniuk. A decay amplitude results from the interferent contributions associated with different SU(6) symmetries. When the interference is destructive, even a small change in the mixing angles or in the transition operator matrix elements can change the sign of the amplitude. This may happen in the $N\pi$ (σ_{in}) as well as in the $N\omega$ (σ_{out}) amplitude.

Concerning the absolute values, there are some major differences, up to one order of magnitude, between Koniuk's and our predictions. These differences can originate in any mixture of the following causes: mixing angles, transition operator, and phase space. However, in

TABLE I. Helicity amplitudes (MeV$^{1/2}$) for $N\pi$ decay and partial wave amplitudes (MeV$^{1/2}$) and total widths (MeV) for $N\omega$ decay. Column 1, resonance; column 2, $N\pi$ amplitude; column 3, mass (MeV); columns 4–8, partial wave amplitudes. Column 9, $N\omega$ width. Row 1 represents our results; row 2 is from Ref. [3].

Resonance	$N\pi$	Mass	$p_{1/2}$	$p_{3/2}$	$f_{1/2}$	$f_{3/2}$	$h_{3/2}$	$\Gamma_{N\omega}$
$F_{17}(1990)$	1.1	1988			−2.3	+2.8	−0.7	14
	3.1	1955			−1.3	+7.2	0	54
F_{15}	1.8	1970		+5.4	−2.2	+2.2		39
	0.4	1955		+12.3	+5.5	−1.2		183
F_{15}	≤0.7	2033		+5.6	+4.3	−1.9		53
	1.3	2025		−10.9	−4.0	−6.7		180
$P_{13}(1720)$	11.0	1720[a]	−0.1	−0.2	−0.1			~0
	6.5	1710	−5.3	+2.1	+0.61			33
P_{13}	1.0	1914	−11.5	+8.2		−6.2		237
	3.2	1870	−9.7	+0.43		+2.0		98
P_{13}	2.1	1979	−10.2	+15.5		−5.2		370
	1.1	1955	−1.2	−9.3		−1.54		90
P_{13}	2.0	1985	+6.6	+4.1		−0.1		60
	1.1	1980	+2.9	−6.7		+1.3		55
P_{13}	2.8	2046	+9.6	−1.2		+0.2		94
	0.5	2060	−1.7	+8.6		+4.5		97
$P_{11}(1710)$	3.7	1710[a]	−0.03	+0.2				~0
	6.7	1705	−0.6	+0.7				1
P_{11}	≤0.5	1930	+2.6	−3.6				20
	4.4	1890	−5.7	+2.3				38
P_{11}	≤0.4	2042	+3.0	−4.3				28
	1.2	2055	−5.1	+2.6				33

[a]Experimental mass.

TABLE II. Partial wave amplitudes ($\mathrm{MeV}^{1/2}$) and total widths (MeV) for $N\omega$ decay with our transition matrix elements but mixing angles of Ref. [19].

Resonance	Mass	$p_{1/2}$	$p_{3/2}$	$f_{1/2}$	$f_{3/2}$	$h_{3/2}$	$\Gamma_{N\omega}$
$F_{17}(1990)$	1955			1.8	2.2	0.6	9
F_{15}	1955		4.7	1.5	2.0		29
F_{15}	2025		5.6	4.3	2.5		56
P_{13}	1870	9.9	7.5	5.4			183

several cases our mixing angles are very close [or identical for $F_{17}(1990)$ which is a pure $^4N(70,2^+)$ state] to those used by Koniuk [19] and the difference in the phase space is negligible. In these cases, large differences in the amplitudes, if any, should be due to the transition operator matrix elements. In order to disentangle the role played by the transition operator matrix elements, we calculated the partial wave amplitudes for those cases, using our transition matrix elements but mixing angles and masses used by Koniuk. The results are displayed in Table II. It turns out that whenever there is a large difference between the two models of Table I (i.e., a factor of about 2 or more in the amplitudes), the results of Table II are closer to ours. This indicates that the role of the transition operator is essential in explaining the differences between the two results.

We recall that a finite size meson emission operator has been assumed in our case and a pointlike one in Koniuk's work. Since no $N\omega$ decay has yet been observed, we turn to the $N\pi$ channel to explain why a finite size meson emission operator should be considered as more realistic. In Ref. [7] we investigated the role of the radial extent of the emitted meson in the calculation of $N\pi$ decay widths. We found that the local limit (zero radius) brought much less satisfactory results. The χ^2 was four times larger in the local limit case than it was when we used a finite size pion wave function which lead to a radius of 0.16 fm. Since the radius of the ω meson is larger than that of the pion, its size may play an even larger role.

The last column of Table I reproduces the $\Gamma_{N\omega}$ width, i.e., the sum of squares of partial wave amplitudes. There are several resonances for which the two models give similar results. These are the fourth and the fifth P_{13} resonances and the last P_{11} resonance. However, this global agreement results from the additive contribution of quite different amplitudes. These resonances have different mixing angles in the two models, and rough similarities in the amplitudes may result from the combined effect of the difference in the mixing angles and in the transition matrix elements.

For completeness, we have also indicated in column 2 of Table I the $N\pi$ amplitude of each resonance. These have been taken from Ref. [20], where further details can be found. Their values are in keeping with the fact that the corresponding resonances have or have not been seen in πN scattering experiments.

In conclusion, our results present important differences with those of Koniuk for which we have some understanding. Our transition operator has no free parameters, and for the reasons explained above we consider it more realistic than a pointlike emission operator. We obtain appreciable $\Gamma_{N\omega}$ widths for most resonances above the threshold, and it would be interesting to attempt their identification experimentally.

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