\[ \pi^0\gamma \] invariant mass distribution in the low energy \[ \gamma p \rightarrow \omega p \] reaction

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Abstract

We study the reaction mechanism for the correlated \[ \pi^0\gamma \] emission in the photon induced reaction on the proton target. Since this reaction is studied in the GeV region, we assume that it proceeds through the formation of the vector meson in the intermediate state. The vector meson, being an unstable particle, decays into \[ \pi^0\gamma \] bosons after propagating certain distance. Our analysis shows that the \[ \pi^0\gamma \] event seen in coincidence in the final state dominantly arises due to the decay of \[ \omega \] meson. The calculated results reproduce the measured \[ \pi^0\gamma \] invariant mass distribution spectra very well.

1 Introduction

The vector meson production in the nuclear and particle reactions has opened up various avenues providing ample opportunities for learning many interesting topics in physics. The leptoproduction of vector meson is a potential tool to investigate the hadron structure of photon [1]. The dilepton production in the intermediate energy region is undoubtly understood due to the decay and the interference of the vector mesons [1]. Since the vector meson strongly couples to the nucleon and its resonances [2, 3], the dynamics of these resonances can be explored by studying the vector meson production process. In fact, there are predictions of many nucleonic resonances (see Ref. [4], and references their in), which are yet to be found. The vector meson production could be an useful probe to search these missing resonances. It should be added that the sub-threshold production of the vector meson can probe the low lying resonances, like \[ N(1520) \] [5].

In the recent years, the production of vector meson in the nuclear reaction has drawn considerable attention to explore its properties in the nuclear medium [6, 7]. Indeed, it is a fundamental issue in the nuclear physics. In this context, the \[ \pi^0\gamma \] invariant mass distribution spectrum was measured, in the recent past, by the CBELSA/TAPS collaboration at the electron stretcher accelerator (ELSA) in Bonn [8] to look for the medium modification on the omega meson in the Nb nucleus. They had also taken data for the above spectrum due to \[ \gamma p \] reaction. Here, we present the reaction mechanism for the \[ (\gamma, \pi^0\gamma) \] reaction on the proton target in
the GeV region. In this energy region, the $\pi^0\gamma$ in the final state (according to the particle data group [9]) can arise due to the decay of the low lying vector mesons, such as $\rho^0(768)$, $\omega(782)$ and $\phi(1020)$. Therefore, we consider this reaction proceeds through three steps: (i) the formation of vector mesons, (ii) the propagation of these vector mesons, and (iii) the decay of these mesons into $\pi^0\gamma$ channel. Symbolically, this reaction goes as $\gamma p \to Vp; \ V \to \pi^0\gamma$, where $V$ stands for the above mentioned vector mesons (i.e., $V^\rho$ for the

\[ \omega \]

for the

\[ \phi \]

in the energy region considered here. For example, the measured cross section at 1.5 GeV beam energy, as reported by various group, are $\sigma_{\gamma p \to \rho^0 p} \approx 23 \mu b$ [10], $\sigma_{\gamma p \to \omega p} \approx 6.51 \mu b$ [11], and $\sigma_{\gamma p \to \phi p} \approx 0.17 \mu b$ [12]. Therefore, the measured $\sigma_{\gamma p \to \rho^0 p}$ is about 3.53 times larger than the measured $\sigma_{\gamma p \to \omega p}$, and the former is about 135.29 times larger than the measured $\sigma_{\gamma p \to \phi p}$. The vector meson propagator $G_V(m)$ is given by

\[ G_V(m) = \frac{1}{m^2 - m_V^2 + i m_V \Gamma_V(m)} \]  

where $V$ stands for $\rho^0$, $\omega$ and $\phi$ mesons as mentioned above. For these mesons, we have values for their resonance masses and total widths [9]: $m_{V(\equiv \rho^0)} \approx 768$ MeV, $\Gamma_V(\equiv \rho^0) \approx 151$ MeV; $m_{V(\equiv \omega)} \approx 782$ MeV, $\Gamma_V(\equiv \omega) \approx 8.43$ MeV; $m_{V(\equiv \phi)} \approx 1020$ MeV, $\Gamma_V(\equiv \phi) \approx 4.43$ MeV. The data taken at ELSA [8] show the peak at $\sim 780$ MeV in the $\pi^0\gamma$ invariant mass distribution spectrum. Around this mass, the propagators for both $\rho^0$ and $\omega$ mesons behave as $G_V(m \approx 782$ MeV) $\sim \frac{1}{m^2 - m_V^2 + i m_V \Gamma_V(m)}$ (\(V \equiv \rho^0, \omega\), where $\phi$ mesons in the $\pi^0\gamma$ branch (according to the Ref. [9]) are $\Gamma(768)_{\rho^0 \to \pi^0\gamma} \approx 0.12$ MeV, $\Gamma(782)_{\omega \to \pi^0\gamma} \approx 0.72$ MeV, and $\Gamma(1020)_{\phi \to \pi^0\gamma} \approx 0.006$ MeV. In fact, $\Gamma_{\rho^0 \to \pi^0\gamma}(m)$ is negligibly larger than 0.12 MeV and $\Gamma_{\phi \to \pi^0\gamma}(m)$ could be much less than 0.006 MeV at $m \approx 782$ MeV. Therefore, at 1.5 GeV the ratios $\frac{\sigma_{\gamma p \to \omega p}}{\sigma_{\gamma p \to \phi p}} \approx 38.29$, $\frac{|G_{\omega}\left(m \approx 782\right)|^2}{|G_{\rho}\left(m \approx 782\right)|^2} \sim 4.2 \times 10^3$, and $\frac{\Gamma_{(m \approx 782)_{\omega \to \pi^0\gamma}}}{\Gamma_{(m \approx 782)_{\phi \to \pi^0\gamma}}} \frac{1}{120}$ show that we can safely ignore the contribution to the cross section originating from the $\phi$ meson of mass around 782 MeV. For $\rho^0$ and $\omega$ mesons, the above data show $\frac{\sigma_{\gamma p \to \omega p}}{\sigma_{\gamma p \to \rho^0 p}} \approx 0.28$, $\frac{|G_{\omega}\left(m \approx 782\right)|^2}{|G_{\rho}\left(m \approx 782\right)|^2} \sim 3.1 \times 10^2$, and $\frac{\Gamma_{(m \approx 782)_{\omega \to \pi^0\gamma}}}{\Gamma_{(m \approx 782)_{\rho^0 \to \pi^0\gamma}}} \approx 6$. Therefore, this analysis illustrates qualitatively that the contribution to the $\pi^0\gamma$ emission from the $\omega$ meson decay is a factor about 521 times larger than that originating due to the $\rho^0$ meson decay. Similar analysis
shows this factor is about $10^3$ at $E_\gamma$ equal to 1.2 GeV.

There were two aspects in the experiment (done at ELSA [8]) to be mentioned. One aspect in this measurement was the gamma beam of wide energy spread ($0.64 - 2.53$ GeV), since it was the tagged photon produced by the bremsstrahlung radiation of the 2.8 GeV electron on the Pb target. This is unlike to the conventional experiments where the beam energy is used to be taken almost monoenergetic. In fact, the measured $\pi^0\gamma$ invariant mass distribution spectrum has been reported for definite $\omega$ meson momentum bin instead of a particular incident energy. The another aspect of this experimental set-up was the large width in the detecting system (55 MeV), which is about 6.5 times larger than the width of the $\omega$ meson (i.e., $\Gamma_\omega(m = 782$ MeV) = 8.43 MeV in the free state) produced in the $\gamma p$ reaction. Therefore, the measured $\pi^0\gamma$ invariant mass distribution spectrum showing its width about 55 MeV can be believed undoubtedly due to the width of the detector resolution. To compare the calculated results with the data, we incorporate these two aspects in our formalism presented in sec. 2. The results of this study are discussed in sec. 3, and we give the conclusion in sec. 4 in this manuscript.

2 Formalism

The formalism for the $\pi^0\gamma$ emission in the $\gamma p$ reaction, as mentioned above, consists of the production, propagation, and the decay of the omega meson produced in the intermediate state, i.e., $\gamma p \rightarrow \omega p' \rightarrow \omega \rightarrow \pi^0 \gamma'$. The primes on $p$ and $\gamma$ are used at present to distinguish them from the initial state particles, which have been dropped afterward for convenience. The T-matrix $T_{fi}$ for this process can be written as

$$T_{fi} = (\pi^0, \gamma' | \Gamma_{\omega\pi\gamma} | \omega)G_\omega(m)F(\gamma p \rightarrow \omega p'),$$

(2)

where $G_\omega(m)$ denotes the propagator for the $\omega$ meson. $(\pi^0\gamma' | \Gamma_{\omega\pi\gamma} | \omega)$ in this equation is the matrix element for $\omega \rightarrow \pi^0\gamma'$ due to intrinsic coordinates. It is governed by the Lagrangian density [13]:

$$L_{\omega\pi\gamma} = \frac{f_{\omega\pi\gamma}}{m_\pi} \epsilon_{\mu\nu\rho\sigma} \partial^\mu A^\nu \pi^0 \partial^\rho \omega^\sigma,$$

(3)

where $A$ appearing in this equation represents the photon field. $f_{\omega\pi\gamma}$ is the constant for the $\omega\pi\gamma$ coupling. It is equal to 0.095, as extracted from the width of $\omega \rightarrow \pi^0\gamma$ [9].

In Eq. (2), $F(\gamma p \rightarrow \omega p')$ describes the production mechanism for the $\omega$ meson.
in the $\gamma p$ reaction. It is given by

$$F(\gamma p \rightarrow \omega p') = -4\pi E_\omega \left[ \frac{1}{E_\omega} + \frac{1}{E_{\omega'}} \right] < \omega, p' | f_{\gamma p \rightarrow \omega p'}(0) | \gamma, p >,$$

where $f_{\gamma p \rightarrow \omega p'}(0)$ is the forward amplitude for the $\gamma p \rightarrow \omega p'$ reaction.

The differential cross section for the reaction described above can be written as

$$d\sigma = \frac{1}{2} E_\gamma (2\pi)^4 \delta^4(k_i - k_f) \frac{m_p}{E_{\omega'}} \frac{d^3 k_{\omega'}}{(2\pi)^3} \frac{1}{2E_{\omega}} \frac{1}{2E_{\gamma'}} \frac{d^3 k_{\gamma'}}{(2\pi)^3}.$$  

The annular bracket around the $T_f$-matrix indicates the average over the polarization and spin in the initial state and the summation over the polarization and spin in the final state. Since the $\pi^0$ and $\gamma$ bosons in the final state are considered originating due to the decay of the $\omega$ meson, the above expression can be worked out in terms of the $\omega$ meson mass $m$ (i.e., the $\pi^0\gamma'$ invariant mass) as

$$d\sigma(m, E_\gamma) = \int d\Omega_\omega [KF] \Gamma_{\omega \rightarrow \pi^0\gamma'}(m) |G_\omega(m)|^2 |F(\gamma p \rightarrow \omega p')|^2.$$

Where $d\Omega_\omega$ is the infinitesimal solid angle subtended by the $\omega$ meson momentum $k_\omega(= k_{\pi^0} + k_{\gamma'})$. $\Gamma_{\omega \rightarrow \pi^0\gamma'}(m)$ denotes the width for the $\omega$ meson of mass $m$ decaying at rest into $\pi^0\gamma$ channel. It is expressed in Eq. (14). $[KF]$ represents the kinematical factor for this reaction, which is given by

$$[KF] = \frac{3\pi^3}{(2\pi)^6} \frac{k_{\omega}^2 m_p m^2}{k_{\omega}(E_{\gamma} + m_p) - k_{\omega}.k_{\omega}E_{\omega}}.$$  

The Eq. (6) illustrates the differential cross section for the $\omega$ meson mass distribution due to fixed beam (gamma) energy $E_{\gamma}$. But the measurement was done by the CBELSA/TAPS collaboration [8], as mentioned earlier, using a range of incident $\gamma$ energy instead of fixed beam energy. We incorporate it in our calculation by modulating the cross section in Eq. (6) with the beam profile function $W(E_{\gamma})$ [14], i.e.,

$$\frac{d\sigma(m)}{dm} = \int_{E_{\gamma}} dE_\gamma W(E_{\gamma}) \frac{d\sigma(m, E_{\gamma})}{dm}.$$  

$E_{\gamma}^{mn}$ and $E_{\gamma}^{mx}$ are equal to 0.64 GeV and 2.53 GeV respectively, as mentioned in Ref. [8]. The profile function $W(E_{\gamma})$ for the $\gamma$ beam, originating due to bremsstrahlung radiation of the electron, varies as $W(E_{\gamma}) \propto \frac{1}{E_{\gamma}}$ [14].

The calculated cross section due to Eq. (8) can’t reproduce the measured distribution, since the detecting system in the experimental set-up (as mentioned earlier)
had large resolution width, i.e., 55 MeV. This issue is incorporated in the formalism by folding the differential cross section in Eq. (8) with a Gaussian function $R(m, m')$:

$$\frac{d\sigma(m)}{dm} = \int dm' R(m, m') \frac{d\sigma(m')}{dm'}.$$ (9)

The function $R(m, m')$ accounts the resolution (or response) for the detector. The expression for it [15] is

$$R(m, m') = \frac{1}{\sigma \sqrt{2\pi}} e^{-\frac{(m-m')^2}{2\sigma^2}}.$$ (10)

Here, $\sigma$ is related to the full width at the half-maxima (FWHM) of this function as FWHM = 2.35$\sigma$. We take the value for FWHM equal to 55 MeV, so that the function $R(m, m')$ can describe properly the resolution for the detector used at ELSA [8].

3 Results and Discussion

The amplitude for the $\gamma p \to \omega p$ reaction, i.e., $f_{\gamma p \to \omega p}(0)$ needed in Eq. (4), is related to the four momentum $q^2$ transfer distribution $d\sigma(\gamma p \to \omega p)/dq^2$ [16] as

$$|f_{\gamma p \to \omega p}(q^2)|^2 = \frac{k_\gamma^2}{\pi} \frac{d\sigma}{dq^2}(\gamma p \to \omega p).$$ (11)

Therefore, the energy dependent values for $|f_{\gamma p \to \omega p}(0)|^2$ (required to calculate the cross sections in Eqs. (8) and (9)) can be extracted from the four momentum transfer distribution $d\sigma(\gamma p \to \omega p)/dq^2$. In fact, the forward $d\sigma(\gamma p \to \omega p)/dq^2$ is obtained by extrapolating the measured $d\sigma(\gamma p \to \omega p)/dq^2$ to $q^2 = 0$ for $E_\gamma \geq 1.6$ GeV [16, 17]. It should be mentioned that the present study dominates over the $\omega$ meson production in the $\gamma p$ reaction at lower energy, i.e., $E_\gamma \leq 1.6$ GeV. Recently, the experiment had been carried out on the low energy $\gamma p \to \omega p$ reaction with SAPHIR detector at electron stretcher ring (ELSA), Bonn [11]. In this measurement, they have reported the measured $d\sigma(\gamma p \to \omega p)/dq^2$ vs $|q^2 - q_{\min}^2|$ ($q_{\min}^2$ is defined in Ref. [16, 18]) in the energy region $E_\gamma = 1.1 - 2.6$ GeV. In addition, they have also shown that the measured $d\sigma(\gamma p \to \omega p)/dq^2$ behaves as $\sim \exp[b(q^2 - q_{\min}^2)]$ in the low four momentum $q^2$ transfer region. Since this energy region is well accord with our study, we extract $|f_{\gamma p \to \omega p}(0)|^2$ from the SAPHIR data and use it in our calculation.

The $\omega$ meson propagator $G_\omega(m)$ in Eq. (6) can be described by the Eq. (1). The total width $\Gamma_\omega(m)$ appearing in it is composed of widths due to omega meson decaying into various channels [9]:

$$\Gamma_\omega \approx \Gamma_{\omega \to \pi^+ \pi^- \pi^0}(88.8\%) + \Gamma_{\omega \to \pi^0 \gamma}(8.5\%) + \Gamma_{\omega \to \pi^+ \pi^-}(2.21\%) + \Gamma_{\omega \to \ell^+ \ell^-}(\sim 10^{-4}\%).$$ (12)
We ignore here widths due to the leptonic decay \( (\Gamma_{\omega \rightarrow l^+l^-}) \), since they are insignificant. The typical magnitudes for them are of the order of keV or less, where as the widths for the \( \omega \) meson decaying into other channels in Eq. (12) are within the range of 100 keV to 10 MeV.

\[ \Gamma_{\omega \rightarrow \pi^+\pi^-\pi^0}(m) \] in the above equation represents the width for the \( \omega \rightarrow \pi^+\pi^-\pi^0 \) channel. We use the form for it as derived by Sakurai [19]:

\[
\Gamma_{\omega \rightarrow \pi^+\pi^-\pi^0}(m) = \Gamma_{\omega \rightarrow \pi^+\pi^-\pi^0}(m_\omega) \frac{m}{m_\omega} \frac{(m - 3m_\pi)^4}{(m_\omega - 3m_\pi)^4} U(m) ,
\]

with \( \Gamma_{\omega \rightarrow \pi^+\pi^-\pi^0}(m_\omega = 782 \text{ MeV}) \approx 7.49 \text{ MeV} \). \( U(m) \rightarrow 1 \) as \( m \rightarrow 3m_\pi \) and \( U(m) \rightarrow 1.6 \) as \( m \rightarrow 787 \text{ MeV} \). We have also taken \( U(m) \) equal to 1.6 for \( m > 787 \text{ MeV} \).

The width \( \Gamma_{\omega \rightarrow \pi^0\gamma}(m) \) in Eq. (12) arises due to \( \omega \rightarrow \pi^0\gamma \) channel. Using the Lagrangian density \( \mathcal{L}_{\omega\pi\gamma} \) given in Eq. (3), it is evaluated as

\[
\Gamma_{\omega \rightarrow \pi^0\gamma}(m) = \Gamma_{\omega \rightarrow \pi^0\gamma}(m_\omega) \frac{k(m)}{k(m_\omega)} ,
\]

with \( \Gamma_{\omega \rightarrow \pi^0\gamma}(m_\omega) \approx 0.72 \text{ MeV} \) at \( m_\omega = 782 \text{ MeV} \). \( k(m) \) denotes the momentum of pion originating due to the \( \omega \) meson of mass \( m \) decaying at rest.

In Eq. (12), \( \Gamma_{\omega \rightarrow \pi^+\pi^-}(m) \) denotes the width for the \( \omega \) meson decaying into \( \pi^+\pi^- \) channel. This channel arises due to the small pure isovector \( \rho \) meson component present in the physical \( \omega \) meson [1]. Using the Lagrangian density \( \mathcal{L}_{\omega\pi\pi} = f_{\omega\pi\pi}(\vec{\pi} \times \partial_\mu \vec{\pi}) \cdot \omega^\mu \), the width for this channel is worked out as

\[
\Gamma_{\omega \rightarrow \pi^+\pi^-}(m) = \Gamma_{\omega \rightarrow \pi^+\pi^-}(m_\omega) \frac{m_\omega}{m} \left( \frac{k(m)}{k(m_\omega)} \right)^3 .
\]

The value for \( \Gamma_{\omega \rightarrow \pi^+\pi^-}(m_\omega = 782 \text{ MeV}) \), according to Ref. [9], is approximately equal to 0.19 MeV. \( k(m) \) represents the pion momentum in the \( \pi^+\pi^- \) cm of system.

We calculate the cross sections for the \( \omega \) meson mass distribution in the \( \gamma \) induced reaction on the proton target. The calculated results have been compared with the measured \( \pi^0\gamma \) invariant mass distribution spectra in the \( p(\gamma, \pi^0\gamma)p \) reaction, since the \( \pi^0 \) and \( \gamma \) in the final state (as mentioned earlier) are assumed to originate due to the decay of the \( \omega \) meson produced in the intermediate state. The measured \( \pi^0\gamma \) invariant mass distribution spectra have been reported in the Ref. [8] for four \( \omega \) meson momentum bins: (i) \( 0.2 \text{ GeV/cm} < k_\omega \) < 0.4, (ii) \( 0.4 \text{ GeV/cm} < k_\omega \) < 0.6, (iii) \( 0.6 \text{ GeV/cm} < k_\omega \) < 1, and (iv) \( 1 \text{ GeV/cm} < k_\omega \) < 1.4. Therefore, we have calculated cross section for (i) \( k_\omega = 0.21 - 0.39 \text{ GeV/cm} \); (ii) \( k_\omega = 0.41 - 0.59 \text{ GeV/cm} \); (iii) \( k_\omega = 0.61 - 0.99 \text{ GeV/cm} \); and (iv) \( k_\omega = 1.01 - 1.39 \text{ GeV/cm} \).
The \( \omega \) meson mass distribution spectra calculated using the Eq. (8) are presented in Fig. 1 by the dash-dot curves. The sharp peak at the mass around 780 MeV and width about 8.43 MeV, appearing in these curves, are the characteristics features for the \( \omega \) meson produced in the free state. The solid curves in this figure illustrate the \( \omega \) meson mass distribution spectra calculated using the Eq. (9). These curves arise due to the folding of the calculated cross section given in Eq. (8) with the detector resolution function \( R(m, m') \) in Eq. (10). Therefore, the incorporation of the detector resolution function in the calculated cross section, as shown in this figure, has widen all spectra and simultaneously, it reduces the cross section at the peak. The enhancement in the width from \( \sim 8.43 \) MeV (dash-dot curves) to \( \sim 55 \) MeV (solid curves) occurs due to the width appearing in the detector resolution function \( R(m, m') \), see Eq. (10).

In Fig. 2, we compare the calculated results due to Eq. (9) with the measured \( \pi^0 \gamma \) invariant mass distribution spectra for all \( \omega \) meson momentum bins. This figure shows that the calculated \( \omega \) meson mass distribution folded duly with the detector resolution function, as described above, reproduce the data very well for all bins of the \( \omega \) meson momentum.

4 Conclusion

We have calculated the differential cross section for the \( \pi^0 \gamma \) invariant mass distribution in the \( \gamma p \) reaction. Our analysis shows that the \( \pi^0 \gamma \) appearing in the final state is occurring dominantly due to the decay of the \( \omega \) meson produced in the intermediate state. The calculated results showing sharp and narrow peak characterize the production of the \( \omega \) meson in the free state. The incorporation of the Gaussian function (to describe the detector resolution) in the calculation broadens the \( \omega \) meson mass distribution spectrum, which is well accord with the data.

5 Acknowledgement

I gratefully acknowledge L.M. Pant for making me aware about the measurement on the omega meson mass distribution at ELSA. The discussion with D.R. Chakrabarty on the detector resolution is highly appreciated. The communication made with E. Oset regarding the beam profile function is very helpful. I acknowledge D. Trnka and V. Metag for sending the data. I thank A.K. Mohanty, R.K. Choudhury and S. Kailas for their support.
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Figure Captions

1. The \( \omega \) meson mass distribution spectra are presented for various \( \omega \) meson momentum bins. The dash-dot curves correspond to the calculated results due to Eq. (8), whereas the solid curves arise due to the Eq. (9) (see text).

2. The calculated \( \omega \) meson mass distribution spectra for various \( \omega \) meson momentum bins are compared with the data (see text). The solid curves correspond to the calculated results due to Eq. (9). The histograms represent the measured counts for the \( \pi^0 \gamma \) invariant mass distribution spectra [8], normalised to the respective calculated peaks.
\[ p(\gamma, \omega \rightarrow \pi^0 \gamma)p \]

\[ k_\omega (\text{GeV}/c) = 0.21 - 0.39 \]

\[ d\sigma/dm (\mu\text{b}/\text{GeV}) \]

\[ m (\text{GeV}) \]

\[ p(\gamma, \omega \rightarrow \pi^0 \gamma)p \]

\[ k_\omega (\text{GeV}/c) = 0.41 - 0.59 \]

\[ d\sigma/dm (\mu\text{b}/\text{GeV}) \]

\[ m (\text{GeV}) \]

\[ p(\gamma, \omega \rightarrow \pi^0 \gamma)p \]

\[ k_\omega (\text{GeV}/c) = 0.61 - 0.99 \]

\[ d\sigma/dm (\mu\text{b}/\text{GeV}) \]

\[ m (\text{GeV}) \]

\[ p(\gamma, \omega \rightarrow \pi^0 \gamma)p \]

\[ k_\omega (\text{GeV}/c) = 1.01 - 1.39 \]

\[ d\sigma/dm (\mu\text{b}/\text{GeV}) \]

\[ m (\text{GeV}) \]