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In-flight (K^-, N) Reactions for Study of Kaon-nucleus Interaction*

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Abstract: We would like to emphasize that the in-flight (K^-, N) reactions are particularly useful for the study of the $\overline{K}$-nucleus interaction. Since the reaction mechanism is well known, there is little ambiguity to derive the $\overline{K}$-nucleus interaction from the measured missing mass spectra. Here we discuss the missing mass spectra of the (K^-, N) reactions on the ^{12}C and ^{16}O targets. The spectra show an appreciable amount of strength below the $\overline{K}$-nucleus threshold which indicates that the $\overline{K}$-nuclear potential is strongly attractive. Comparison of the missing mass spectra with theoretical calculations leads to a potential depth of around −190 MeV for the $^{12}C(K^-, n)$ reaction. A less deep potential of around −160 MeV reproduces well that of the $^{12}C(K^-, p)$ reaction. The difference can be due to isospin dependence of the interaction. Our data show that the $\overline{K}$-nucleus potential is very deep to realize kaon condensation in the core of neutron stars.

Key words: neutron star; kaon condensation; kaon-nucleus interaction

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1 Introduction

It has been well recognized that the $\overline{K}$-nucleus interaction is a key to understand dense nuclear matter, particularly, core of neutron stars[1—4]. Density of electron is limited by degeneracy pressure which also limits proton density due to charge neutrality. Possible existence of negatively charged particles increases density of the core of the neutron stars. It reduces mass of neutron stars. Candidates of negatively charged particles are π^-'s, K^-'s and Σ^-'s. The key information is their interaction with a nuclear matter for which K^-'s have been known the least.

Extensive analysis of X-rays from K^- atoms concludes that the potential is strongly attractive[5]. It is as deep as −200 MeV which opens a possibility of kaon condensation at around 3 times normal nuclear density. Since atomic X-ray data tell the phase shift at the nuclear surface, a different treatment of the nuclear surface gives a shallow potential of around −80 MeV[5]. Recent reanalysis concludes that a deep potential gives a better fit to the data[6]. Although study of heavy ion reactions suggests attractive potential, its discussion requires long volume and is beyond this article scope. Theoretical calculations based on a chiral Lagrangian[7—9] or meson exchange potential[10] predict shallow potentials of −50 to −80 MeV which are also consistent with the data[11]. On the other hand, theoretical calculations based on phenomenologically obtained $\overline{K}$ nucleon interaction predicts deep potentials[12].

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If the interaction is strongly attractive, one expects to have a kaonic nucleus that is a bound state of $\bar{K}$ and a nucleus. Observation of kaonic nuclear states gives an answer on the potential depth. The (K$^-$, N) reactions with an in-flight K$^-$ beam was proposed[13] and the same reaction with stopped K$^-$ beam was investigated[12]. Recently, candidates for deeply bound kaonic nuclear states in the range of binding energy $BE \approx 100-200$ MeV have been reported[14—18]. Data in Ref. [16, 17] indicate potential depth of −200 MeV which is similar to the deeper solution of the X-ray data. Others[14, 15, 18] suggest much deeper potentials of a few to several −100 MeV. It has been argued, however, that the modification of a core nucleus to realize such deep potential is unrealistic. Other processes to explain the experimental data unrelated to deeply bound states have been proposed[19].

2 The (K$^-$, N) Reaction and Kaonic Nuclei

We have been employing the in-flight (K$^-$, N) reaction for the study of the $\bar{K}$-nucleus interaction. The reaction is graphically represented in Fig. 1. It provides a virtual K$^-$ or $\bar{K}^0$ beam which is appropriate to excite kaonic nuclear states. Treatment of distortion may change the cross sections a little[20], although they are within a reach of experimental sensitivity. One can clearly observe kaonic nuclear state if the potential is deep and its imaginary part is small. The spectrum shape, in particular, peak structure is obscured by the imaginary part. What is relevant to the kaon condensation is the real part and the gross structure of the spectrum is largely determined by it.

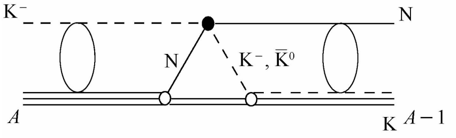

Fig. 1 Formation of kaonic nuclei via the (K$^-$, N) reaction is shown graphically. The bubble represents distortion.

The in-flight (K$^-$, N) reaction is affected little by backgrounds. The nucleon from the reaction has almost the highest momentum when we use the K$^-$ beam of ~1 GeV/c or higher momentum. Only conceivable process to produce a nucleon with a momentum higher than that of the (K$^-$, N) reaction is the two-nucleon absorption process of $K^- + N + N \to Y + N$. It is, however, found to be negligible as shown later. The cross section of the (K$^-$, N) reaction is very large due to the large elementary cross section and Jacobian of center-of-mass to laboratory system. It make the background contribution almost negligible.

Ground states of kaonic nuclei appears deeper for heavier nuclei[13]. One thus expects appreciable strength in the bound region for heavier nuclear target. The pioneering study was first attempted at BNL where neutrons from the ^{16}O(K$^-$, n) reaction were measured[16, 17]. The obtained missing mass spectrum shows appreciable strength in the bound region indicating strongly attractive interaction and the potential depth of −200 MeV was suggested. However, the experiment employed a water target, thus the spectrum inevitably included the p(K$^-$, n) reaction which made quantitative comparison of the ^{16}O(K$^-$, n) reaction with theoretical calculation difficult. More statistics are needed to make the conclusion convincing.

3 KEK PS-E548

A new experiment at KEK(PS-E548) was carried out to overcome such shortage. The PS-E548 experiment studied both the ^{12}C(K$^-$, N) and ^{16}O(K$^-$, N) reactions[21]. Results of the experiment have been presented in a recent publica- tion[22]. Here we describe what is relevant to the present discussion. Polyethylene (CH_2) and graphite (C) were used as targets. A water target was also studied although we confine our discussion on the carbon target and the ^{16}O(K$^-$, N) reaction will be discussed in future publications. The K$^-$ beam was provided by the K2 beam line of the 12 GeV proton synchrotron of KEK (KEK-PS). The K$^-$ beam momentum was 1 GeV/*c* and the beam intensity was typically 10^4/spill for 2×10^{12} protons/spill. Neutrons from the ^{12}C(K$^-$, n) reaction were measured by a neutron detector set at 9.8 m downstream of the target. Protons were measured by the KURAMA magnetic spectrometer.

Particles decaying from kaonic nuclear states were measured by a decay counter surrounding the target. Two sets of 25 NaI detectors were placed below and above the target to give total energy for charged particles. Each NaI has dimensions of 6.5 cm×6.5 cm ×30 cm. In front of the NaI detector 1 cm thick plastic scintillators were placed to identify charged particles. In order to make background negligible, more than one hit in the decay counter were required. In the following we focus our discussion on spectra with this hit requirement. Peak positions of the p(K$^-$, p)K$^-$ and p(K$^-$, n)K^0 reactions on protons in the CH$_2$ target were used to check the momentum calibration and momentum resolution of the KURAMA spectrometer and those of the TOF, respectively. Momentum resolution of protons and neutrons are good enough for the present argument since we discuss rather gross structure as described later. Observed yields of the p(K$^-$, p)K$^-$ and the p(K$^-$, n)K^0 reactions are consistent with the tabulated elementary cross sections[23] within ~20%. Since the observed yields of the ^{12}C(K$^-$, N) reaction can be normalized to the yields of the elementary cross sections, the precision of the absolute cross sections matters is little in the later discussion.

4 Missing Mass Spectra

The missing mass spectrum of ^{12}C(K$^-$, n) and ^{12}C(K$^-$, p) reactions on the graphite target are shown in Fig. 2. Here the horizontal axis is the binding energy of K$^-$ to residual nuclei (R) which are either ^{11}C or ^{11}B represented by $-BE = M_{\mathrm{KN}} - (M_{\mathrm{R}} + M_{\mathrm{K^-}})$. Scattering angles ($\theta_{\mathrm{sc}}$) of neutrons and protons were restricted to $\theta_{\mathrm{sc}} < 4.1°$ which is much narrower than experimental acceptance in order to avoid energy dependent correction of the acceptance. We studied the effect of the hit requirement on the spectrum shape. We found that the ratio of coincidence spectrum to inclusive one depends little on the binding energy, so spectrum shape is not affected by requiring coincidence[24].

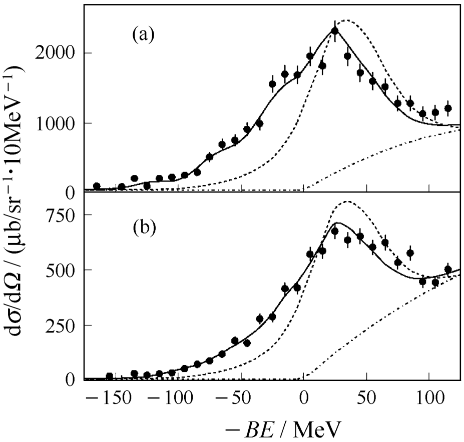

Fig. 2 Missing mass spectra of the ^{12}C(K$^-$, n) reaction (a) and ^{12}C(K$^-$, p) reaction (b) are shown. — are calculated best fit spectra for potentials of Re(V) = −190 MeV and Im(V) = −40 MeV (a) and Re(V) = −160 MeV Im(V) = −50 MeV (b). ··· are calculated spectra for Re(V) = −60 MeV and Im(V) = −60 MeV. -·- represent a background process (see text).

Energetic nucleons from the two-nucleon absorption K$^-$ + N + N → Y + N might give an enhancement at $BE \approx 300$ MeV region. Since we see no enhancement, we found that the two-nucleon absorption is negligible. Although the two-nucleon absorption requires a K$^-$ to see two nucleons simultaneously, it is less probable for the energetic K$^-$ which has short wave length. On the other hand the two-nucleon absorption is the dominant background for the stopped K$^-$ which has a long wave length [14, 15]. The smallness of the twonucleon absorption in the in-flight (K$^-$, N) reaction clarify the signal to produce kaonic nuclei.

An energetic hyperon may be produced by the N(K$^-$, π)Y reaction in which a pion is scattered backwards. Decay of the hyperon produces an energetic nucleon. However, the cross section[23] and detector arrangement tell that the process is negligible. One can think any kind of background processes to produce energetic nucleons in forward direction. However, they naturally accompany backward scattered particles due to momentum conservation. We thus should see backward enhancement in our decay counter. However, the decay counter shows no enhancement which ensures that such background processes are not important.

5 Comparison with Theoretical Calculations

The observed spectra are fitted by theoretically calculated ones. We used the Green function method[25] which gives a consistent description of spectrum shape from bound to unbound regions. Its application to the (K^-, N) reaction has been demonstrated[26]. It has to be noted that one cannot use spectrum just for the quasifree process when final state interaction is particularly strong as for this case. We calculate missing mass spectra of all binding energy region for given real ($\mathrm{Re}(V)$) and imaginary ($\mathrm{Im}(V)$) parts of the potential (V). $\mathrm{Im}(V)$ has binding energy dependence due to phase space volume of decaying particles. For instance, pion emission is closed at $-BE \approx m_\pi$. We followed the procedure given in Ref. [26], which was originally developed in Ref. [6] where 80% for pion emission and 20% for two nucleon absorption at the threshold. Potential shape is taken as $F(r)=1/(e^x+1)$ where $x=(r-R)/a$. We used $R=2.45$ fm and $a=0.55$ fm in our calculation[27].

The spectra show no statistically significant strength below $-BE=-150$ MeV for both $^{12}C(K^-, n)$ and $^{12}C(K^-, p)$ reactions. On the other hand, we see processes other than (K^-, N) reaction contribute substantially in the unbound region of 100 MeV or above. We fitted the spectrum shapes of (K^-, n) and (K^-, p) reactions by quadratic functions in $-BE=100$—200 MeV region as shown in Fig. 2. This quadratic shape is particularly evident for the (K^-, p) reaction. The cross section of the (K^-, n) reaction is larger than that of the (K^-, p) reaction, because the (K^-, n) reaction includes contribution from both the $n(K^-, n)K^-$ and $p(K^-, n)\overline{K}^0$ reactions[13].

We obtained the effective nucleon number $N_{\mathrm{eff}}=1.5$ from the integrated cross sections of the $^{12}C(K^-, p)$ and the $p(K^-, p)$ reactions using the inclusive spectra of the CH_2 target. The eikonal approximation with total cross sections of $\sigma_{KN}=40$ mb and $\sigma_{NN}=40$ mb gives $N_{\mathrm{eff}}=1.44$ and 1.27 when no ($A-1$) correction is included. Good agreement of the N_{eff} tells that the strength we see in the bound region is mostly from the $^{12}C(K^-, N)$ reaction and background processes are not substantial even they exist as discussed above.

Potential depth of $\mathrm{Re}(V)=-190$ MeV gives best χ^2 for $^{12}C(K^-, n)$ reaction. The calculated ground state is at around $BE=120$ MeV which is not seen as a peak but a bump. We take $\mathrm{Re}(V)=-60$ MeV and $\mathrm{Im}(V)=-60$ MeV as a typical potential by chiral unitary model[8] which does not reproduces the observed spectra as shown in Fig. 2.

The spectrum of $^{12}C(K^-, p)$ reaction is best reproduced by a potential depth of $\mathrm{Re}(V)=-160$ MeV. In this case ground state is expected at around $BE=100$ MeV. Bump structure is poorly seen because the imaginary part smears structure for states with smaller binding energy. The obtained potential is almost same as that obtained in $^{12}C(K^-, n)$ reaction. However, it is ~ 30 MeV shallower than that of the $^{12}C(K^-, n)$ reaction.

6 Isospin Dependence

Let us discuss that the ~ 30 MeV difference of potential depth observed in the (K^-, n) and (K^-, p) reactions is reasonable. One can assume that the attractive interaction is solely from the $I=0$ $\overline{K}N$ pair. Then the potential depth is proportional to the number of $I=0$ pairs in kaonic nuclei. The operator to extract the $I=0$ pair is represented by $(1/4)(1-4\boldsymbol{t}_K \cdot \boldsymbol{t}_N)$ where $\boldsymbol{t}$ represents isospin vector and subscripts are self-evident. The isospin dependence of the potential is given by taking summation of the operator over number of nucleons (A) in a kaonic nucleus. Generally, a state with smaller total isospin has larger $I=0$ pair.

The ^{12}C(K$^-$, n) reaction produces $I_z=0$ state although the ^{12}C(K$^-$, p) reaction produces $I_z=1$ state. Thus total isospin is $I_{KN}=0$, 1 for the ^{12}C(K$^-$, n) reaction and $I_{KN}=1$ for the ^{12}C(K$^-$, p), respectively. The potential depth is $V=1.27\ V_0$ for $I_{KN}=0$ and $0.91\ V_0$ for $I_{KN}=1$ state, respectively. We assume that $I=1$ and $I=0$ states are equally produced in the ^{12}C(K$^-$, n) reaction. Thus observed Re(V) $=-190$ MeV for the ^{12}C(K$^-$, n) reaction predicts Re(V) $=-158$ MeV for the ^{12}C(K$^-$, p) reaction for the observed -160 MeV. The observed difference is almost the same as that of the calculation which is another evidence that potential depth is as deep as 200 MeV.

7 Conclusion

We have studied the depth of the $\overline{\text{K}}$-nucleus potential. Our data show deep potential depth of -160 to -190 MeV. The values clearly selects deeper potential obtained in theHJ analysis of X-ray data. Shallow potentials of -50 to -80 MeV cannot reproduce our data. The deep attractive potential observed here opens the possibility of kaon condensation on neutron stars at around 2—3 times of normal nuclear density.

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