Quantum interference in the $e^+e^-$ decays of $\rho^0$ and $\omega$-mesons produced in $\pi^-p$ reactions

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Abstract

The study of the $\pi^-p \rightarrow \rho^0 n$ and $\pi^-p \rightarrow \omega n$ amplitudes close and below the vector meson production threshold ($1.2 < \sqrt{s} < 1.8$ GeV) reveals a rich dynamics arising from the presence of specific baryon resonances in this energy range. The interference pattern of the $e^+e^-$ decays of the $\rho^0$- and $\omega$-mesons produced in $\pi^-p$ reactions reflects directly this dynamics. We discuss this interference pattern in the $\pi^-p \rightarrow e^+e^-n$ reaction as function of the total center of mass energy $\sqrt{s}$. We emphasize the importance of an experimental study of this reaction, which could be made with the HADES detector and the available pion beam at GSI.

1 Introduction

The coupling of light vector mesons [$\rho(770)$ and $\omega(782)$] to low-lying baryon resonances is still to a large extent unknown. This lack of information is a particularly important source of uncertainties in the theoretical description of the propagation of vector mesons in a nuclear medium, where resonance-hole states are expected to contribute largely to the dynamics.

The $\pi^-p \rightarrow \rho^0 n$ and $\pi^-p \rightarrow \omega n$ processes have been described recently in the framework of a relativistic coupled-channel model [1]. They are particular processes included in a broader scheme aiming at reproducing data on pion-nucleon elastic scattering and pion-induced production reactions involving the $\pi\Delta$, $\rho N$, $\omega N$, $K\Lambda$, $K\Sigma$ and $\eta N$ channels. The model is restricted to $s$-wave scattering in the $\rho N$ and $\omega N$ channels. The corresponding $s$- and $d$-wave resonances in the $\pi N$ channel are generated dynamically. The meson-baryon
coupling strengths are determined from the fit to the available data on the channels included in the calculation.

The $\pi^- p \rightarrow \rho^0 n$ and $\pi^- p \rightarrow \omega n$ amplitudes are very sensitive to the presence of the s- and d-wave pion-nucleon resonances lying below the vector meson production threshold ($1.3 < \sqrt{s} < 1.7$ GeV). This point is discussed and illustrated in Section 2. Data that directly reflect these amplitudes would provide very useful constraints on the underlying dynamics. The $\pi^- p \rightarrow e^+ e^- n$ reaction appears as a particularly relevant process to study the $\pi^- p \rightarrow \rho^0 n$ and $\pi^- p \rightarrow \omega n$ amplitudes. This reaction offers the possibility to test experimentally the $\rho^0$ and $\omega$ strengths below threshold and the quantum interference in the $e^+ e^-$ decays of the $\rho^0$- and $\omega$-mesons is very sensitive to the magnitudes and the relative phase of the production amplitudes. In Section 3 we present briefly the formalism and preliminary numerical results. The perspectives of this work are discussed in Section 4.

2 The $\pi^- p \rightarrow \rho^0 n$ and $\pi^- p \rightarrow \omega n$ amplitudes close to the vector meson production threshold

The $\pi^- p \rightarrow \rho^0 n$ and $\pi^- p \rightarrow \omega n$ amplitudes of Ref. [1] entering our calculation of the $\pi^- p \rightarrow e^+ e^- n$ reaction are displayed in Fig. 1. We shall restrict our discussion to $e^+ e^-$ pairs of invariant masses ranging from 0.5 to 0.8 GeV. The exclusive measurement of the $e^+ e^-$ outgoing channel ensures that the $e^+ e^-$ pairs come from vector meson decays (pseudoscalar mesons decay into an $e^+ e^-$ pair and an additional photon). We recall however that only s- and d-wave pion-nucleon resonances are at present included in the model of Ref. [1]. To be complete, the description of the $\pi^- p \rightarrow e^+ e^- n$ reaction in the energy range discussed in this work ($1.2 < \sqrt{s} < 1.8$ GeV) should include also the effect of other partial waves. We will return to this question in Section 4.

The $\pi^- p \rightarrow \rho^0 n$ and $\pi^- p \rightarrow \omega n$ scattering amplitudes of Fig. 1 illustrate the importance of baryon resonances in vector meson production below threshold. These resonances induce a rich structure in both the real and imaginary parts of the amplitudes. In particular, the presence of the d-wave $N^*(1520)$ resonance is clearly reflected in the $J=3/2$ amplitudes for $\rho^0$ and $\omega$ production. This is an immediate consequence of the strong coupling of the $N^*(1520)$ to both the $\rho^0 n$ and $\omega n$ channels [1]. The strong couplings imply that there is considerable vector-meson strength in the $N^*$-hole modes in the nuclear medium.
Fig. 1. Amplitudes in GeV$^{-1}$ for the $\pi^- p \to \rho^0 n$ and $\pi^- p \to \omega n$ processes obtained in Ref. [1]. The amplitudes are averaged over isospin and shown for the two spin channels.

An experimental test of the N*N$\rho^0$ and N*N$\omega$ vertices through the $\pi^- p \to e^+ e^- n$ reaction below the vector meson production threshold would be a most valuable constraint on the in-medium propagation of $\rho^0$- and $\omega$-mesons.

3 The $\pi^- p \to e^+ e^- n$ reaction

The $\pi^- p \to \rho^0 n$ and $\pi^- p \to \omega n$ amplitudes are simply related to the $\pi^- p \to e^+ e^- n$ amplitudes through the Vector Dominance assumption [2, 3]. In this picture, the $e^+ e^-$ decay of vector mesons is described by their conversion into time-like photons which subsequently materialize into $e^+ e^-$ pairs. The magnitude of the coupling constants $f_{\rho}$ and $f_{\omega}$, which characterize the conversion of $\rho$- and $\omega$-mesons into photons, is determined from the measured partial widths of $\rho^0$- and $\omega$-mesons into $e^+ e^-$ pairs [4]. The relative phase of the $\rho$ and $\omega$ amplitudes is not determined by hadronic observables. We determine this phase
in each channel by comparing with the photon-decay helicity amplitudes of the corresponding resonance \[4\], assuming Vector Meson Dominance. We use \( f_{\rho} = 0.036 \text{ GeV}^2 \) and \( f_{\omega} = 0.011 \text{ GeV}^2 \) \[5\].

\[\begin{align*}
\left| \langle ne^+e^-|\pi^-p \rangle \right|^2 &= \left| \frac{f_{\rho} M_{\pi^-p\rightarrow\rho n}}{m^4} \right|^2 \left( \frac{m^2 - m_{\rho}^2 + im_{\rho} \Gamma_{\rho}(m)}{m^2 - m_{\omega}^2 + im_{\omega} \Gamma_{\omega}(m)} \right)^2,
\end{align*}\]

where the first term of the right-hand side describes the propagation of the time-like photon and its decay into an \( e^+e^- \) pair of invariant mass \( m \) and the second term contains the vector meson production dynamics. The vector mesons are characterized by their mass \( m_V \) and energy-dependent width \( \Gamma_V(m) \). The interference of the complex \( M_{\pi^-p\rightarrow\rho n} \) and \( M_{\pi^-p\rightarrow\omega n} \) amplitudes (Fig. 1) in the \( \pi^-p \rightarrow e^+e^-n \) cross section is sensitive to their relative phase. The importance of measuring such a phase in the \( e^+e^- \) or \( \pi^+\pi^- \) decays of \( \rho^0 \)- and \( \omega \)-mesons has been evidenced by the contribution of such data to the understanding of other processes, like the photoproduction of \( \rho^0 \)- and \( \omega \)-mesons in the diffractive regime \( (\gamma Be \rightarrow e^+e^- Be) \) \[6\] and the \( e^+e^- \rightarrow \pi^+\pi^- \) reaction \[7, 8\].

Fig. 2. Squared amplitude for the \( \pi^-p \rightarrow e^+e^-n \) reaction with intermediate \( \rho^0 \)- and \( \omega \)-mesons.
We indicate the magnitude of the $\rho^0 - \omega$ interference in the $\pi^- p \to e^+ e^- n$ reaction as function of the total center of mass energy in Fig. 3. We have selected $e^+ e^-$ pairs of invariant mass $m=0.55$ GeV. This figure illustrates the role of baryon resonances with masses in the range of 1.5 to 1.6 GeV in generating strong interference effects.

Above the vector meson threshold, the $\rho^0 - \omega$ interference in the $\pi^- p \to e^+ e^- n$ cross section is particularly interesting for $e^+ e^-$ pair invariant masses close to the $\omega$ mass. This effect is manifested in the invariant mass spectrum displayed in Fig. 4 ($\sqrt{s}=1.8$ GeV). The model of Ref. [1] for the $M_{\pi^- p \to \rho^0 n}$ and $M_{\pi^- p \to \omega n}$ amplitudes predicts a constructive interference at this energy. This feature appears to be a very sensitive test of the model.
Fig. 4. Differential cross section $d\sigma/dm^2$ for the $\pi^- p \rightarrow e^+ e^- n$ reaction as function of the $e^+ e^-$ pair invariant mass for a fixed total center of mass energy $\sqrt{s}=1.8$ GeV.

A detailed discussion of these interference patterns will be presented in a forthcoming publication [9].

4 Perspectives

The study of the $\pi^- p \rightarrow e^+ e^- n$ reaction provides a particularly stringent test of the $\pi^- p \rightarrow \rho^0 n$ and $\pi^- p \rightarrow \omega n$ amplitudes close and below the vector meson production threshold ($1.2 < \sqrt{s} < 1.8$ GeV).

We have computed the cross section of the $\pi^- p \rightarrow e^+ e^- n$ reaction using the model of Ref. [1] for the vector meson production amplitude and indicated its main features as function of the total center of mass energy.
A natural extension of the present work would be to include the p-wave pion-nucleon resonances in the coupled channel scheme of Ref. [1], thereby increasing the expected domain of validity of the $\pi^-p \rightarrow \rho^0n$ and $\pi^-p \rightarrow \omega n$ amplitudes. Projecting the coupled-channel amplitudes on specific $s$- and $t$-channel exchanges could be a useful step in providing a simple interpretation of our numerical results.

We note that the study of the quantum interference of $\rho^0$- and $\omega$-mesons produced in the $\pi^-p \rightarrow \rho^0n$ and $\pi^-p \rightarrow \omega n$ reactions in other channels than the $e^+e^-$ decay ($\pi^0\gamma$ for example) may also be of interest.

Data on the $\pi^-p \rightarrow e^+e^-n$ cross section in the energy range considered in this work are at present not available. Such measurements would provide an important test of the dynamics in a reaction which is crucial for the understanding of the in-medium propagation of vector mesons.

5 Acknowledgements

One of us (M. S.) acknowledges the generous hospitality of the Theory Group of GSI, where much of this work was done.

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