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Hadron Structure

STUDY OF THE LOW ENERGY INTERACTION OF HADRONS AT COSY-11

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Abstract

We summarize the studies of the low energy hadronic interaction of the $K\bar{K}$ and pK system performed by the COSY-11 collaboration. We discuss also the question of the existence of the $\eta - ^3He$ bound state in the context of the experiments conducted by means of the COSY-11 facility.

1 Introduction

Investigation of the hadronic interaction in the low energy regime enable to understand the production mechanism of various particles, their properties, and is the interesting subject on itself. Due to the lack of the mesonic targets, and in some cases also the lack of mesonic beams, the interaction between the mesons and nucleons cannot be investigated in the direct elastic scattering experiments. Therefore, the more sophisticated methods have to be used to extract the qualitative and quantitative information about meson-nucleon final state interaction, involving the analysis of the shape of the excitation function, the differential cross section, the invariant mass distribution, polarization observables. and also the analysis of the Dalitz plots population for a three body final state reactions, and Chodrow and Goldhaber plots for a four body final state.

For the summary of the investigations of the η and η'–nucleon interaction studied via the $pp \to pp\eta$ and $pp \to pp\eta'$ reactions, and summary of the studies of the hyperon–nucleon interaction performed by the COSY-11 collaboration, the interested reader is referred to the quoted references 1, 2, 3, 4). Here, we would like to focus on this aspect of our studies concerning the low energy pK and K^+K^- final state interaction and as the second topic we have chosen the studies of the possible existence of the η–light nuclei bound states.

2 K^+K^- and the kaon–nucleon interaction

Studies of the strength of the K^+K^- and KN interaction serve to understand the nature of the scalar resonances $a_0(980)$ and $f_0(980)$. The striking feature here is that the masses of these resonances are close to the sum of K^+ and K^- masses. Different interpretations to the nature of $a_0(980)$ and $f_0(980)$ resonances have been proposed. Apart from the possibilities of a $q\bar{q}$ meson, $qq\bar{q}\bar{q}$ states, hybrid $q\bar{q}$/meson–meson systems or even quarkless gluonic hadron state, there was a postulate 5) that these objects could possibly be the $K\bar{K}$ molecules. If the latter scenario is true, the interaction between the kaons should be attractive and strong enough to form a molecule.

Direct measurements of the K^+K^- scattering length in the scattering experiments is at present impossible, due to lack of kaon targets. However, the information about the K^+K^- interaction can be accessed in indirect way via studies of the shape of the excitation function for the $pp \to ppK^+K^-$ reaction or the analysis of the Chodrow and Goldhaber plots for this reaction 6).

Fig. 1 (left) depicts the excitation function for the $pp \to ppK^+K^-$ reaction in the near threshold region of excess energies, as measured by the COSY-11 7, 8), ANKE 9), and DISTO 10) collaborations. Dotted line in this figure shows the pure phase space parameterization of a total cross section for the four-body reaction, normalized to the DISTO data point (Q = 114 MeV), while the dashed line depicts the cross section prediction based on the four body phase space population with inclusion of the proton-proton final state interaction by folding its parameterization known from the three body final state. What can be easily noticed in this figure is that even the latter parameterization, which by far better describes the experimental data, underestimates the experimental results by a factor of 5 in the vicinity of the kinematical threshold. This difference possibly originates from the pK or $K\bar{K}$ final state interaction.

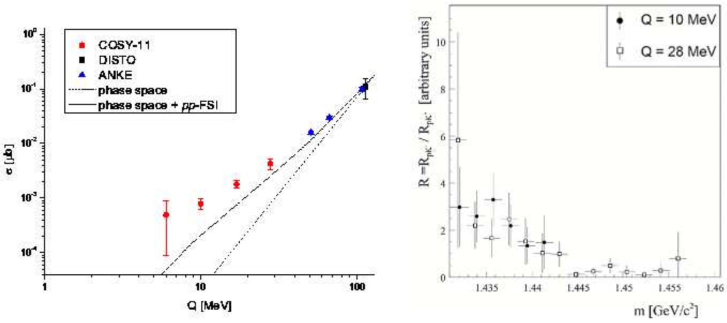

Figure 1: *(left) Excitation function for the* $pp \rightarrow ppK^+K^-$ *reaction. (right) Ratio of the number of events with the* K^-p *and* K^+p *as a function of the* Kp *invariant mass.*

In order to get a closer insight into the nature of the final state interaction in the ppK^+K^- system, the analysis of the differential spectra have been performed [8]. Fig. 1 (right) shows the ratio of the invariant masses in the pK^-/pK^+ systems. A visible enhancement of this ratio near the reaction threshold indicates the stronger nature of the pK^- final state interaction with respect to the one in the pK^+ system. Also the total cross section data for the hyperon production in the $pp \rightarrow pK^+\Lambda$, $pp \rightarrow pK^+\Sigma^0$ and $pp \rightarrow nK^+\Sigma^+$ channels [3, 11, 12] confirm that the final state interaction between K^+ and proton is relatively weak. as the data fairly follow the parameterization of the total cross section given by the three body phase space with inclusion of the final state proton-hyperon interaction.

Yet still the question whether the enhancement of the total cross section for the $pp \rightarrow ppK^+K^-$ reaction in the close-to-threshold region originates from the pK^- or K^+K^- FSI remains open. The attempts are made to resolve this problem via the analysis of the Chodrow and Goldhaber plots 6).

3 Searching for the η meson bound state in light nuclei

Another topic strictly connected with the low energy hadronic interaction is the existence of the bound state of the η meson with the nucleons.

As early as in 1985 Bhalerao and Liu 13) performed a coupled-channel analysis of the $\pi N \to \pi N$, $\pi N \to \pi\pi N$ and $\pi N \to \eta N$ reactions in the close-to-threshold region, and discovered that the interaction between the nucleon and the η meson is attractive. This finding inspired Haider and Liu to postulate the existence of the η–mesic nuclei 14), in which the chargeless η meson might be bounded with the nucleons by the strong interaction. The formation of such a bound state can only take place in such nuclei, for which the real part of the η–nucleus scattering length is negative (attractive nature of the η–nucleus interaction), and the modulus of the real part of η–nucleus scattering length is greater than the modulus of its imaginary part 15):

$$|Re(a_{\eta-nucleus}) > |Im(a_{\eta-nucleus})|. \quad (1)$$

The relatively small s-vawe ηN scattering length known in 1980's ($a_{\eta N} = (0.28+0.19i)$ fm 13)), limited considerations of Haider and Liu to the possibility of forming the η–mesic nuclei only by the nuclei with A ≥ 12 14). This estimation was also confirmed by the calculations in 16).

Recent studies of the η meson production in NN collisions 17, 18), and also the analysis of the Dalitz plot and invariant mass distribution for the $pp \to pp\eta$ reaction brought more evidence for a strong attractive interaction between the η meson and the nucleons, visible in the shape of the excitation curve for the $NN \to NN\eta$ reaction, as well as in the enhancement in the Dalitz plot and invariant mass distribution of proton–η system, in the region of small relative momenta of these particles 2, 19, 20). Indeed, recent theoretical considerations of hadronic- and photoproduction of the η meson result in a wide range of possible values of the η–nucleon s-wave scattering lengths from $a_{\eta N} = (0.270 + 0.220i)$ fm up to $a_{\eta N} = (1.050 + 0.270i)$ fm, with the suggested average value of $a_{\eta N} = (0.5 + 0.3i)$ fm. Such a high value of η–nucleon scattering length may enable the formation of a bound η–nucleus states in such light nuclei as $^{3,4}He$ 21, 22) and even in deuteron 23).

Analysis of the data from the pioneering measurements of the total cross section for the $dp \rightarrow {}^3He\eta$ reaction performed by the SPES-4 [24] and SPES-2 [25] collaborations, especially the negative sign of the real part of η^3He scattering length and the large value of $a_{\eta^3He} = (-2.31 + 2.57i)$ fm [21], led to the suggestion [21] of a possible existence of a η bound state in the ${}^3He - \eta$ system, though the conclusive statement could not have been drawn, as the condition given in Eq. 1 was not fulfilled.

Recently, the indication for a η–nucleus bound state have been observed in the $\gamma - {}^3He$ experiment [26], yet the observation was questioned [27] due to the low statistics, and the virtual state has been postulated as a possible explanation of the behavior of the production amplitude.

Search for a η–nucleus bound state has also been performed in the hadronic channel at the cooler synchrotron COSY, where the COSY-11 and ANKE collaborations independently, using different detection setups, performed the measurements of the excitation function and differential cross sections for the $dp \rightarrow {}^3He\eta$ reaction in the vicinity of the kinematical threshold [28, 29, 30]. Both groups in order to reduce the systematic errors used the momentum ramping technique of the beam of deuterons. Measurements have been performed with the beam momenta changed from below reaction threshold, up to the excess energy of circa 8.5 MeV in the case of COSY-11 experiment and about 11.5 MeV in the case of ANKE experiment. Data taken below the kinematical threshold were used to search for a signal in different decay channels of ${}^3He - \eta$ bound state, i.e. via the $dp \rightarrow {}^3He\pi^0$ reaction [31], while the measurements above the threshold enabled the study of the forward-backward asymmetries of the differential cross sections and the extraction of the η^3He scattering length.

Excitation function, as measured in both experiments is shown in Fig. 2 (left). Presented data points were parameterized with the s-wave scattering length formula [21, 28, 30] and from the fit to the COSY-11 data set the value of the η^3He scattering length has been extracted and equals $a_{\eta^3He} = [\pm(2.9 \pm 0.6) + (3.2 \pm 0.4)i]$ fm [28]. The sign of the $Re(a_{\eta^3He})$ cannot be fixed in this parameterization. Taking into consideration the value of the a_{η^3He} one can notice that within the statistical uncertainties the condition (1) may be fulfilled, thought due to the large uncertainties of the real and imaginary parts of the scattering length the conclusive statement about the possible formation of the ${}^3He - \eta$ nuclei cannot be made.

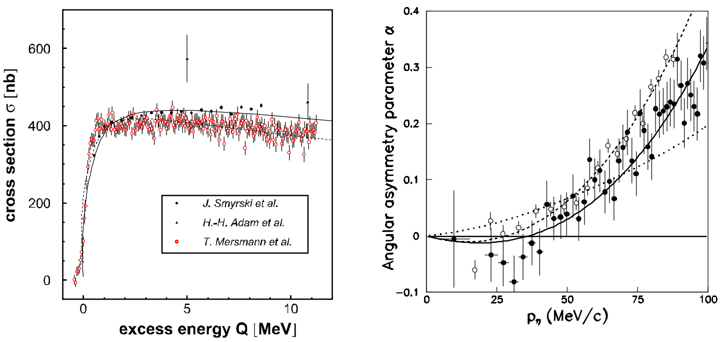

Figure 2: *(left) Close-to-threshold total cross section for the* $dp \to {}^3He\eta$ *reaction plotted as a function of the excess energy* Q. *Shown are the measurements performed at the COSY accelerator by ANKE collaboration* 30) *(open circles) and COSY-11 group:* 28) *(full dots) and* 29) *(triangles). The solid line represents the scattering length fit to the COSY-11 data* 28)*, while the dashed line is the analogous fit to the data set of Ref.* 30)*. (right) Angular asymmetry parameter* α*. Closed circles are the experimental data from COSY-ANKE* 30)*, whereas open circles represent the data set of COSY-11 group* 28)*. The dashed and solid lines are the theoretical parameterization* 32) *explained in the text. Figure is adopted from Ref.* 32)*.*

As has been indicated in 32), a steep rise of the total cross section in the very close-to-threshold region followed by a plateau, visible in both data sets, may originate from existence of a pole of the $\eta^3He \to \eta^3He$ scattering amplitude in the complex excess energy plane Q with $Im(Q) < 0$ 32). Author shows that the occurance of the pole changes the phase and the magnitude of the s-wave production amplitude. This information cannot be extracted from the excitation curve. Basing on the observation, that the $dp \to \eta^3He$ differential cross sections are linear in $\cos\theta_\eta$ 28), it was shown that the variation of the asymmetry parameter α, defined as:

$$\alpha = \frac{d}{d\cos\theta_\eta}\ln\frac{d\sigma}{d\Omega} \tag{2}$$

taken at $\cos\theta_\eta = 0$, can only be satisfactorily described (see solid line in Fig. 2 (right)) if the very strong phase variation associated with the pole is included in the fits 32). Otherwise one obtains the discrepancy between the experimental data and the theoretical description (see dashed line in in Fig. 2 (right)). This is the behavior of the the momentum dependence of the angular distribution for the $dp \rightarrow \eta^3He$ reaction, expected from the occurance of a bound or virtual η^3He state. However, as pointed out in Ref. 32), the information whether the pole lies on the bound state or virtual part of the Q plane cannot be accessed.

The COSY-11 measurements 31, 33) have also been used to investigate the cusp effect observed at SATURNE 24, 25, 34) in the threshold excitation curve for the $dp \rightarrow {}^3HeX$ reaction. The analysis of the data was revisited with much higher statistics and the assumptions were made to fulfill the conditions of the SATURNE acceptance. The high statistics COSY-11 data had revealed no cusp close to the η meson production threshold.

In the end of the day it is worth mentioning that recently there has been positively approved proposal for studies of the η bound state via the measurements of the excitation function for the $\vec{d}d \rightarrow p\pi X$ reaction with WASA-at-COSY detection setup 35). The signature of a possible bound state of η-${}^4He$ may be visible in a structure in the excitation function below the η-${}^4He$ threshold. It has been estimated that within one week of measurements with WASA-at-COSY apparatus, the precise scan of the profile of the excitation curve will allow to determine the binding energy and the width of the η-${}^4He$ bound states or at least it will permit to lower the present upper bound for the cross section of the production of the η-helium nucleus by more than two orders of magnitude down to the value of a few nanobarns 35). Also, taking the advantage of the polarized deuteron beam it will be possible to determine the beam momentum with a precision of an order of magnitude better than in the quoted experiments. Such a precision is important to better determine the pole position of the $\eta^4He \rightarrow \eta^4He$ scattering amplitude in the complex Q plane. It will be also possible to measure the vector analysing powers for the $\vec{d}d \rightarrow p\pi X$ reaction. These factors should put more constraints to the theoretical interpretation of the data 32) and enable better understanding of the physics underlying the formation of the η–nucleus bound states.

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