Experiments on Hadrons in Nuclei: and mesons

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Experiments on Hadrons in Nuclei: ω and η mesons

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Abstract. Data on the photoproduction of ω mesons on nuclei have been re-analyzed in search for in-medium modifications. The data were taken with the Crystal Barrel(CB)/TAPS detector system at the ELSA accelerator facility in Bonn. The extracted ω line shape was found to be sensitive to the background subtraction.

In experiments at the tagged photon facility of the Mainz MAMI accelerator photoproduction of mesons from light nuclear targets (deuteron and ^{3}He) has been studied. The experiments used the combined Crystal Ball/TAPS setup in Mainz. Measurements of η- and π^0-photoproduction off a liquid ^{3}He-target have been used for the search for the formation of η-mesic ^{3}He. The installation of the WASA detector at COSY opened a unique possibility to search for the $^4\mathrm{He} - \eta$ bound state with high statistics and high acceptance.

1. The ω Meson in Medium

A possible modification of hadron properties in a strongly interacting medium is a much debated issue. In-medium changes of hadron properties have been identified as one of the key problems in understanding the non-perturbative sector of QCD. Fundamental symmetries in QCD provide guidance in dealing with strong interaction phenomena in the non-perturbative domain. Furthermore, QCD sum rules have been applied to connect the quark-gluon sector to hadronic descriptions and QCD-inspired hadronic models have been developed to calculate the in-medium self-energies of hadrons and the spectral functions. Mass shifts and/or in-medium broadening as well as more complex structures in the spectral function due to the coupling of vector mesons to nucleon resonances have been predicted. A recent overview is given in [1]. The studies have motivated several experimental attempts to confirm or refute theoretical predictions.

Heavy-ion collisions and reactions with photons and protons have been used to extract experimental information on in-medium properties of hadrons. The experiments have focused on the light vector mesons ρ, ω, and ϕ where decay lengths are comparable to nuclear dimensions in a nuclear reaction. However, in order to ensure a reasonable decay probability in the strongly interacting medium, cuts on the recoil momentum are required for the longer lived ω and ϕ mesons. A full consensus has not yet been reached among the different experiments. A detailed account of the current status of the field is given in comprehensive reviews [2, 3]. An in-medium broadening of the vector mesons is reported by almost all experiments and the majority of experiments does not find evidence for a mass shift. Apart from [4] only one other experiment at KEK [5] reports a possible drop of the ρ and ω mass by 9 % at normal nuclear matter density. Studying ω meson production in ultra-relativistic heavy-ion collisions, the NA60 collaboration observes a suppression of the meson yield for ω momenta below 1 GeV/c which is even more pronounced for more central collisions [6]. This is interpreted as evidence for in-medium modifications of slow ω mesons but it cannot be concluded whether this is due to a mass shift, a broadening, or both.

The search for mass shifts has turned out to be more complicated than initially thought for those cases where a strong broadening of the meson is observed as for the ω [7] and ϕ mesons [8]. In the $\omega \rightarrow \pi^0\gamma$ decay mode the increase in the total width of ω drastically lowers the branching ratio for in-medium decays into this channel and thereby reduces the sensitivity of the observed ω signal to in-medium modifications. Data taken with the CB/TAPS detector at ELSA, Bonn on the photoproduction of ω mesons on Nb and LH_2 have been re-analyzed. The first results from an analysis of the same data were published by D. Trnka et al. [4], claiming a mass shift of the ω meson by -14% at normal nuclear matter density. This information was extracted from a comparison of the ω signals on Nb and LH_2, reconstructed in the $\pi^0\gamma$ channel. As pointed out in the literature [9] the deduced line shapes are very sensitive to the background subtraction. While in the initial work the background was determined by fitting the $\pi^0\gamma$ invariant mass spectrum, a much more refined background determination is used in the current analysis. The re-analysis is described in detail by M. Nanova et al. in [10] where it is also stated that the earlier claim of an in-medium lowering of the ω mass is not confirmed. The strong broadening of the ω meson in the nuclear medium, due to inelastic processes as determined in the transparency ratio measurements, suppresses contributions to the observed ω signal from the interior of the nucleus. The branching ratio for in-medium decays into the channel of interest is drastically reduced. Thereby, the sensitivity is shifted to the nuclear surface, making the line shape analysis less sensitive to a direct observation of in-medium modifications. Theoretical predictions that a higher sensitivity to in-medium effects may be found near the production threshold [11] have been investigated experimentally. However, a significant medium modification of the ω line shape has not been observed [12]. Data with higher statistics will be needed to gain further insight. A corresponding experiment has been performed at the MAMI C electron accelerator using the Crystal Ball/TAPS detector setup. The analysis is ongoing.

2. Search for Light η Mesic Nuclei

2.1. Photoproduction of Mesons from Light Nuclei

The study of the interaction of mesons with nucleons and nuclei has significantly contributed to the understanding of the strong force. In the case of long-lived mesons like charged pions or kaons, secondary beams can be prepared. However, the interaction of short-lived mesons with nuclei is only accessible in indirect ways when the mesons are first produced in the nucleus from the interaction of an incident beam and then subsequently undergo final state interactions in the same nucleus. The pion-nucleon interaction at small momenta is weak, so that pion-nucleus states, bound due to the strong force, cannot exist. The strong interaction is not only weak but even repulsive at small momenta because of the s-wave term dominance. However, the η-N interaction at small momenta is dominated by the s-wave nucleon resonance $S_{11}(1535)$, which couples strongly to the Nη-channel [13]. The possible formation of η - nucleus bound states, η-mesic nuclei, has been intensively discussed in the literature. The first suggestion for A>10 nuclei goes back to Liu and Haider [14]. Even lighter quasi-bound η-nucleus systems have been sought for in experiments investigating the threshold behavior of hadron induced η-production reactions. Quasi-bound states in the vicinity of the production threshold will give rise to an enhancement of the cross section relative to phase space behavior. Results were reported for $pp \rightarrow pp\eta$ [15, 16, 17], $np \rightarrow d\eta$ [18, 19], $pd \rightarrow {}^3\mathrm{He}\eta$ [20], $dp \rightarrow {}^3\mathrm{He}\eta$ [21, 22], $\vec{d}d \rightarrow \eta\,{}^4\mathrm{He}$ [23], and $pd \rightarrow pd\eta$ [24]. Threshold effects have been found in most reactions. In fact, the measurement of $dp \rightarrow {}^3\mathrm{He}\eta$ in [21, 22] shows an extremely sharp rise of the production cross section at threshold. If these effects are related to (quasi-)bound states, they should show up independent of the initial state of the reaction. Threshold photoproduction of η-mesons from light nuclei (deuteron, helium isotopes) was also investigated [25, 26] and again threshold enhancements were observed.

The most promising signal so far was found in the ^{3}He$(\gamma,\eta)^3$He reaction [26], although the statistical significance was weak. Photoproduction off ^{3}He has previously been investigated with the TAPS detector at the MAMI accelerator in Mainz, Germany, and some indication for the existence of an η-mesic state has been found. The cross section of coherent η-production showed a strong threshold enhancement. The excitation function of $p\pi^0$ back-to-back pairs in the photon-helium cm-system, which may arise from the $S_{11} \rightarrow N\pi$ decay after re-capture of the quasibound η by a proton, showed a peak around the η-production threshold. However, both effects suffered from poor statistical quality of the data. The experiment has now been repeated with the much larger acceptance of the new 4π detector setup. Preliminary results are reported in [27]. The excitation function for coherent η-photoproduction is very similar to the results from hadron induced reactions [21, 22] where the cross section rises abruptly at the coherent production threshold. Within the first 4 MeV above threshold it reaches roughly 50% of its maximum value, which is strong evidence for a resonance-like threshold enhancement. Data with better resolution of the incident photon energy are still under analysis. The ongoing analysis is revealing that nucleon resonances produce opening angle dependent structures in excitation functions. Therefore, the method of subtracting the excitation functions for different opening angles can produce artificial structures making it very difficult to isolate the small signature from an η-mesic state in such a complicated landscape.

2.2. Search for a $\eta -^4$ He State with WASA-at-COSY

The installation of the WASA detector [28] at the COSY accelerator in Jülich, Germany, opens a unique possibility to search for the ^{4}He $-\,\eta$ bound state with high statistics and high acceptance. The pilot experiment, conducted in June 2008, used a deuteron pellet target and a deuteron beam with a ramped momentum corresponding to a variation of the excess energy for the ^{4}He $-\,\eta$ system from -51.4 MeV to 22 MeV. At present the data are evaluated and some preliminary results are reported [30]. The experiment will be continued in 2010 [31] with a two week run scheduled with WASA-at-COSY.

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