Status and results of E548

KEK-PS E548 collaboration

T. Kishimoto[1] T. Hayakawa[1], S. Ajimura[1], F. Khanam[1], T. Itabashi[1], K. Matsuoka[1], S. Minami[1], Y. Mitoma[1], A. Sakaguchi[1], Y. Shimizu[1], K. Terai[1], R. E. Chrien[2], P. Pile[2], H. Noumi[3], M. Sekimoto[3], H. Takahashi[3], T. Fukuda[4], W. Imoto[4] and Y. Mizoi[4]

[1] Department Physics, Osaka University, Toyonaka, Osaka, 560-0043, Japan

[2] Brookhaven National Laboratory (BNL), Upton, New York 11973, USA

[3] High Energy Accelerator Research Organization (KEK), Tsukuba, Ibaragi, 305-0801, Japan

[4] Osaka Electro-Communication University, Neyagawa, Osaka 572-8530, Japan

KEK-PS E548

KEK-PS E548 experiment was performed to study kaonic nuclei by the in-flight (K^-, N) reaction [1] at KEK-PS K2 beam line in April in 2005 for the beam time of 52 shifts. In addition to the primarily purpose, search for X particles[2] was also carried out for which additional 9 shifts were employed. Recently we have published our results for kaonic nuclei in a letter paper. The current situation of the kaonic nuclei is somehow chaotic. The result of the E548 shows that the $\bar{K}$-nucleus potential is deep enough to realize kaon condensation in the core of neutron stars. We believe that our result is most reliable currently. In the following we briefly describe the E548 experiment and its result. For the X-particle search we need a little more time to extract result.

Physics motivation of the E548 experiment.

It has become recognized that kaon condensation may play a substantial role in the cores of neutron stars where $\bar{K}$-nucleus interaction has to be strongly attractive [3, 4]. However, little is known with regards to the $\bar{K}$-nucleus interaction. Extensive analysis of X-rays from K^- atoms has revealed that the interaction is strongly attractive [5]. In fact, the potential depth may be as deep as -200 MeV, which suggests the possibility of kaon condensation at around three times normal nuclear density. However, a shallow potential of around -80 MeV also gave equally good reproduction of the experimental data [5] where kaon condensation is irrelevant. Recent reanalysis concludes that -200 MeV gives a better fit to the data[6].

The production rate of K^- in heavy ion reactions suggests an attractive interaction of around -80 MeV although derivation depends on the reaction mechanism. Theoretical calculations prefer potentials of -50 to -80 MeV. On the other hand, naive $\bar{K}$ nucleon interaction from $\Lambda(1405)$ predict deep potentials of around -200 MeV.

The direct observation of kaonic nuclear states should give an answer regarding the potential depth. Recently, possible identification of deeply bound kaonic nuclear states in the range of binding energies BE ∼100-200 MeV have been reported [8, 9, 10, 11, 12]. The ref. [10, 11] indicate a potential depth of -200 MeV, as suggested by X-ray data. Other experimental results [8, 9, 12] suggest much deeper potentials of -300 to -600 MeV which is rather unacceptable and other explanations unrelated to deeply bound states have been proposed [13].

In the E548 experiment we studied the in-flight $^{12}\mathrm{C}(K^-, N)$ reaction to clarify the situation. The nature of the reaction mechanism is clear, and the cross sections to produce kaonic nuclear states have been predicted, [7]. We can observe kaonic nuclear states if the potential is deep and its imaginary part is small. Even though the peak structure is not evident, due to a large imaginary part, the spectrum shape provides information concerning the potential depth. The ground states of kaonic nuclei are expected to become lower in energy for heavier nuclei [7]; we thus studied ^{12}C and ^{16}O target.

Experimental condition

The experiment was carried out at the K2 beam line of the 12 GeV proton synchrotron of KEK (KEK-PS). Details of the experiment can be found in a proposal [1], annual report [14], and recent publications []. An incident K^- momentum of 1 GeV/c was chosen so as to maximize the product of the $N(K^-, N)\bar{K}$ reaction cross section and the beam intensity [1]. The beam intensity was typically 10^4/spill for 2×10^{12} protons/spill. A spill consisted of 1.7 sec of continuous beam every 4 sec. The beam-line spectrometer measured the incident K^- momentum. The momentum of the outgoing proton was measured by the KURAMA spectrometer, which has a momentum resolution of 15 MeV/c(FWHM). The schematic view of the KURAMA spectrometer is shown in figure 1.

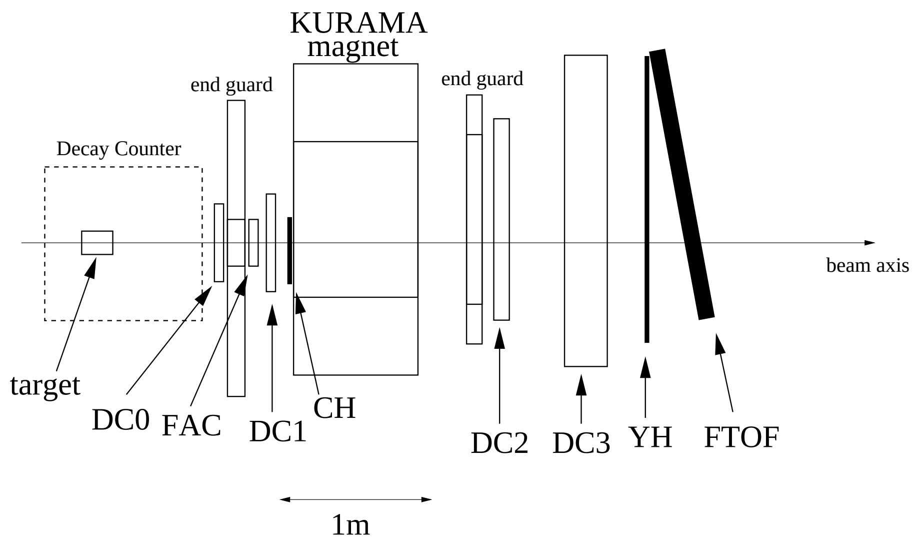

Figure 1: Schematic view of KURAMA spectrometer.

Neutrons from the $^{12}\mathrm{C}(K^-, n)$ reaction were measured by a neutron detector set at 9.8 m downstream of the target. It consists of a liquid scintillator and plastic scintillators. The liquid scintillator has a thickness of 20 cm and covers an area of 1.5×1.5 m^2. The liquid scintillator increased detection efficiency cost effectively. The two layers of each plastic scintillator with a thickness of 5 cm cover the same area. The momenta of the neutrons from the reaction were approximately 1.2 GeV/c, in which momentum region, protons from the $p(n, p)n$ reaction are mostly emitted in the forward direction. We require that the two consecutive plastic scintillators fire in the beam direction and that their pulse heights be consistent with the dE/dX of a proton at around 1.2 GeV/c. The time resolution of the plastic scintillator is approximately 100 ps. The missing mass resolution of the (K^-, n) reaction is 10 MeV/c(σ) at around $BE = 0$ region including all experimental conditions. The background from charged particles was found to be negligible. Figure 2 shows neutron counter schematically.

Particles decaying from kaonic nuclear states were measured by a decay counter surrounding the target. The target had dimensions of $2 \times 10 \times 20$ cm^3. Polyethylene (CH_2), graphite (C) and water (H_2O) were used as targets. The target was sandwiched by five 1 cm thick plastic scintillator hodoscopes with 5 cm granularity in the z (beam) direction. Two sets of

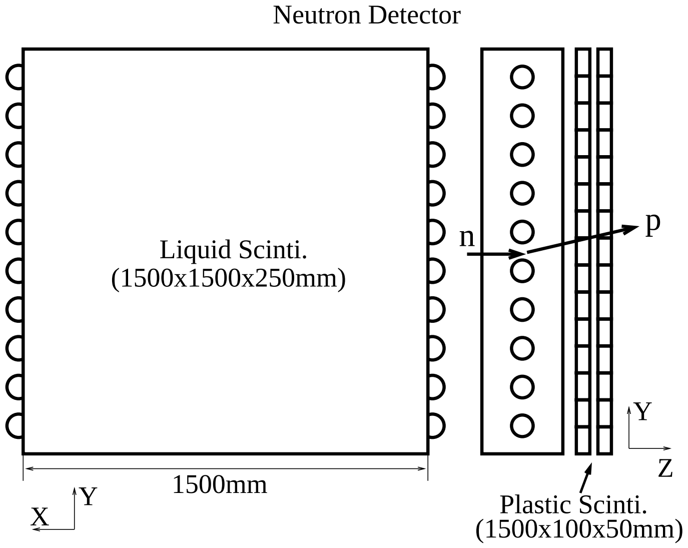

Figure 2: Schematic view neutron detector. Left side is the front view and right side is the side view.

25 NaI detectors were placed below and above the target to measure total energy of charged particles. Each NaI has dimensions of $6.5 \times 6.5 \times 30$ cm^3. In front of these NaI detectors, 1 cm thick plastic scintillators were placed to identify charged particles. In order to reduce number of background events, more than one charged particle hit in the decay counter was required. In particular, K_L produced at the target by the $(K^-, \bar{K}^0)$ reaction was suppressed to a negligible level.

Results

Recently we have published our result on the carbon target [18]. We first tried PRL although we encountered strong objection. It finally appeared in PTP. We briefly describe the result based on the publication. The missing mass spectrum of the ^{12}C(K^-, n) and ^{12}C(K^-, p) reactions with the graphite target are shown in Fig. 3. Here, the horizontal axis corresponds to the mass of kaonic nuclei M_{KN}, represented by the binding energy of K^- to the residual nuclei (R), which are either ^{11}C or ^{11}B. This binding energy is given by $-BE = M_{KN} - (M_R + M_{K^-})$. The observed spectra were fitted to theoretically calculated ones. We used the Green function method, [17] which gives a consistent description of the spectrum shape from bound to unbound regions. It has been previously applied to the (K^-, N) reaction and details of the calculation can be found in ref. [?].

One can see an appreciable strength in the bound region in Fig. 3 which indicates strongly attractive interaction. Actually, a potential depth of Re(V)=-190 MeV was found to give the best value χ^2 for the ^{12}C(K^-, n) reaction. A shallow potential of -60 MeV, for instance, from chiral unitary model [?] does not reproduce the observed spectra, as shown in Fig. 3. The statistical errors in the fitting are approximately 9 MeV for Re(V) and 18 MeV for Im(V).

Conclusion on the study of kaonic nuclei.

We have studied potential the depth of the $\bar{K}$-nucleus potential. Our data clearly support the deep potential of around -200 MeV. Shallow potentials of -80 MeV or less cannot reproduce our data. The deep attractive potential observed here opens the possibility of kaon

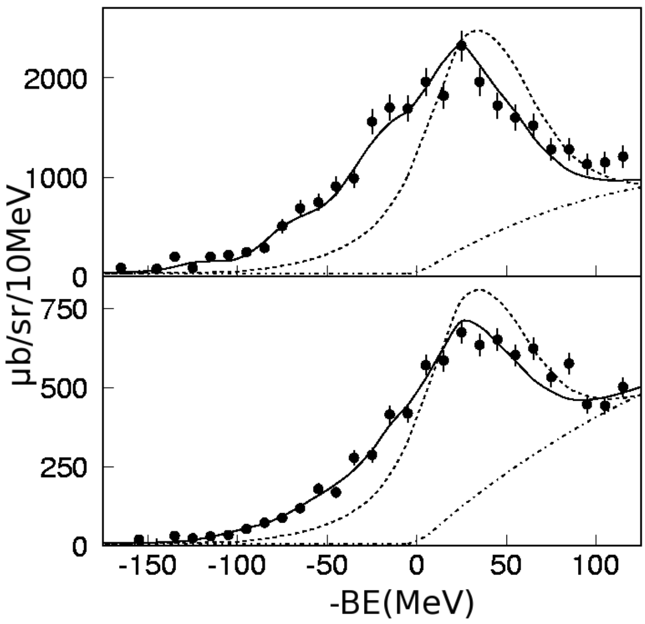

Figure 3: Missing mass spectra of the ^{12}C(K^-, n) reaction (upper) and ^{12}C(K^-, p) reaction (lower). The solid curves represent the calculated best fit spectra for potentials with Re(V)=-190 MeV and Im(V)=-40 MeV (upper) and Re(V)=-160 MeV Im(V)=-50 MeV (lower). The dotted curves represent the calculated spectra for Re(V)=-60 MeV and Im(V)=-60 MeV. The dot-dashed curves represent a background process (see main text).

condensation on neutron stars at around 2-3 times normal nuclear density.

It has to be noted that our experiment is based on the reaction which is well understood. The observed cross section is consistent with theoretical calculation with experimentally known elementary cross sections. Theoretically calculated spectra with the best potential depth can give reasonably good fit to the experimental data. Furthermore the best fit potential depth is consistent with one of two suggested by the study of kaonic X-ray data.

X particle search

Search for X particle was carried out as a parasite experiment. The experiment was motivated by the penta quark. There was suggestion that it may be due to bound state of kaon, pion and nucleon. In order to make it reality, one needs to have strongly attractive interaction between kaon and pion. It may be possible that the strong attractive interaction make the bound state which we call X particle. We searched for the $X \to K^+\gamma\gamma$ process where X is produced by the K^+ induced reaction. The experimental setup was almost the same as that for kaonic nuclei. Difference is that K^+ beam was used instead of K^- and the neutron detector was not used. The brief description of X particle search can be found in Ref [15, 1, 16] and the details are also given by Y. Mitoma's Master Thesis[19]. We need further time to extract results from the experiment.

Publications

Publications related to the present research are as follows.
Ref. [7] is the motivation of the present experiment.
Ref. [10, 11] report our early study based on BNL test experiemnt and preparation for the E548 experiment.
Ref. [18] reports the present result.
We are preparing paper to report whole results our from both ^{12}C and ^{16} targets.

Thesis.
T. Hayakawa, Doctor thesis, Osaka University (2007)
Y. Mitoma, Master thesis, Osaka Univsesity (2005)

References

[1] T. Kishimoto *et al.* KEK-PS proposal E548, (2004)
[2] T. Kishimoto and T. Sato, Prog. Theo. Phys. **116** (2006), 241.
[3] D. B. Kaplan and A. E. Nelson, Phys. Lett. B **175** (1986), 57.
[4] G. E. Brown, Nucl. Phys. A **574** (1994),217.
G. E. Brown and M. Rho, Phys. rep. **269** (1996), 333.
C. H. Lee, Phys. rep. **275** (1996), 255.
[5] C.J. Batty, E. Friedman and A. Gal. Phys. rep. **287** (1997), 385 and references therein.
[6] J. Mares, E. Friedman and A. Gal, Phys. Lett. B **606** (2005), 295; Nucl. Phys. A **770** (2006), 84.
[7] T. Kishimoto, Phys. Rev. Lett. **83** (1999), 4701.
[8] T. Suzuki *et al.* Phys. Lett. B **597** (2004), 263.
[9] T. Suzuki *et al.* Nucl. Phys. A **754** (2005), 375c.
[10] T. Kishimoto *et al.* Prog. Theo. Phys. **149** (2003), 264.
[11] T. Kishimoto *et al.* Nucl. Phys. A **754** (2005), 383c.
[12] M. Agnello, *et al.* Phys. Rev. Lett. **94** (2005), 212303.
[13] E. Oset and H. Toki, Phys. Rev. C **74** (2006), 015207.
[14] T. Hayakawa *et al.*, OULNS annual report (2003).
[15] T. Hayakawa *et al.*, OULNS annual report (2004).
[16] T. Kishimoto *et al.*, KEK-PS Proposal E548 (request for extension), (2004).
[17] O. Morimatsu and K. Yazaki, Nucl. Phys. A **435** (1985), 727; ibid, (1988), 493.
[18] T. Kishimoto *et al.* Prog. Theo. Phys. **118** (2007), 181.
[19] Y. Mitoma, Master Thesis, Osaka Univ., (2005).