Photoproduction of quasi-bound $\omega$ mesons in nuclei*

E. Marco** and W. Weise

Physik-Department,
Technische Universität München,
D-85747 Garching, Germany

November 20, 2018

Abstract

We propose the ($\gamma, p$) reaction as a means of producing possible quasi-bound states of $\omega$ mesons in nuclei. We use an effective Lagrangian, based on chiral $SU(3)$ symmetry and vector meson dominance, in order to construct the $\omega$-nuclear potential. The contribution of bound $\omega$ states is observable in the missing energy spectra of protons emitted in forward direction for several nuclei.

PACS: 13.60.Le; 25.20.Lj

---

*Work supported in part by DFG.
**Fellow of the A.v.Humboldt Foundation
The behaviour of vector mesons in the nuclear medium is one of the topics which attracts much attention in current nuclear physics. At high temperatures (and possibly at extremely high densities), the chiral symmetry of QCD is expected to be restored and vector and axial vector mesons become degenerate. At moderate densities characteristic of nuclei, one expects to see a downward shift of the spectral distributions of vector mesons. QCD sum rules together with current algebra considerations [1, 2] suggest that the first moment of vector meson mass spectra should be linked to the “chiral gap”, $4\pi f_\pi \sim 1$ GeV, and one expects the pion decay constant $f_\pi$ to decrease with increasing baryon density, roughly like the square root of the chiral (quark) condensate.

Several studies, mostly concerned with the $\rho$ meson spectrum and its possible implications for dilepton spectra produced in heavy-ion collisions, hint at a decrease of vector meson masses in the nuclear medium. The study of QCD sum rules in the medium [3] and the Brown-Rho scaling hypothesis [4] suggest a dropping of the vector meson masses by approximately 15% at normal nuclear matter density. Dynamical studies of the behaviour of vector mesons in the medium predict a considerable increase of the $\rho$ width, but no significant decrease in its mass [5, 6, 7]. For the $\omega$ meson [8], such models predict a decrease of its mass accompanied by a moderate increase of its width, so that the $\omega$ appears to be a better candidate for in-medium studies than the $\rho$.

The $(d,^3\text{He})$ reaction with recoiless kinematics has been proposed in order to search for possible $\eta$ and $\omega$ meson bound states in nuclei [8, 9, 10]. This reaction allows the study of the in-medium behaviour of mesons under well controlled conditions, complementary to heavy-ion collisions.

In this paper we propose the use of the $(\gamma,p)$ reaction in nuclei to explore the behaviour of the $\omega$ meson in the nucleus. The difference between the $(d,^3\text{He})$ and $(\gamma,p)$ reactions is that in the latter case, distortion effects are restricted only to the proton in the final state. The optimal energies needed to produce the $\omega$ at rest, around 2.75 GeV in the photoproduction case, are available at several experimental facilities such as ELSA in Bonn and Spring8 in Japan.

In our calculation we have used the model developed in [7, 11, 12] to generate the (complex) potential experienced by the $\omega$ in the nucleus. It is derived using an effective Lagrangian which combines chiral $SU(3)$ and vector meson dominance. One of the important features of the model is that the self-energy of the $\omega$ in the medium is strongly energy dependent, in contrast to the calculations of [9], where a static potential is used. At nuclear matter density the $\omega$ mass is reduced by approximately 15% and its width is increased up to around 40 MeV. Unlike the $\rho$ meson with its prohibitively large in-medium width, the $\omega$ has chances of being observed as a quasiparticle state in the nucleus.

Our choice of the kinematic conditions is such that the $\omega$ is produced practically at rest in the nucleus. Its longitudinal and transverse self-energies are therefore nearly the same [7], and it is justified to work with a single scalar self-energy $\Pi(E,\vec{r})$. In the local density approximation, the potential that the $\omega$
Table 1: Complex energy eigenvalues (see Eqs. (3,4) of an \( \omega \) meson bound to several nuclei.

Experiences in the nuclear medium can be expressed as

\[
\Pi(E, \vec{r}) \equiv 2EU(E, \vec{r}) = -\text{Re}T_{\omega N}(E)\rho(\vec{r}) - i \left[ E\Gamma_{\omega}^{(0)}(E) + \text{Im}T_{\omega N}(E)\rho(\vec{r}) \right],
\]

where, \( \Gamma_{\omega}^{(0)}(E) \) is the free \( \omega \) decay width, and \( T_{\omega N}(E) \) is the energy-dependent \( \omega \)-nucleon amplitude in free space, which we take from \[7\].

To evaluate the \( \omega \) bound states one must solve the wave equation with the potential \[4\],

\[
\left[ E^2 + \nabla^2 - m_\omega^2 - \Pi(E, \vec{r}) \right] \phi(\vec{r}) = 0,
\]

self-consistently to obtain the (complex) quasi-bound state energies \( E_{\lambda} \). We use a two parameter Fermi distribution to describe the nuclear density distributions. The quasi-bound \( \omega \) states found for different nuclei are tabulated in Table 1, where we have introduced

\[
\varepsilon_{\lambda} = \text{Re}E_{\lambda} - m_\omega,
\]

and the total decay widths

\[
\Gamma_{\lambda} = -2\text{Im}E_{\lambda}.
\]

One observes that the \( \omega \) is bound even in light nuclei such as \( ^6\)He. The widths are around \( 35 \sim 45 \) MeV. Their origin is primarily the reaction \( \omega N \rightarrow \pi N \) in the nucleus, as calculated in ref. [7]. Although these widths prohibit identifying individual peaks for each state, one should nevertheless be able to observe strength at energies below the threshold for quasifree \( \omega \) production.
The reaction that we propose in order to detect bound $\omega$ states is ($\gamma, p$) on nuclei. At an incoming photon energy of around 2.75 GeV, and with the proton emitted in forward direction, the $\omega$ is produced nearly at rest. One can scan the contributions of the bound $\omega$ states by observing the missing energy spectrum, i.e. by measuring the energy of the outgoing proton in the forward direction and plotting the differential cross section as a function of $E_{\omega} - m_\omega + |B_p| = E_\gamma + m_p - E_p - m_\omega$, where $E_p = m_p + T_p$ is the detected energy of the outgoing proton, and $B_p$ is the binding energy of the bound initial proton.

In order to evaluate the cross section we use the distorted wave impulse approximation method (DWIA) \cite{13, 14, 15}. The nuclear $\omega$ meson photoproduction cross section, with the proton emitted at zero angle, is expressed as

$$
\left( \frac{d^2\sigma_{\gamma + A \rightarrow p + \omega(A-1)}}{dEd\Omega} \right)_{\theta_p=0} = \left( \frac{d\sigma_{\gamma + p \rightarrow p + \omega}}{d\Omega} \right)_{\theta_p=0} S(E). \quad (5)
$$

For the free cross section, $d\sigma_{\gamma + p \rightarrow p + \omega}/d\Omega$, we take a value of 0.3 $\mu$b/sr from ref. \cite{16}.

$S(E)$ is the response function, which takes into account the removal of the proton from the nucleus, the binding of the $\omega$ meson in the nucleus and the
distortion of the outgoing proton wave. The following expression holds for $S(E)$:

$$S(E) = \sum_{j_p l_p} \sum_{l, L} N_p \frac{2l + 1}{4\pi} (l_p 0 l 0 | L 0)^2 \times \text{Im} \int_0^\infty dr' r'^2 w_L^*(r') \psi_{j_p l_p}^*(r') \int_0^\infty dr \ r'^2 w_L(r) \psi_{j_p l_p}(r) g_l(E - B_p, r', r).$$

Here $\psi_{j_p l_p}(r)$ is the radial wave function of the initial bound proton, $g_l(E - B_p, r', r) = 2iE u_l(k, r_\perp) v^*_l(k, r_\parallel)$ (6) is the radial Green function of the $\omega$ meson for a given angular momentum $l$, expressed in terms of the regular and outgoing solutions of the wave equation (3), and

$$w_L(r) = \int_{-1}^1 d \cos(\Theta) e^{i(p_\perp - p_\parallel) r \cos \Theta} D(z(\Theta), b(\Theta)) P_L(\cos \Theta),$$

with Legendre polynomials $P_L$. The distortion factor $D(\vec{r})$ is evaluated using the eikonal approximation for the wave function of the outgoing proton:

$$\psi_\uparrow^l(\vec{p}_p, \vec{r}) = e^{-ip_p z} D(\vec{r}).$$

This approximation is justified, given that the proton has a kinetic energy of $1 \sim 2$ GeV in our cases of interest. In terms of $z = r \cos \Theta$ and the impact parameter $b$, the distortion factor has the form

$$D(\vec{r}) = \exp \left[ -\frac{\sigma_{pN}}{2} \int_z^\infty dz' \rho(z', b) \right].$$

For the proton-nucleon cross section we have taken a value $\sigma_{pN} = 40$ mb. Fig. 1 shows $D(\vec{r})\rho(\vec{r})/\rho(0)$ in order to illustrate the “active” zone of the process. One observes that the reaction takes place predominantly in the rear hemisphere of the nucleus, since the protons are distorted on their way out. In the case of the $(d, ^3\text{He})$ reaction, only the edges of the nuclear surface are actively involved [8], because the incoming deuteron and the outgoing $^3\text{He}$ are both strongly absorbed. As a consequence, the reduction of the $(d, ^3\text{He})$ cross section for $\omega$ production is about 10 times stronger than in the photoproduction case.

In Fig. 2 we show the calculated proton missing energy spectrum for the $^{12}\text{C}(\gamma, p)^{11}\text{B}$ reaction with an incoming photon energy of 2.75 GeV. This is the energy at which a free $\omega$ would be produced at rest. Pronounced structures coming from different bound $\omega$ states can be seen below the threshold for quasi-free $\omega$ production. The figure also shows separately the contributions of two of the more prominent combinations of $\omega$ and proton states. The prominent structure seen at $E_\omega - m_\omega + |B_p| \simeq 13$ MeV is characteristic of $\omega^{11}\text{B}$ with the $\omega$ and the initially bound proton in $p$-orbitals, and reflects a threshold effect.
Figure 2: Missing energy spectra for the $^{12}\mathrm{C}(\gamma,p)^{11}\mathrm{B}$ reaction at $E_\gamma = 2.75$ GeV. Dotted lines represent the contributions from two particular combinations of bound $\omega$ and proton-hole states.

The results for the $(\gamma,p)$ reaction on $^{40}\mathrm{Ca}$ at $E_\gamma = 1.5$ GeV and 2.75 GeV are shown in Figs. 3 and 4 respectively. In both cases there are important contributions coming from the bound $\omega$ mesons. For $E_\gamma = 1.5$ GeV, a free $\omega$ meson would have a momentum of around 130 MeV/c, comparable to that in the suggested $(d,^3\mathrm{He})$ experiments [8, 9], at $T_\omega = 4$ GeV. The cross section at $E_\gamma = 2.75$ GeV is slightly higher than at $E_\gamma = 1.5$ GeV.

If only the missing energy of the recoiling proton is detected, the spectrum of produced quasibound $\omega$ mesons is expected to sit on a background, the cross section of which may be approximately five times as large as the $\omega$ meson signal itself. This background should be flat, resulting primarily from the $(\gamma,p)$ reactions leading to $\rho$ meson and continuum $\pi\pi$ production, with the $\rho$ meson width strongly increased in the presence of the nucleus. Ideally, the background would be reduced by detecting a characteristic decay mode of the $\omega$ meson together with the forward proton.

We thank Albrecht Gillitzer, Satoru Hirenzaki, Paul Kienle, Eberhard Klempt, Berthold Schoch and Hiroshi Toki for helpful discussions.
Figure 3: Missing energy spectra for the $^{40}\text{Ca}(\gamma,p)^{39}\text{K}$ reaction at $E_{\gamma} = 1.5$ GeV.

Figure 4: Missing energy spectra for the $^{40}\text{Ca}(\gamma,p)^{39}\text{K}$ reaction at $E_{\gamma} = 2.75$ GeV.
References

[1] E. Marco and W. Weise, Phys. Lett. B 482 (2000) 87; F. Klingl and W. Weise, Eur. Phys. J. A 4 (1999) 225.

[2] M. Golterman and S. Peris, Phys. Rev. D 61 (2000) 034018.

[3] T. Hatsuda and S.H. Lee, Phys. Rev. C 46 (1992) 34.

[4] G.E. Brown and M. Rho, Phys. Rev. Lett. 66 (1991) 2720.

[5] G. Chanfray, R. Rapp and J. Wambach, Phys. Rev. Lett. 76 (1996) 368.

[6] R. Rapp and J. Wambach, to appear in Adv. Nucl. Phys. (2000), hep-ph/9909229.

[7] F. Klingl, N. Kaiser and W. Weise, Nucl. Phys. A 624 (1997) 527.

[8] F. Klingl, T. Waas and W. Weise, Nucl. Phys. A 650 (1999) 299.

[9] R.S. Hayano, S. Hirenzaki and A. Gillitzer, Eur. Phys. J. A (1999) 99.

[10] K. Saito, K. Tsushima, D.H. Lu and A.W. Thomas, Phys. Rev. C 59 (1999) 1203.

[11] F. Klingl, N. Kaiser and W. Weise, Z. Phys. A 356 (1996) 193.

[12] N. Kaiser, T. Waas and W. Weise, Nucl. Phys. A 612 (1997) 297.

[13] O. Morimatsu and K. Yazaki, Nucl. Phys. A 483 (1988) 493; A 435 (1985) 727.

[14] J. Hüfner, S.Y. Lee and H.A. Weidenmüller, Nucl. Phys. A 234 (1974) 42.

[15] C.B. Dover, L. Ludeking and G.E. Walker, Phys. Rev. C 22 (1980) 2073.

[16] E. Klempt, in: Proceedings Int. Conf. “Baryons ’98”, D. Menze and B. Metsch, eds., World Scientific (1999), p. 25.