PROCEEDINGS OF SCIENCE

Spectroscopy of η' mesic nuclei using (p, d) reaction

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The η-PRiME collaboration (Japan-Germany-Austria) searches for $\eta'(958)$ meson-nucleus bound states. The mass of the η' meson is much greater than the values if it were a pure Goldstone boson associated with spontaneously broken chiral symmetry. The extra mass is to be attributed to non-perturbative gluon dynamics and the QCD axial anomaly. The η' in media will be influenced through chiral restoration and the axial U(1) dynamics, causing accordingly a sizable mass reduction and a strong binding to the nucleus, on which an observation of such states will provide valued information. The data taking (S437 experiment) using inclusive missing mass spectroscopy of (p,d) reaction off carbon target will take place in summer 2014 at the FRS spectrometer at GSI.

XV International Conference on Hadron Spectroscopy-Hadron 2013
4-8 November 2013
Nara, Japan

 http://pos.sissa.it/

PoS(Hadron 2013)166

1. Introduction

QCD predicts that the vacuum property is altered at finite density and/or temperature. Hadron properties can reflect this modification, notably their masses. The vast fraction of hadron mass is to be addressed to the spontaneous breaking of chiral symmetry [1]. Placing a hadron at finite density and/or temperature, and observing experimentally a modification of its property is a challenging but necessary mission in order to understand the QCD and the dynamical origin of hadron mass [2].

A measurement of the meson-nucleus systems is a successful experimental technique to probe the hadron property at finite density [2, 3]. Despite a limited degree of freedom of the probed density, its smaller ambiguity of the environmental condition which is probed by the meson is an advantage over its alternative technique, i.e. heavy-ion collision. This makes these two experimental approaches complementary each other.

Pions and kaons are pseudo Nambu-Goldstone bosons associated with chiral symmetry, however, the η' mesons are too massive by about 300-400 MeV for them to be pure Nambu-Goldstone states [4, 5, 6], implying there is an additional mechanism which generates mass. The extra mass is to be addressed to gluon dynamics associated with the QCD axial U(1) anomaly, making η' mesons unique among pseudoscalar meson nonet.

There is an increasing interest on the medium property of η' mesons [4, 5, 6, 7, 8, 9] since valuable new information about dynamical chiral and axial U(1) symmetry breaking in low energy QCD will be obtained. While there are numerous experiments on meson-nucleus bound states with pions and kaons [2, 3], much has not been done so far for η' mesic states.

An in-medium η' mass reduction of at least 200 MeV was claimed in an analysis of the ultra-relativistic Au+Au collision at $\sqrt{s_{NN}} = 200$ GeV [10]. A mass reduction of as large as 150 MeV also in nuclear medium is indicated by the NJL model calculation [5]. On the other hand, a low-energy η' production with pp collisions by COSY-11 experiment deduced a smaller scattering length of the s-wave η'-proton interaction, $|\mathrm{Re}\, a_{\eta' N}| < 0.8$ [11]. A similar value is expected by the quark-meson coupling model [6] which corresponds to a mass reduction of a few tens MeV. Another analysis of the COSY-11 data leads even a smaller interaction $|a_{\eta' p}| \sim 0.1$ fm [12] which leads a potential depth of only 8.7 MeV at the normal nuclear density [13].

Very recently the CBELSA/TAPS collaboration deduced the real part of the η'-nucleus potential depth to be $-(37 \pm 10(stat.) \pm 10(syst.))$ MeV from the excitation function and momentum distribution measurement [14], and the imaginary part of the potential to be $-(10 \pm 2.5)$ MeV from the transparency ratio measurement [15, 16]. The small imaginary potential is favorable in observing peak structures of such mesic states. This encourages an experimental search for η' mesic nuclei.

2. Experimental Approach

The (p,d) reaction on a carbon target at $T_p = 2.5$ GeV is proposed to search for the η' mesic

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†This work is supported by the Grant-in-Aid for Scientic Research (No. 20002003, No. 20540273, No. 22105510, No. 22740161, No. 24105705, No. 24105707, No. 24105712, No. 24540274 and No. 25707018) in Japan. Financial support by HIC-for-FAIR is also acknowledged.

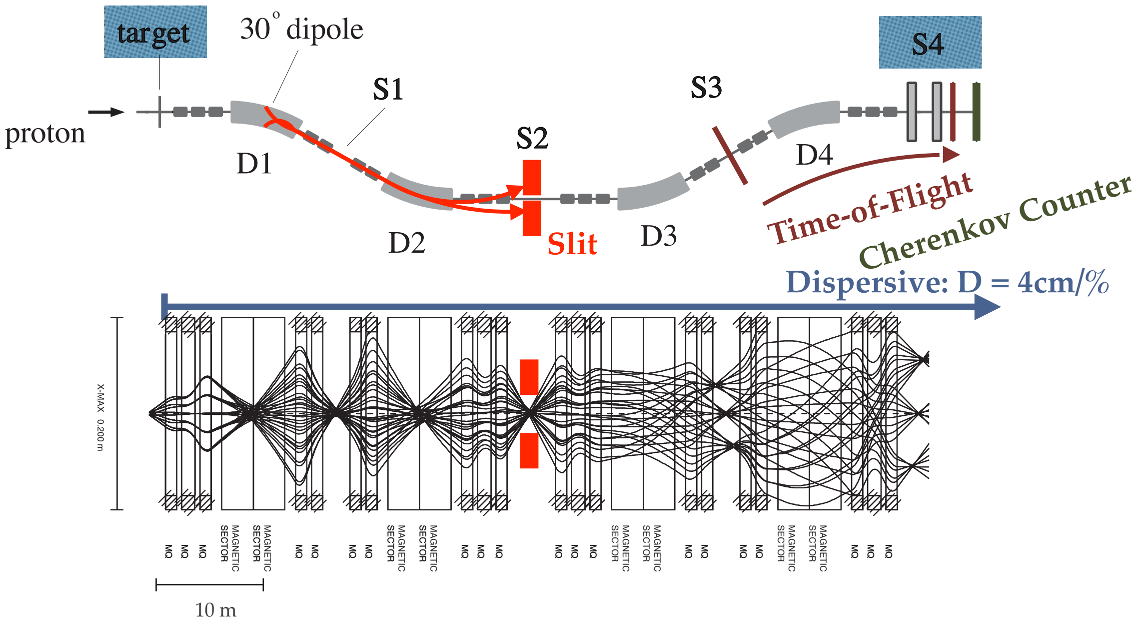

Figure 1: Experimental setup at the FRS spectrometer. A detector configuration is show in the top view of the spectrometer (top). An ion optics setting is also schematically shown (bottom).

nuclei [17, 18]. η's at this condition are produced with finite momentum transfer (400-500 MeV/c) which will be a good compromise of a background rejection capability with the proposed experimental setup and an expected cross section. Bound states of η' meson will produce structures below the mass threshold in the missing mass spectrum. Different shell states from which a neutron is picked up by the (p,d) reaction will superimpose spectra of η' bound states associated to each neutron hole state, resulting in a complex composition of mass spectrum [17, 18, 19].

The experiment will be performed at GSI Helmholtzzentrum, Darmstadt, Germany. An experimental setup is shown in Fig. 1. The SIS-18 synchrotron provides a high intensity proton beam ($\sim 10^{10}$/s). The primary proton beam is lead to a 4 g/cm^2 carbon target placed at an entrance of the FRS spectrometer which is composed by four 30° bending sections. Each bending section is equipped with a pair of quadruple triplets and doublets. An additional sextuple magnet is used for a correction of higher oder aberrations.

The ejectile deuteron with momentum of ~ 2.8 GeV/c is analyzed by the spectrometer from the target to the final focal plane (S4) with the resolving power of about 4 cm/%. With the deuteron momentum we obtain the missing mass of the reaction. Deuteron tracks are measured by two sets of multi-wire drift chambers (MWDCs) at the S4 focus area. MWDCs will be placed with 1 meter distance between each other and the overall horizontal tracking resolution will be $\sim 150\,\mu$m (FWHM) which will translates a mass resolution of 1.6 MeV/c^2. This is sufficiently small compared to the expected decay width. The intense primary beam dumped in the first dipole magnet will produce many secondary particles. In order to suppress this background we adopt a momentum-compaction optics at the central focal plane (S2) where we install slits. Particles which do not originate from the target will be scraped off by the slits as schematically indicated in the bottom panel of Fig. 1.

Proton background produced by the (p, p') reaction in the target will reach the final focal plane. In order to reject this proton background, we install Cherenkov counter with aerogel (n=1.18) at S4 making use of the velocity difference of deuteron ($\beta \sim 0.84$) and of proton ($\beta \sim 0.95$). The aerogel Cherenkov counter provides a sufficient rejection of proton background at trigger level. Scintillation counters will be installed at S3 and S4, providing a time-of-flight measurement with a flight path of ~ 18 m. Additional offline cut on the time-of-flight spectrum will safely remove the rest of the proton background.

Quasi-free multi pion production reactions can produce deuterons, e.g. $pp \to dX$ and $pn \to dX$ $(X = 2\pi, 3\pi, 4\pi, \omega)$ in a broad momentum range. This will be a main background source in this inclusive measurement. The total background level from these channels is estimated to be around $4\,\mu$b/sr/MeV [17, 18, 20] which is to be compared to, for example, the peak cross section of η' bound state $(0p_{3/2})_n^{-1} \otimes d_{\eta'}$ ~40 nb/sr/MeV when the to the η'-nucleus potential of $(V_0, W_0) = -(100, 10)$ MeV is assumed. In this case clear structures of η'-carbon bound states will be identified. Probability of finding a statistically significant structure under various scenarios of optical potential is studied in Ref. [17, 18, 20].

3. Summary and Outlook

An experimental program to search for an η' mesic nuclei in the inclusive (p, d) reaction at GSI is presented. Despite the relatively poor signal-to-noise ratio, we expect a reasonable chance to observe η' nuclear bound states [17, 18, 20]. A small imaginary part of the η'-nucleus potential suggested from the recent transparency ratio measurement by CBELSA/TAPS collaboration [15, 16] favors the preferred scenario. A final test of detectors and data acquisition system will be performed in January/February 2014 at the COSY-JESSICA external beam line of the COSY accelerator facility at Forschunszentrum Jülich, Germany. A production run will take place in July 2014 (GSI/S437 experiment).

The program will be extended at future FAIR facility to exploit a higher beam intensity available at SIS100 and Super-FRS. Also the new facility will allow us to install an event tagging counter around the target. This will improve the signal-to-noise ratio drastically.

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