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Light Vector Meson Photoproduction off of ^{1}H at Jefferson Lab and ρ–ω Interference in the Leptonic Decay Channel

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Although the phenomena of ρ–ω interference has been studied at great length in pionic decay channel over the past 50 years, a study of the interference in a purely electromagnetic production and decay channel has never been performed on an elementary proton target until now. The only published photo-production data of the ρ-ω leptonic decay channel was obtained in the early seventies on C and Be. An investigation of the ρ-ω interference on a Hydrogen was recently completed at Jefferson Lab with the CLAS detector. The di-lepton spectra was fit with two interfering relativistic Breit-Wigner functions, and the interference phase was extracted. Preliminary results will be compared to the previous experimental studies in nuclei.

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1. Introduction

Quantum interference between the ρ and ω mesons [1] had to be considered when interpreting ρ–ω mass spectra reconstructed from detected pions in particle experiments of the 1960's. An investigation of the interference in a purely electromagnetic channel, photo-production of ρ–ω with a e^+e^-decay, was conducted on carbon targets by Biggs *et al* in 1970 [2] and on beryllium targets by Alvenslaben *et al* in 1971 [3]. The derived interference phases were different from those obtained in the pionic decay channels and the discrepancies were never resolved. The work presented in this paper is the first ever exploration of the e^+e^-decay of the ρ–ω interference from photo-production on a proton target.

Recently there has been renewed interest in the ρ–ω interference stemming from different results of in-medium modification studies of the ω meson. One study by Wood *et al* [4] of the ω in heavy nuclei shows a significant broadening through absorption studies, resulting in an absorption cross-section well over 150 mb. The ω yields were extracted by generating a e^+e^-mass spectrum and subtracting the ρ contribution; interference effects were not taken into account. A similar study was done by Kotulla *et al* [5] through the $\omega \rightarrow \pi^0\gamma$ decay shows significantly less broadening, around 70 mb, in a channel for which the ρ is isospin restricted and therefore cannot significantly interfere. The work presented in this paper could shed some light on the importance of the ρ–ω interference when interpreting the transparancy ratios measured for the ω meson.

2. The g12 experiment at JLab

This study was performed at the Thomas Jefferson National Accelerator Facility (JLab) with the CEBAF Large Acceptance Spectrometer (CLAS) [6] and the photon tagging facility [7]. In the JLab experiment E-04-005 (aka experiment "g12"), we studied the reaction $\gamma p \rightarrow VX \rightarrow e^+e^-X$ where V includes the ρ and ω and X is constrained to be a proton through missing mass restrictions. A high luminosity tagged Bremsstrahlung photon beam of energies between 1.2 GeV and 5.4 GeV incident on a 40cm LH2 target resulted in over 3M triggers with identified e^+e^-pairs.

The e^+e^-data sample was then cleaned with vertex position and timing cuts, a missing mass cut on the recoiling proton, acceptance corrected, and restricted to the ρ–ω mass range of interest; 650 MeV to 950 MeV. The remaining data are then comprised of a ρ–ω signal, a Bethe-Heitler background (largest contributing background), and a negligible contribution from ω Dalitz and η Dalitz decays ($< 1\%$). The Bethe-Heitler events are subtracted from the data sample through simulation produced from the GiBUU Monte Carlo software [8, 9]. GiBUU is a hadronic transport model which provides a unified framework for various types of elementary reactions on nuclei as well as heavy-ion collisions; GiBUU provided in-medium transport calculations for both of the above mentioned medium modification studies of Wood *et al* and Kotulla *et al*. The invariant mass spectrum, and the simulated Bethe-Heitler background are shown in Fig. 1. After subtraction of the Bethe-Heitler background, the remaining e^+e^-invariant mass spectrum is then fit with two interfering Breit-Wigner functions to obtain the interference phase. Contributions from Bethe-Heitler and ρ or ω meson interference is expected to be two or more orders of magnitude below the total ρ–ω contribution [10] and its effect on the calculation of the ρ–ω is included in the calculation of the systematic uncertainties.

3. Interference formalism

The formalism for defining the interference phase is important to interpreting the results; the exact definition of the interference phase can vary quite significantly from publication to publication, and one must take this into consideration when comparing results. The phase presented in this paper is derived from an effective lagrangian mass-term matrix with symmetric off-diagonal non-zero interference constants. The diagonal terms are the standard relativistic Breit-Wigner mass terms. The resulting amplitude calculation is written as:

$$F_{g12}^2 = \frac{DA_\rho^2 m_\rho^4}{m} \left| \frac{1}{(m_\rho^2 - m^2) + i m_\rho \Gamma_\rho} + \frac{A_\omega}{A_\rho} \frac{m_\omega^2}{m_\rho^2} \frac{e^{i\phi}}{(m_\omega^2 - m^2) + i m_\omega \Gamma_\omega} \right|^2 \tag{3.1}$$

where D is a normalization constant, A_V, m_V, and Γ_V are the total amplitude, mass, and width of the meson respectively. Here m with no subscript is the experimentally reconstructed e^+e^-invariant mass. The phase ϕ_ρ is then further defined by:

$$1 - e^{i\phi_\rho} = -\frac{\delta}{M_\rho} \left(\frac{T_\rho S_\omega + T_\omega S_\rho}{T_\omega S_\omega} \right) \tag{3.2}$$

where δ is the off-diagonal interference term of the mass matrix, and T_V, S_V, and M_V are the decay amplitude, production amplitude, and Breit-Wigner mass term respectively. The functional form of Eqn. 3.1 is convoluted with a gaussian, to account for resolution smearing effects, and then fit to the invariant e^+e^-mass spectrum (Bethe-Heitler subtracted). Free parameters of the fit include the ρ and ω mass, the ratio of amplitudes A_ω/A_ρ, the interference phase ϕ_ρ, the gaussian width of the mass resolution, and an over-all normalization constant. The only mesonic properties fixed in the fit are the ω and ρ width, Γ_ω to the value of 8.49 MeV and Γ_ρ of 149.1 MeV as reported by the Particle Data Group [11]. These parameters are fixed to minimize fitting conflicts with the mass resolution parameter. The fit is shown in Fig. 2 and the parameters are reported in Tab. 1.

Table 1: Preliminary fit results of two relativistic interfering Breit-Wigner functions to the e^+e^-invariant mass spectrum in the ρ–ω interference region. Uncertainties listed are statistical only.

m_ρ	0.775 ± 0.006 GeV
m_ω	0.781 ± 0.001 GeV
A_ω/A_ρ	0.111 ± 0.007
ϕ_ρ	0.556 ± 0.210 rad

The experimental data were also fit to the functional formalism of Biggs *et al* and Alvenslaben *et al* for comparison. The Biggs *et al* formalism is shown in Eqn. 3.3. Here the function is quite similar to F_{g12}^2, if one extracts the VM-N coupling constants from the decay amplitude T_V and absorbs $m_\rho^8 |A_{\rho N}|^2/g_\rho^4$ into the normalization constant D. A significant difference in the fit comes from an over all factor m^{-2} instead of m^{-1} as in F_{g12}^2. The values for m_ρ, Γ_ρ, and Γ_ω were fixed to their published values at the time. The fit results in a phase ϕ_ρ = 0.322 ± 0.151 rad (statistical uncertainty only).

$$F^2_{Biggs} = \frac{D}{m^2}\left|\frac{1}{m^2 - m^2_\rho + i m_\rho \Gamma_\rho} + \left(\frac{m_\omega}{m_\rho}\right)^4 \frac{\eta}{9}\frac{e^{i\phi}}{m^2 - m^2_\omega + i m_\omega \Gamma_\omega}\right|^2 \tag{3.3}$$

Alvensleben *et al.* used a functional form shown in Eqn. 3.4. Here the numerator of the last term describes the ratio of the ρBe and ωBe scattering amplitudes: $A_{\rho Be}/A_{\omega Be} = |R|e^{i\phi}$. The masses and widths of the ω and ρ were fixed, as well as the value $|R| = 1$. The Alvensleben *et al.* interference function has a m^{-4} mass term; different from the m^{-2} term of F^2_{Biggs} and the m^{-1} term of F^2_{g12}. The fit results in a phase ϕ_ρ = 6.242 ± 0.155 rad (statistical uncertainty only).

$$F^2_{Alvensleben} = \frac{D m^4_\rho}{m^4}\left|\frac{1}{m^2_\rho - m^2 - i m_\rho \Gamma_\rho} + \frac{g^2_\rho}{g^2_\omega}\frac{m^2_\omega}{m^2_\rho}\frac{|R|e^{i\phi}}{m^2_\omega - m^2 - i m_\omega \Gamma_\omega}\right|^2 \tag{3.4}$$

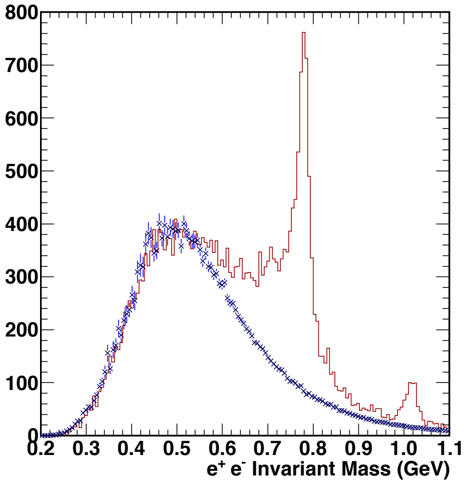

Figure 1: The e^+e^-invariant mass spectrum (red) overlayed with the simulated Bethe-Heitler contribution (blue).

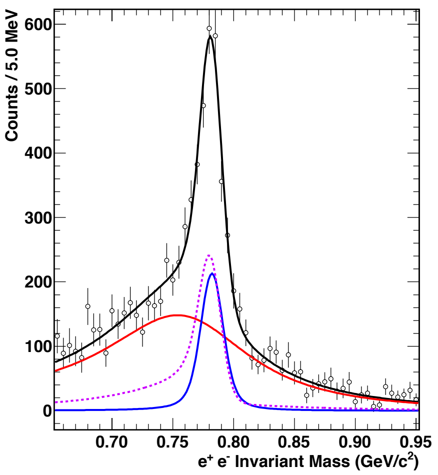

Figure 2: The e^+e^-invariant mass spectrum fit to Eqn. 3.1. The black line is the total fit function, the red line represents the ρ term, the blue line represents the ω term, and the dashed purple line represents the interference term.

The derived values for the ϕ_ρ interference phase depend on the formalism used. However using the same formalism one can compare the ϕ_ρ phase obtained in this experiment on the proton to the ϕ_ρ phases previously measured in Be and C. The phases are quite different and could be an indication of a possible A (and/or medium) dependence of the interference phase.

4. Summary and conclusions

Preliminary measurements of the interference phase is reported for the first time ever from the electron-positron decay channel through photo-production of the ρ–ω off a ^{1}H target. This phase can be used to calculate more accurately the pion-channel ρ–ω interference phase from the Orsay phase measured in $e^+e^- \rightarrow \pi^+\pi^-$ reactions[12]. The e^+e^-interference spectra shows a slight enhancement on the low-mass side of the ω peak and a shift of the interference peak "mean" of approximately 1 MeV. Additionally, the interference is completely constructive and mostly overlapping with the ω peak. Should the interference spectra be similar on heavier targets relative to ^{1}H, this interference effect could explain the depletion of ω yield on the high mass side of the ω peak in the absorption studies published by Wood *et al* [4]. Additionally, if the constructive effects of the interference contribute greater yields to the ^{12}C target data along with less constructive, or even destructive, interference for the heavier target data; this could explain the dramatic increase in ω absorption cross section for heavier targets as compared to the ^{12}C target baseline. However, a definitive argument cannot be made until the ρ–ω interference phase is extracted from a systematic study on heavier targets.

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