PROCEEDINGS OF SCIENCE

Meson Properties at Finite Density from Mesic Atoms and Mesic Nuclei = Recent Topics on π and $\eta'(958)$ in Nuclei =

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We study the meson-nucleus systems as the very interesting objects to deduce the hadron properties precisely and to obtain new information on the aspects of the strong interaction at finite density. We briefly introduce the recent research activities on pionic atoms and $\eta'(958)$ mesic nuclei in this article. The $(d,^3\mathrm{He})$ reactions for the formation of the pionic atoms are considered at finite angles and on the odd-neutron nuclear targets to develop the systematic and accurate studies of the pion properties at various nuclear densities. $\eta'(958)$-nucleus systems are quite interesting in the context of the effects of the $U_A(1)$ anomaly at finite density. The possible formation of the nuclear bound states of the η' meson by the (p,d) reactions is discussed to deduce the information on the mass shift of the exceptionally heavy η' meson.

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1. Introduction

In contemporary hadron-nuclear physics, various hadron properties such as their masses and interactions are believed to have close connection to the aspects of quantum chromodynamics (QCD) symmetry [1]. The light pseudoscalar mesons are considered as the Nambu-Goldstone bosons associated with the spontaneous breaking of the chiral symmetry and the complicated mass spectrum of these mesons with the heavier $\eta'(958)$ meson is believed to be the consequence of the explicit breaking of flavor symmetry by current quark masses and of the breaking of the axial $U_A(1)$ symmetry.

One of the most interesting subjects in this field is the study of the aspects of QCD symmetry in extreme conditions with high density and/or temperature. It is quite natural to expect that the meson properties in these conditions provide important information of the aspects of the symmetries. In this context, meson-nucleus systems such as mesic atoms and mesic nuclei are very interesting objects to deduce the hadron properties precisely at finite density.

In this article, we briefly introduce the recent research activities on pionic atoms and $\eta'(958)$ mesic nuclei.

2. Pionic Atoms

Pionic atom is one of most interesting objects to perform spectroscopic studies of the hadron bound systems because of the relatively small widths [2]. Especially, deeply bound pionic atoms, which cannot be reached by the X-ray experiments, are known to provide valuable information on chiral symmetry at finite density [3] based on the theoretical foundation [4, 5].

To develop the study of the deeply bound pionic atoms further, we need to beat the difficulties due to the so-called Seki-Masutani correlation between pion-nucleus potential parameters, which indicates the insensitivities of the atomic pion to nuclear densities other than $\sim 0.6\rho_0$ [6, 7]. In Fig.1, we show the effective nuclear densities [8] probed by the atomic pions [9]. We can see clearly that all atomic pions probe only around $0.6\rho_0$. At the preliminary stage of our exploration, this robustness of the sensitivity to the specific density was helpful to deduce the information on symmetry less ambiguously. At present, we have theoretical predictions of the density dependence of the chiral condensate beyond the linear density approximation [10] and we need to have new information on the pion properties at different densities from $0.6\rho_0$.

For this purpose, we need systematic and accurate studies of the pionic atoms. We have developed the formulation and obtained the numerical results of the pionic atom formations by the $(d,^3\mathrm{He})$ reactions at finite angles [11] and on the odd-neutron nuclear target cases [12]. In Fig.2, we show the theoretical results of the $(d,^3\mathrm{He})$ reactions at finite angles for the pionic atom formation.

We will study pionic atoms further along with this line to develop the high precision spectroscopic studies of the pionic atoms. New experimental results are expected to be obtained in near future [13].

3. $\eta'(958)$-Mesic Nucleus

The $\eta'(958)$ meson properties at finite density have been discussed for a long time in the context of the effects of the $U_A(1)$ anomaly at finite density [1, 14, 15, 16]. The possible formation

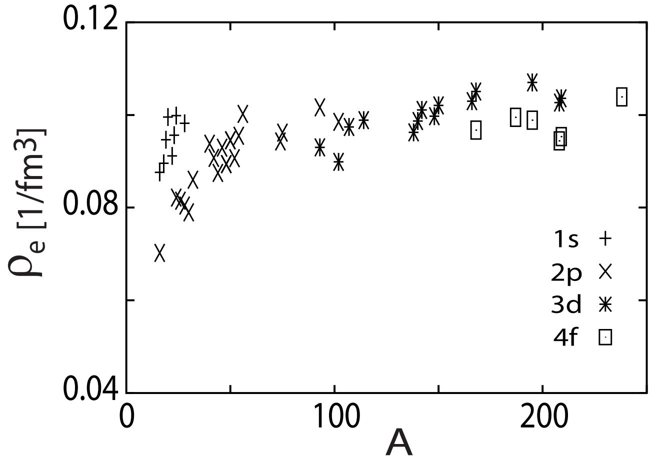

Figure 1: Calculated effective nuclear densities ρ_e reported in Ref. [9] for the observed pionic atoms by pionic X-ray are plotted as a function of nuclear mass number A. The quantum numbers of each atomic state are indicated in the figure.

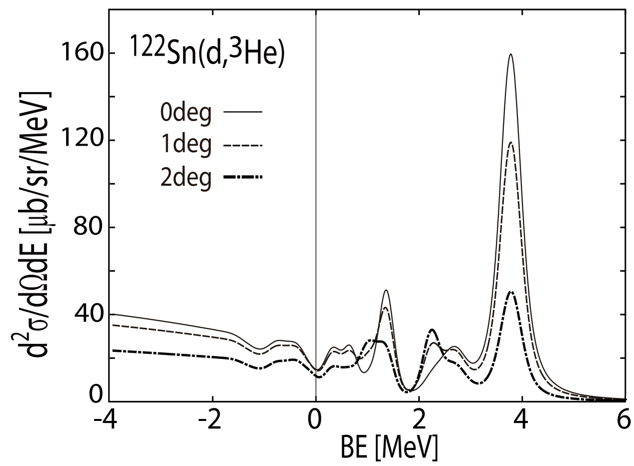

Figure 2: Calculated spectrum obtained in Ref. [12] for the formation of pionic states in the ^{122}Sn$(d,^3$He$)$ reactions as functions of the pion binding energy. Three different angles of the emitted ^{3}He are considered as indicated in the figure.

of the nuclear bound states of the η' meson is also discussed [17] to deduce the information of the mass shift in nucleus of the exceptionally heavy η' meson. The η' mass is believed to be quite large because of the anomaly effects, thus, we expect to know the effects of the anomaly at finite densities by knowing the properties of the η'-nuclear systems. Actually, a model calculation indicates the large mass reduction of η' at normal nuclear density [18] and consequently indicates the existence of the strong attractive potential between η' and nucleus. The η' properties are also discussed recently based on the symmetry of the strong interaction [19]. We show the recent results [20] of the formation cross section of the $\eta'(958)$ bound states in Fig. 3. The experimental feasibility of the (p,d) reaction is considered seriously [20, 21] and the experiment is expected to be performed

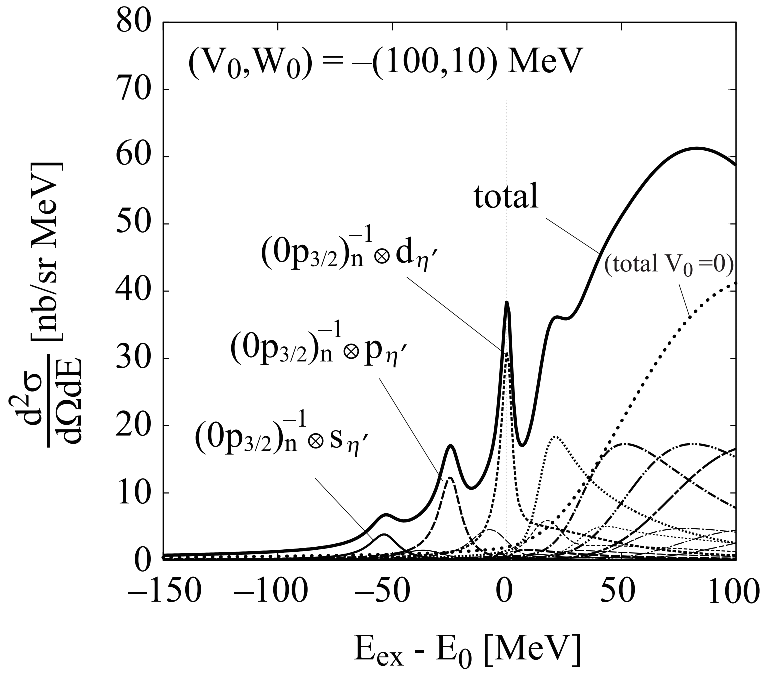

Figure 3: Calculated spectra obtained in Ref. [20] of the $^{12}\mathrm{C}(p,d)^{11}\mathrm{C}\otimes\eta'$ reaction for the formation of η'-nucleus systems as functions of the excited energy E_{ex}. E_0 is the η' production threshold energy. Incident proton kinetic energy is T_p =2.5 GeV and emitted deuteron angle is 0°. The depths of the complex η'-nucleus optical potential are indicated in the figure. The contributions of dominant subcomponents and the total spectrum for $(V_0,W_0) = -(0,10)$ MeV are also shown.

in near future.

Recently, several other theoretical and experimental results have also been reported [22, 23, 24, 25, 26]. We think that this subject is very interesting and we expect to obtain new information smoothly to deepen our insights.

4. Summary

We have studied the meson-nucleus systems such as mesic atoms and mesic nuclei as the very interesting objects to deduce the hadron properties precisely and to obtain new information on the aspects of the strong interaction at finite density. We briefly introduce the recent research activities on pionic atoms and $\eta'(958)$ mesic nuclei in this article. We think that our studies based on the spectroscopy of the meson-nucleus systems are unique and are complementary to those using the heavy-ion collisions.

References

[1] For review: T. Hatsuda and T. Kunihiro, Phys. Rept. **247**, 221 (1994).

[2] For review: T. Yamazaki, S. Hirenzaki, R. S. Hayano and H. Toki, Phys. Rep. **514**, 1 (2012).

[3] K. Suzuki *et al.*, Phys. Rev. Lett. **92**, 072302 (2004).

[4] E. E. Kolomeitsev, N. Kaiser and W. Weise, Phys. Rev. Lett. **90**, 092501 (2003).

[5] D. Jido, T. Hatsuda and T. Kunihiro, Phys. Lett. B **670**, 109 (2008).

[6] R. Seki and K. Masutani, Phys. Rev. C **27**, 2799 (1983).

[7] H. Toki, S. Hirenzaki, T. Yamazaki and R. S. Hayano, Nucl. Phys. A **501**, 653 (1989).

[8] T. Yamazaki and S. Hirenzaki, Phys. Lett. B **557**, 20 (2003).

[9] N. Ikeno, R. Kimura, J. Yamagata-Sekihara, H. Nagahiro, D. Jido, K. Itahashi, L. S. Geng and S. Hirenzaki, Prog. Theor. Phys. **126**, 483 (2011).

[10] S. Goda and D. Jido, Phys. Rev. C **88**, 065204 (2013)

[11] N. Ikeno, H. Nagahiro and S. Hirenzaki, Eur. Phys. J. A **47**, 161 (2011).

[12] N. Ikeno, J. Yamagata-Sekihara, H. Nagahiro and S. Hirenzaki, Prog. Theor. Exp. Phys. **2013**, 063D01 (2013).

[13] S. Itoh, "Precision spectroscopy of deeply bound states in the pionic ^{121}Sn atom", Doctor Thesis, University of Tokyo, December (2011); K. Itahashi *et al.*, Few-Body Systems **54**, 1573, (2013).

[14] R. D. Pisarski and F. Wilczek, Phys. Rev. D 29, 338 (1984).

[15] J. Kapusta, D. Kharzeev, and L. McLerran, Phys. Rev. D 53, 5028 (1996).

[16] V. Bernard, R. Jaffe, and U. G. Meissner, Nucl. Phys. B308, 753 (1988).

[17] H. Nagahiro and S. Hirenzaki, Phys. Rev. Lett. **94**, 232503 (2005).

[18] H. Nagahiro, M. Takizawa and S. Hirenzaki, Phys. Rev. C **74**, 045203 (2006).

[19] D. Jido, H. Nagahiro and S. Hirenzaki, Phys. Rev. C **85**, 032201(R) (2012).

[20] H. Nagahiro, D. Jido, H. Fujioka, K. Itahashi and S. Hirenzaki, Phys. Rev. C **87**, 045201 (2013).

[21] K. Itahashi *et al.*, Prog. Theor. Phys. **128**, 601 (2012).

[22] K. Tsushima, Nucl. Phys. A670, 198 (2000).

[23] P. Moskal *et al.*, Phys. Lett. B474, 416 (2000), Phys. Lett. B482, 356 (2000).

[24] S. D. Bass and A. W. Thomas, Phys. Lett. B634, 368 (2006).

[25] H. Nagahiro, S. Hirenzaki, E. Oset and A. Ramos, Phys. Lett. B 709, 87 (2012).

[26] M. Nanova *et al.*, Phys. Lett. B 710, 600 (2012).