STUDYING MEDIUM MODIFICATIONS OF MESONS IN ELEMENTARY REACTIONS*

Volker Metag

II. Physikalisches Institut, Justus-Liebig-Universität Giessen
Heinrich Buff Ring 16, 35392 Giessen, Germany

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Experimental searches for medium-modifications of vector mesons in photon and proton induced nuclear reactions are reviewed. Results on ρ, ω, and Φ mesons are presented. At normal nuclear matter density, the ω and Φ meson are found to be lowered in mass by 9–14% and 3.5%, respectively. Compared to the free particle properties increases in widths by factors of about 16 and 3.6, respectively, are observed. For the ρ meson conflicting results on in-medium mass shifts and broadening have been reported.

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1. Introduction

In our present understanding of the evolution of the universe there were two phases of mass generation. Very shortly after the big bang elementary particles known within the Standard Model got their masses through their interaction with the Higgs field. The search for the Higgs particle has been one of the motivations for building the Large Hadron Collider LHC at CERN. Once the properties of the Higgs particle are known this mechanism of mass generation will be much better understood. A second phase of mass generation is believed to have occurred when the universe had cooled down to temperatures of about 10^{12} K corresponding to energies of some 100 MeV when free quarks condensed to form hadrons. Following pioneering experiments at the CERN SPS this phase transition from the quark–gluon plasma to hadrons is being studied in ultra-relativistic nucleus–nucleus collisions at the Relativistic Heavy Ion Collider RHIC and, starting in 2008, also at the LHC. The origin of hadron masses is one of the intriguing issues in strong interaction physics. The mass of the nucleon ($m_N = 0.938\,\mathrm{GeV}/c^2$)

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is much larger than the summed masses of the quarks and must therefore be generated dynamically through the interaction between quarks and gluons. In the GeV energy regime Quantum Chromodynamics (QCD), the theory of the strong interaction, can not be treated perturbatively because of the large coupling strength. Remarkable progress has been achieved in this non-perturbative regime by lattice QCD calculations. Most of the theoretical predictions are, however, still made in the frame work of hadronic models. To probe our current understanding on the origin of hadron masses theoretical predictions on the change of hadron masses and widths in a nuclear environment have been made. Only recently, experiments have advanced to a level to provide serious tests of these theoretical predictions.

2. Theoretical predictions

Many theory groups have contributed to developing the field of hadrons in the medium [1–5]. As examples for the many model calculations performed, Fig. 1 illustrates the characteristic features of possible in medium modifications for ρ and ω mesons: While some groups predict a lowering of the ω mass [7, 10, 11], others have suggested a rising mass [12–14] or spectral functions with several structures [8, 9] implying a spreading of strength due to coupling of mesons to nucleon resonances.

Furthermore, the momentum dependence of spectral functions has been investigated. As an example for such studies, Fig. 2 shows that structures in the ρ spectral function fade out at ρ momenta larger than 500 MeV/c relative to the nuclear medium. Experimental programs have been initiated at several accelerators to search for such medium modifications. The current status of these studies with elementary probes like photon and proton beams are discussed in the following sections. Corresponding experiments using heavy ion reactions are reviewed by Salabura [16].

3. Experimental approaches

The mass of hadrons in a nuclear environment can be determined by measuring their decay within the medium. The mass m can be reconstructed from the 4-momentum vectors p_1, p_2 of the decay products according to

$$m(\vec{p}, \rho, T) = \sqrt{(p_1 + p_2)^2}\,. \tag{1}$$

In general, the mass depends on the baryon density ρ and temperature T of the medium as well as on the momentum of the hadron with respect to the nuclear medium. An extrapolation to 3-momentum zero gives the mass of the meson at rest in the nuclear medium which is to be compared to the mass listed in PDG [17] in order to establish a medium effect. This comparison is, however, hampered by the fact that the experimental mass distribution does not represent the spectral function directly but rather a convolution of the spectral function $A(m)$ with the partial decay width $\Gamma_{H\to X_1,X_2}(m)$ into the channel being studied [18]:

$$\frac{d\sigma_{H\to X_1,X_2}}{dm} \sim A(m)\,\frac{\Gamma_{H\to X_1,X_2}(m)}{\Gamma_{\rm tot}(m)}\,. \qquad (2)$$

Since $\Gamma_{H\to X_1,X_2}(m)$ depends itself on the invariant mass m this may lead to deviations of the experimentally determined mass distribution from the true spectral function, in particular for broad resonance states.

As a prerequisite for extracting in-medium hadron properties one has to ensure that the meson decays do occur in the medium, *e.g.* by placing cuts on the 3-momentum of the meson. The light vector mesons (ρ,ω,Φ) with lifetimes in the 2–44 fm/c range are sufficiently short lived to decay

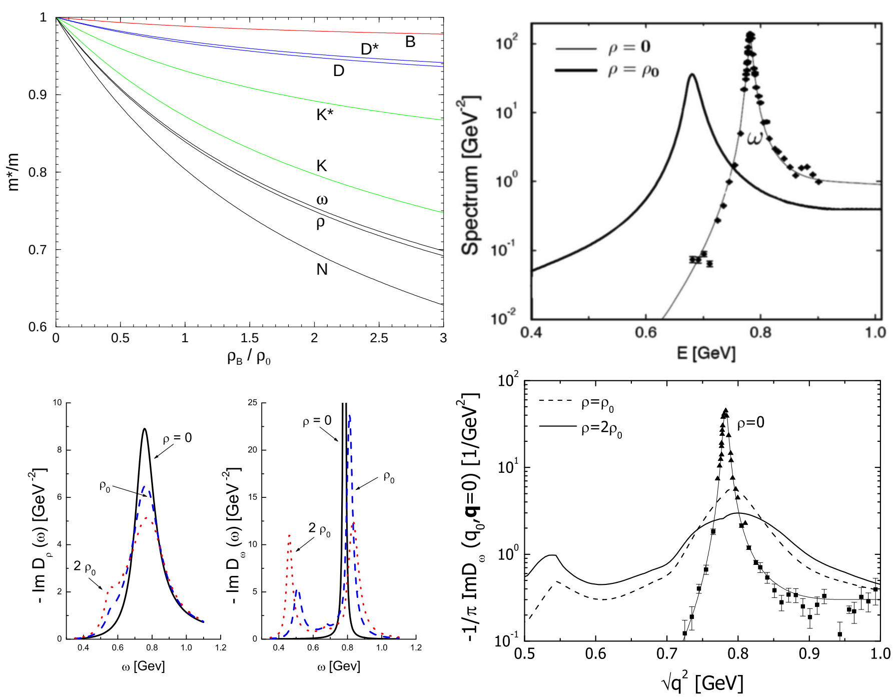

Fig. 1. Upper left: Hadron masses as a function of baryon density predicted within the QMC model [6]. Upper right: The ω spectral function in vacuum and at normal nuclear matter density [7]. Down: Spectral functions of the ω and ρ meson calculated for zero, normal, and twice normal nuclear matter density [8, 9].

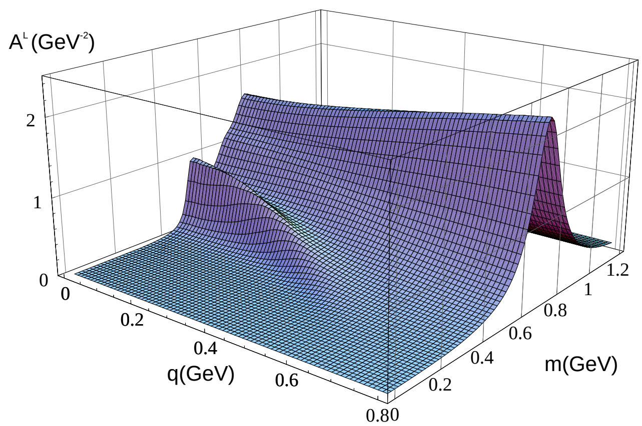

Fig. 2. Modification of the ρ spectral function with ρ momentum at normal nuclear matter density [15].

in the nuclear medium with a sizable fraction after their production in elementary photon or proton induced nuclear reaction. The best approach to measure their mass distribution is dilepton spectroscopy, *i.e.* the investigation of the decay modes $\rho, \omega, \Phi \to e^+e^-$or $\mu^+\mu^-$. Despite the extremely small branching ratio of the order of 10^{-5}–10^{-4} the essential advantage of dilepton spectroscopy is that the leptons escape from the strongly interacting system without strong final state interactions, thereby providing undistorted information on the in-medium properties of the decaying meson.

In contrast to heavy ion reactions, where most experimental observables represent an integration over the full spacetime evolution of the reaction with strong variations in densities and temperatures, there is no time dependence of the baryon density and the temperature $T = 0$ is constant when in-medium effects are studied in elementary photon and proton induced reactions. These well controlled conditions facilitate the theoretical interpretation of the data [19]. This presentation is focused on the study of in-modifications of the vector mesons ρ, ω and Φ in elementary reactions.

3.1. In-medium properties of the ρ and Φ meson from photon and proton induced reactions

Information on the ρ meson has been obtained in two experiments at Jlab [20] and KEK [21], irradiating various targets with photon beams of $E_\gamma = 0.6$–3.8 GeV and 12 GeV protons, respectively. Although the e^+e^- invariant mass spectra measured in both experiments (see Fig. 3) exhibit similar features both groups come to conflicting conclusions: while Naruki *et al.* [21] claim a drop of the ρ and ω meson mass by 9% and no in-medium

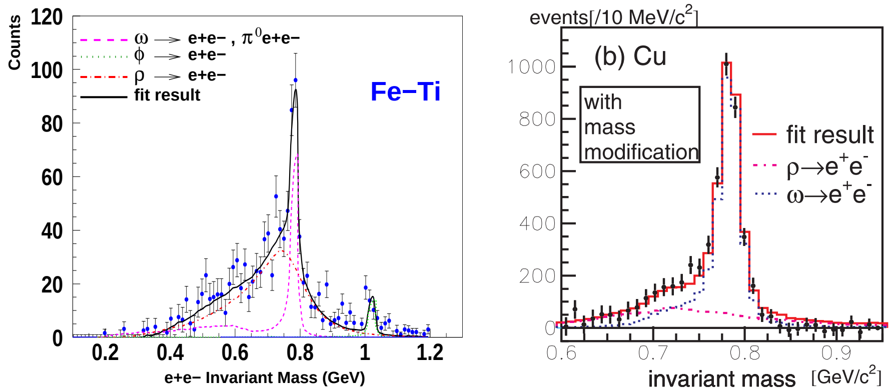

Fig. 3. e^+e^- invariant mass spectra after background subtraction obtained (left) in photonuclear reactions ($E_\gamma = 0.6$–$3.8\,$GeV) [20] and (right) in 12 GeV proton induced reactions [21].

broadening, the Jlab experiment [20] reports no mass shift and a small in-medium broadening of the ρ meson. The discrepancy may be due to the treatment of the combinatorial background. The Jlab group normalizes the combinatorial background to the yield of like sign lepton pairs while the KEK group derives the shape of the combinatorial background from event mixing and its height by fitting the measured e^+e^- invariant mass spectrum.

At KEK one has also studied the in-medium properties of the Φ meson (see Fig. 4) [22]. For slow Φ mesons ($\beta\gamma < 1.25$) with a higher in-medium decay probability in a Cu nucleus, they report a drop of the Φ mass by 3.6% and an increase of the Φ width by a factor 3.6 at normal nuclear matter density ρ_0.

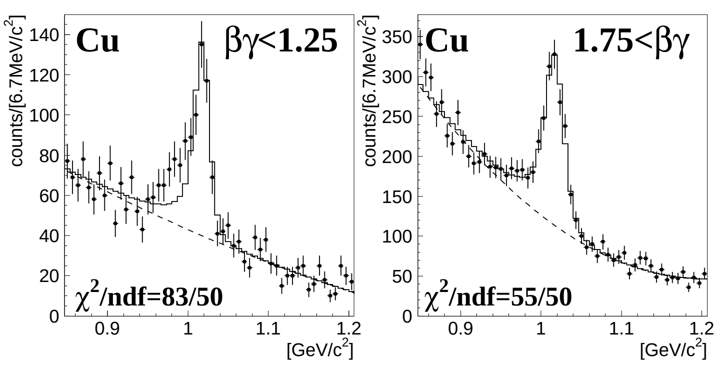

Fig. 4. e^+e^- invariant mass spectra near the Φ mass peak for slow ($\beta\gamma < 1.25$) (left) and fast Φ mesons ($\beta\gamma > 1.25$)(right) [22].

It should be noted, however, that all these experiments have significant acceptance only for 3-momenta of vector mesons above 0.5–0.8 GeV/c. Therefore, these experiments are insensitive to possible in-medium modifications as illustrated in Fig. 2 which fade out at momenta above 500 MeV/c.

3.2. In-medium properties of the ω meson from photonuclear reactions

The ω meson in the medium has been studied at much lower momenta ($<$ 500 MeV/c) in a photoproduction experiment [23] by the CBELSA/TAPS collaboration. In contrast to the experiments described above which use the *golden* dilepton channel for reconstructing the vector mesons, the decay mode $\omega \to \pi^0\gamma \to \gamma\gamma\gamma$ has been investigated in this experiment. This decay mode has the advantage of a much higher branching ratio (9%). Furthermore, the experiment is insensitive to possible in-medium modifications of the ρ meson as the latter decays into the $\pi^0\gamma$ channel only with a 100 times smaller probability of 7×10^{-4}. The drawback of this decay mode is that a hadron, the π^0 meson, is involved which may undergo strong final state interactions within the nucleus. This effect has been carefully studied in simulations [24]. It is found to be almost negligible for invariant masses in the range of interest (700–800 MeV/c^2) and can be further reduced by appropriate cuts.

The 3 γ final state calls for a photon detector which covers almost the full solid angle. A schematic drawing of the experimental setup at the electron accelerator ELSA in Bonn is shown in Fig. 5. It consists of the crystal barrel with 1290 CsI(Tl) crystals and 528 BaF_2 modules of the TAPS detector in a forward wall configuration. With this detector system, the 3 photon final state from the decay of an ω meson can be registered even if the ω meson

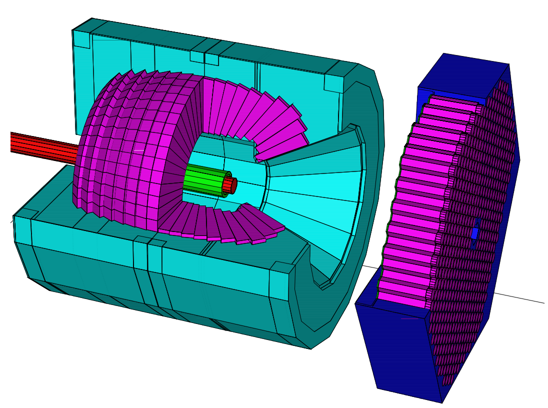

Fig. 5. Schematic drawing of the CBELSA/TAPS experiment at the Bonn electron accelerator ELSA.

is at rest in the laboratory. The sensitivity to low momentum ω mesons is essential for testing possible in-medium modifications which are predicted to be predominant in the low momentum range (see Fig. 2.)

Trnka *et al.* [23] performed a comparative study of ω photoproduction on nuclei and on the proton to identify possible in-medium modifications. From the subgroup of 3 γ events $\pi^0\gamma$ invariant mass spectra were deduced. After fitting and subtracting the background the comparison of the corresponding invariant mass spectra for Nb and LH_2 targets exhibited a shoulder on the low mass side of the ω signal from the nuclear target which was interpreted in terms of an ω in-medium mass shift by 60^{+10}_{-35} MeV at an average nuclear density of 0.6 ρ_0. An extrapolation to normal nuclear density leads to a drop in the ω mass by $\approx 14\%$.

The shape of the ω signal is sensitive to the way the background is treated. In [23] the background was fitted with an arbitrary function. In a more rigorous treatment one could try to reproduce the background by summing up all possible sources which can contribute to the $\pi^0\gamma$ channel due to limited acceptances and/or particle misidentification. Another possibility is to determine the background with the mixed-event technique as used in the lepton pair experiments. In a first step, this approach has been chosen for the analysis of new data taken on a carbon target.

Fig. 6 shows the $\pi^0\gamma$ invariant mass spectrum together with the uncorrelated $\pi^0\gamma$ background obtained by event-mixing [25]. Here, the invariant mass is calculated by combining a π^0 from one event with a photon from another event. The mixed-event background describes the experimental data over an invariant mass range of about $400\,\mathrm{MeV}/c^2$ with an accuracy of better than 5%. This is demonstrated in Fig. 6 (right) which shows the ratio of the data to the mixed event background on a linear scale.

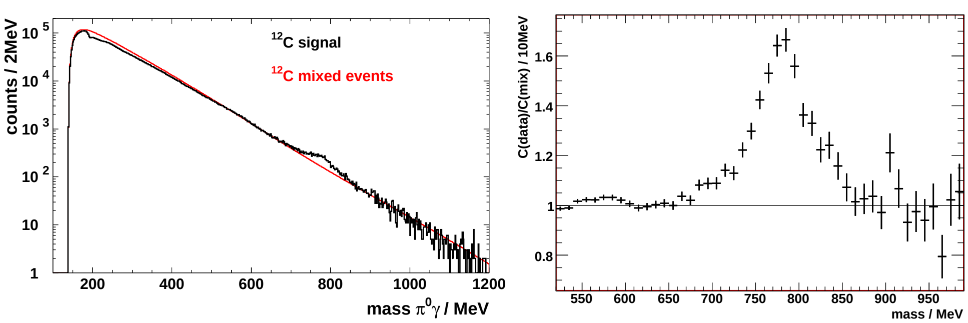

Fig. 6. Left: $\pi^0\gamma$ invariant mass distribution for a photonuclear reaction ($E_\gamma = 0.7$ –2.5 GeV) on carbon in comparison to a mixed event background (see text) [25]. Right: ratio of the data to the mixed event background.

Subtracting this combinatorial background leads to the ω signal shown in Fig. 7 which again exhibits a shoulder on the low mass side in comparison to the ω signal measured on the liquid hydrogen target and to a simulation of the free ω signal folded with the experimental resolution. Thereby, the observation of an in-medium lowering of the ω meson [23] is confirmed. To quantify the effect, the ω signal has to be decomposed into an in-medium decay and an in-vacuum decay contribution. The line-shape of the in-vacuum decay component is known from the measurement on the LH_2 target, the in-medium decay distribution is taken from BUU simulations [26]. A best fit to the signal is obtained by assuming a drop of the ω mass by 14 % at normal nuclear matter density in accordance with [23].

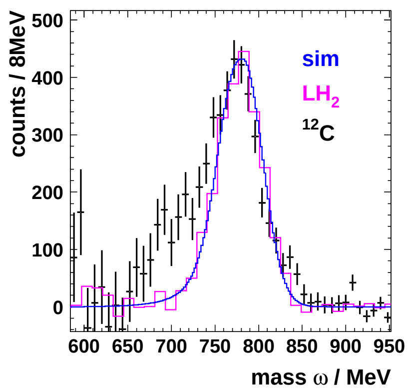

Fig. 7. $\pi^0\gamma$ invariant mass distribution near the ω mass after subtracting the mixed event background of Fig. 6. For comparison the line shape from the corresponding measurement on the LH_2 target (histogram) and from a simulation (curve) are shown.

Because of the sensitivity of the ω signal to the background treatment an approach [27, 28] to *assume* the background on the nuclear target to be the same as for the LH_2 target can only lead to wrong conclusions. The experimental data clearly show that the background distributions for the LH_2 and nuclear targets are different. This becomes evident when one compares the background distributions over a wider mass range than the limited one considered in [27, 28].

Because of the limited detector resolution and the uncertainties associated with decomposing the ω signal into in- and out-of-medium decay contributions the in-medium width of the ω meson could not be reliably determined in the experiment by Trnka *et al.* [23]. An independent access to the inelastic in-medium width of the ω is provided by measuring the transparency ratio T [28–30]

$$T = \frac{\sigma_{\gamma A \to \omega X}}{A\, \sigma_{\gamma N \to \omega X}}\,, \tag{3}$$

i.e. the ratio of the ω production cross section on a nucleus divided by the number of nucleons A times the ω production cross section on a free nucleon. If nuclei were completely transparent to ω mesons, the transparency ratio T would be $T = 1$. T is thus a measure for the loss of ω flux via inelastic processes in nuclei and can be determined in attenuation experiments on nuclei of different mass A.

Within the low density approximation the ωN absorption cross section is related to the inelastic ω width by $\Gamma_\omega = \hbar\rho v\sigma$. A comparison of data from the CBELSA/TAPS collaboration with calculations of the Valencia [28] and Giessen [29] theory groups is shown in Fig. 8. Here, the transparency ratio has been normalized to the carbon data to avoid systematic uncertainties because of the unknown ω production cross section on the neutron and because of possible secondary production processes involving more than one nucleon. The comparison yields an in-medium ω width of about 130–150 MeV at normal nuclear matter density and for an average ω momentum of 1.1 GeV/c, implying an in-medium broadening of the ω meson by a factor ≈ 16 compared to the width in vacuum. Assuming the momentum dependence of the ω width given in [29] this value corresponds to an inelastic width of the ω meson at rest in the medium of about 70 MeV.

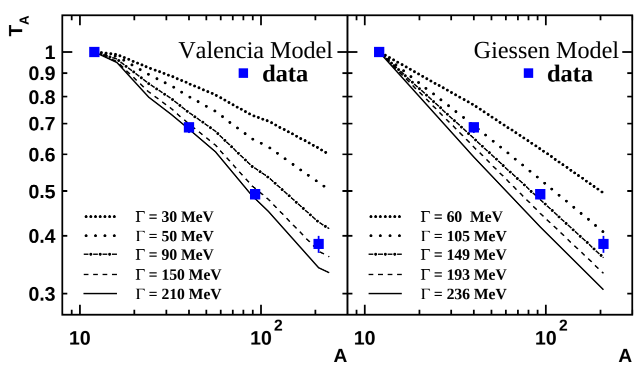

Fig. 8. Transparency of nuclei for ω mesons. The preliminary data of the CBELSA/TAPS collaboration [30] are normalized to ^{12}C and compared (left) to calculations by Kaskulov *et al.* [28] and (right) by Mühlich *et al.* [29].

The results on medium modifications of vector mesons obtained in elementary reactions are summarized in the Table I.

TABLE I

	KEK	Jlab	CBELSA/TAPS
Reaction	pA 12 GeV	γA 0.6–3.8 GeV	γA 0.7–2.5 GeV
Momentum accept.	$> 0.5\,\mathrm{GeV}/c$	$> 0.8\,\mathrm{GeV}/c$	$> 0\,\mathrm{MeV}/c$
ρ	$\Delta m/m = -9\%$	$\Delta m \approx 0$ some broadening	
ω	no broadening		$\Delta m/m \approx -14\%$ $\Gamma_\omega(\rho_0)/\Gamma_\omega \approx 16$
Φ	$\Delta m/m = -3.4\%$ $\Gamma_\Phi(\rho_0)/\Gamma_\Phi = 3.6$		

4. Search for ω mesic states

A lowering of the ω mass in the nuclear medium would indicate an attractive ω nucleus interaction, raising the question whether this attraction may be sufficiently strong to allow for the existence of ω-nucleus bound states. Several theory groups have addressed this issue [31, 32, 34]. Their model calculations do indeed indicate sufficiently deep ω nucleus potentials with a depth of the order of 100 MeV.

Marco and Weise [31] suggested to exploit recoilless ω photoproduction for the population of ω mesic states. As illustrated in Fig. 9 the momentum of the incoming photon is taken over by the participating nucleon. At an incident photon energy of 2.75 GeV the ω meson will be produced at rest.

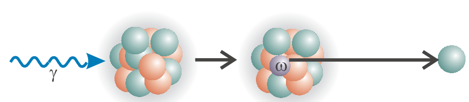

Fig. 9. Illustration of recoilless ω photoproduction. At an incident photon energy of 2.75 GeV the momentum of the incoming photon is completely taken over by the forward going nucleon, leaving the produced ω meson at rest in the nucleus.

For an in-medium omega mass of 740 MeV the incident photon energy for recoilless production is lowered to 2.12 GeV. For nucleons not registered at exactly zero degree the incident photon energy would even have to be lowered further to achieve a minimum momentum transfer to the ω meson. The kinematics of this process have been studied in detail by Kaskulov *et al.* [33].

For a strictly forward going recoil proton Marco and Weise [31] predict a proton missing energy spectrum as shown in Fig. 10. Pronounced structures arising from different bound ω states can be seen below the threshold for quasi-free ω production. A corresponding experiment searching for the existence of ω bound states is being performed by the CBELSA/TAPS collaboration.

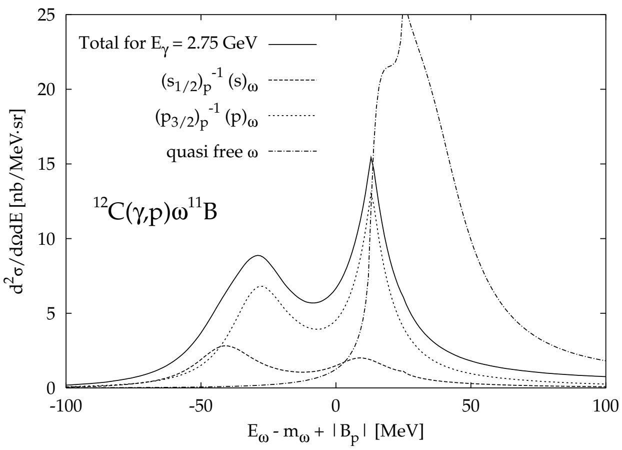

Fig. 10. Predicted missing energy spectrum for the reaction $^{12}\mathrm{C}(\gamma,p)\omega^{11}B$ at $E_\gamma = 2.75$ GeV. Dotted lines represent the contributions from two particular combinations of bound ω and proton-hole states [31].

5. Conclusions

Most recent experimental results on in-medium properties of the light vector mesons ρ, ω and Φ have been discussed. The reported in-medium changes of masses and widths are summarized in Table I. Hereby it should be noted that the CBELSA/TAPS experiment is sensitive to low momentum ω mesons for which the strongest in-medium modifications are theoretically expected while the acceptances of the Jlab and KEK experiments become significant only at higher meson momenta. Experiments searching for ω nucleus bound states are in progress.

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