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KEK Preprint 97-197
October 1997
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T. NAGAE

5w9827

*Invited talk at the 15th International Conference on Few-Body Problems in Physics,
Groningen, The Netherlands, 22 - 26 July, 1997.*

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Few-Body Hypernuclear Systems

Tomofumi Nagae^a

^aHigh Energy Accelerator Research Organization (KEK),
1-1 Oho, Tsukuba, Ibaraki 305, Japan

Recent experimental efforts on hypernuclei at KEK and BNL have been extending the research field of baryon many-body systems in the flavor SU(3) world. Regarding Σ -hypernuclei, two recent experiments, E887 and E905, at BNL-AGS have drawn important conclusions concerning the narrow-width problem and the bound-state problem of Σ -hypernuclei based on the high-statistics data of the ${}^9\text{Be}(K^-, \pi^\pm)$ and ${}^4\text{He}(K^-, \pi^\pm)$ reactions. There has also been an attempt to determine the binding energy of light double- Λ hypernuclei. These new data on few-body hypernuclear systems may reveal new interesting aspects from the viewpoint of baryon few-body systems.

1. INTRODUCTION

The study of hypernuclei is an extension of studies of the baryon many-body system into flavor SU(3). Still, our knowledge concerning hypernuclear systems is limited compared with that of normal nuclei. The most familiar system investigated so far is Λ -hypernuclei. Even for Λ -hypernuclei, the number of observed bound states is less than 100, and the number of spin-assigned states is less than 10. These are two orders of magnitude less than those of normal nuclei, and these data are mainly obtained for light hypernuclei. However, they are significantly increasing owing to the recent efforts at KEK and BNL. The high-intensity K^- beams now available at BNL-AGS, in particular, enable us to extend our study into new systems such as Σ -hypernuclei, double- Λ hypernuclei, and Ξ -hypernuclei.

In this paper, a report is given on what kinds of data are now available for few-body hypernuclear systems, or will be available in the near future. After a short discussion about the general interests in few-body hypernuclear systems, the recent topics concerning Σ -hypernuclei are discussed based on the very high-statistics data obtained in two recent experiments at BNL-AGS, E887 and E905. Then, new efforts to study double- Λ hypernuclei are introduced at the end.

At present, there are two major directions in studying hypernuclei, from a personal view.

One is to pursue the high-resolution spectroscopy on Λ -hypernuclei. At this moment, the best energy-resolution data are being produced at KEK by using the SKS spectrometer[1]. The energy resolution is about 2 MeV(FWHM). However, there are several projects to overcome this energy resolution. At BNL, there is presently an experiment to obtain data from the (stopped K^-, π^0) reaction by using a high-resolution π^0 spectrometer, NMS, which aims to achieve an energy resolution of better than 1 MeV. At Thomas Jefferson

Lab., the $(e, e'K^+)$ measurement is in progress, with an energy resolution of better than 1 MeV. There is also another attempt to use the (stopped K^-, π^-) reaction at DAΦNE. At KEK, we are constructing a Ge detector system to measure the hypernuclear gamma-ray transitions with an energy resolution of a few keV!

The other direction is to extend the strangeness nuclear world by using the high-intensity K^- beam, which is the main subject of this paper.

1.1. General interests in few-body hypernuclei

The few-body hypernuclei discussed here are not really a few-body system, strictly speaking. They are many-body systems comprising a few-body nucleus and one (two) hyperon(s), or a few clusters (d, t, α) and one (two) hyperon(s). Still, we could apply the theoretical methods developed for the few-body problem with minor modifications for these few-body hypernuclear systems. For example, important insights have been obtained in the studies of the hyper-triton(${}^3_\Lambda\text{H}$) binding energy [2], charge-symmetry breaking in the ${}^4_\Lambda\text{H}$ - ${}^4_\Lambda\text{He}$ binding energy [3], etc.

Some other interesting features in few-body hypernuclear systems are suggested from the view point of a cluster-model approach. First, a Λ hyperon plays a glue-like role in a core nucleus. For example, while ${}^5\text{He}$ and ${}^8\text{Be}$ are unbound, these unbound states become particle-stable in ${}^6_\Lambda\text{He}$ and ${}^9_\Lambda\text{Be}$ due to the existence of a Λ hyperon. Therefore, spectroscopic studies are available for these bound states. Further, the inter-cluster distance may change because of this energy stabilization, as shown in Fig. 1, which results in a big change of the E2-transition rates ($B(E2)$).

Figure 1. Calculated inter-cluster distances in the low-lying states of ${}^9_\Lambda\text{Be}$, ${}^8_\Lambda\text{Li}$, and ${}^7_\Lambda\text{Li}$, and those of the corresponding core nuclei [4].

The other interesting aspect is that new symmetry appears in the few-body hypernuclei because a hyperon is distinguishable to nucleons. Here is an example of such new states in ${}^9_\Lambda\text{Be}$. In ${}^9\text{Be}$ ($2\alpha+n$), a neutron in the p-orbit can only have motion perpendicular to the two α -cluster axis, while the motion along the two α -cluster axis is not allowed because

of the Pauli principle. In contrast, the energy levels corresponding to this motion would appear in the energy spectrum of ${}^9_{\Lambda}\text{Be}$. These states are called *genuine hypernuclear states* (see Fig. 2) [4].

Figure 2. Orbital motions of a Λ hyperon in the low-lying states of ${}^9_{\Lambda}\text{Be}$ with the $\alpha+\alpha+\Lambda$ cluster model. The bottom one is not allowed in ${}^9\text{Be}$, and only appears in ${}^9_{\Lambda}\text{Be}$.

These are the interesting aspects of the few-body hypernuclei predicted in several theoretical calculations, which should be verified in future experiments. The experimental data needed to search for the genuine hypernuclear states in the ${}^9\text{Be}(\pi^+, K^+)$ reaction have recently been obtained at KEK (KEK-PS E336), and are being analyzed. Also, a proposal to measure $B(E2)$ in ${}^7_{\Lambda}\text{Li}$ (KEK-PS E419) has recently been approved.

2. Σ -HYPERNUCLEI

Λ -hypernuclei have been rather intensively studied since their discovery in 1952. We have various information on many ground states and several excited states, mainly for light Λ -hypernuclei. Information concerning heavy Λ -hypernuclei is also available now [5].

In comparison, experimental data on Σ -hypernuclei have been very limited in statistical quality and the number of hypernuclear species studied. This is mainly due to the limited K^- beam flux so far available. The recent rapid increase in the primary proton intensity at BNL-AGS has greatly improved this situation in studies of Σ -hypernuclei. Almost one order of magnitude higher statistics data have been produced in two recent experiments, E887 and E905.

Before these high-statistics data, the theoretical and experimental situation was well reviewed by Dover, Millener, and Gal [6] in 1989. The main issue at that time in the study of Σ -hypernuclei was the “narrowness” of the Σ -hypernuclear states.

2.1. Narrow-width problem

Information concerning a Σ -nucleus potential has been extracted using the Σ^- -atom X-ray data: the shifts and widths of the X-ray peaks. Assuming a naive potential form proportional to the nucleon density, the potential depth at the nuclear center is estimated to be $-(25\sim 30)$ MeV for the real part and $-(10\sim 15)$ MeV for the imaginary part [7]. Thus, the width of a Σ -hypernuclear state was expected to be too large (20~30 MeV) to be observed as a clear peak, due to the strong $\Sigma N \rightarrow \Lambda N$ conversion process.

In this context, it was surprising that the Saclay-Heidelberg group reported two narrow structures in the unbound region of the ${}^9\text{Be}(K^-, \pi^-)$ spectrum [8]. The spectrum is shown in Fig. 3.

Figure 3. Λ -(Top) and Σ -(Bottom) hypernuclear spectra in the ${}^9\text{Be}(K^-, \pi^-)$ reaction at $p_K = 720 \text{ MeV}/c$, $\theta = 0^\circ$, from Bertini *et al.* [8].

Based on a comparison with the ${}^9_{\Lambda}\text{Be}$ spectrum, they claimed that there were two peaks with a width of less than 8 MeV. Thereafter, the problem of the narrow width of Σ -hypernuclear states has been intensively studied both theoretically and experimentally. Experimental data were obtained on ${}^6\text{Li}(K^-, \pi^\pm)$, ${}^7\text{Li}(K^-, \pi^-)$, ${}^{12}\text{C}(K^-, \pi^\pm)$, and ${}^{16}\text{O}(K^-, \pi^\pm)$ (See the references in [6]) at CERN, BNL, and KEK in 1980's. Several nar-

row peaks in the unbound region were reported. However, no experiments could confirm the narrow structures in much better statistics than the original ${}^9\text{Be}$ data; in some reactions they found no such structures.

In 1994, after 14 years from the first ${}^9\text{Be}$ experiment, about ten-times better statistics have been accumulated in the ${}^9\text{Be}(K^-, \pi^-)$ reaction in BNL-AGS E887, which was carried out at the C6 beam line by using the Moby Dick spectrometer [9].

Figure 4. Spectra of the ${}^9\text{Be}(K^-, \pi^\pm)$ reactions at $p_K = 600 \text{ MeV}/c$, $\theta = 4^\circ$.

As shown in Fig. 4, we found no such narrow structures above the binding threshold, nor in the ${}^6\text{Li}(K^-, \pi^\pm)$ reaction. By implication, we could exclude all previously claimed examples of such narrow structures, because they are all statistically weaker than the first ${}^9\text{Be}$ data.

Thus, the problem concerning the narrow widths of the Σ -hypernuclear states in the unbound region has been negatively resolved experimentally.

Here, it is mentioned that we also have a ${}^9\text{Be}(K^-, \pi^+)$ spectrum. At first glance, it seems that the spectrum has just a simple quasifree shape. However, the difference in the quasifree shapes between ${}^9\text{Be}(K^-, \pi^-)$ and ${}^9\text{Be}(K^-, \pi^+)$ is very remarkable. Simple calculations based on a quasifree model suggest that the difference is too large to be explained with a simple quasifree picture [10].

2.2. Bound-state problem

Still, the well depth of the real part of the Σ -nucleus potential was not fully understood at that time. There exists a large ambiguity to extract it only from the Σ^- -atom X-ray data, which is not sensitive to the potential form inside a nucleus. A recent reanalysis using a potential form non-linear in the nucleon density suggests that there exist no bound states in heavy nuclear systems. It predicts a very shallow potential or a repulsive potential for the real part, so that Σ is not bound any more. Therefore, it is essential to measure the binding energies of the Σ -hypernuclear bound states, if any, in order to answer the following question: how deep is the real part of the Σ -nucleus potential?

Evidence of a bound state of ${}^4_\Sigma\text{He}$ was reported by Hayano *et al.* in 1989 in the (stopped K^-, π^-) reaction [11]. This is the only example of a *bound* Σ -hypernucleus so far observed.

Figure 5. Spectrum of the ${}^4\text{He}(\text{stopped } K^-, \pi^-)$ reaction [12]. A bump structure (c) just below the threshold corresponds to the bound state of ${}^4_\Sigma\text{He}$. The components (e), (f1) and (f2) correspond to the decay backgrounds from Λ 's and Σ 's.

There exist, however, some difficulties to obtain the binding energy and the width of the bound state both theoretically and experimentally. The ambiguity in the initial wave function of atomic K^- orbits from which the kaon is absorbed gives us different spectrum shapes in theoretical calculations. This results in the ambiguity to extract the potential depths. Experimentally, as shown in Fig. 5, there is a large experimental background under the bump structure to be subtracted. In the (stopped K^-, π^-) reaction, the momentum range of pions from the decays of Λ and Σ produced in the quasifree process overlaps the bound region of the Σ -hypernucleus. Because of these ambiguities, there has been no conclusive answer to the question whether this bump structure is the bound state or not.

In contrast to the (stopped K^-, π^-) reaction, since the reaction mechanism of the in-flight (K^-, π^-) reaction is simple, theoretical calculations are more reliable. Also, the large background of pions from the decays of Λ and Σ is out of range in momentum.

Therefore, the E905 experiment at BNL-AGS was carried out at 600-MeV/c K^- incident momentum for ${}^4\text{He}(K^-, \pi^\pm)$ reactions. We took the data in March and April, 1996.

As for the (K^-, π^-) reaction, the main background comes from the three-body decays of K^- in-flight (K_{e3} and $K_{\mu 3}$). Therefore, good particle identification of pions from electrons and muons is necessary. In E905 and E887, these backgrounds are almost completely rejected by using a time-of-flight hodoscope and a muon range filter.

Figure 6. Spectra of the ${}^4\text{He}(K^-, \pi^\pm)$ reaction at $p_K = 600 \text{ MeV}/c$, $\theta = 4^\circ$ obtained in E905. A clear peak is found in the bound region only in the ${}^4\text{He}(K^-, \pi^-)$ spectrum.

As shown in Fig. 6, we could confirm the existence of the bound state as a clear peak below the Σ -binding threshold in the ${}^4\text{He}(K^-, \pi^-)$ reaction. No peak is found in the ${}^4\text{He}(K^-, \pi^+)$ reaction, as in the ${}^4\text{He}(\text{stopped } K^-, \pi^+)$ reaction. Since the ${}^4\text{He}(K^-, \pi^-)$ reaction can populate both $T=3/2$ and $T=1/2$ states while the ${}^4\text{He}(K^-, \pi^+)$ reaction can only produce $T=3/2$ final state, the experimental data suggest this ${}^4_2\text{He}$ bound state has $T=1/2$. The existence of this $T=1/2$, $S=0$ bound state in ${}^4_2\text{He}$ was first predicted by Harada *et al.* [13]. The unique nature of this state is due to the large isospin dependence in their potential. The $T=1/2$ state is attractive while the $T=3/2$ state is strongly repulsive (see Fig. 7). The existence of a central repulsion in the Σ -nucleus potential reduces the

overlap between the Σ wave function and the core nucleus, which results in the reduction of the conversion width due to the $\Sigma N \rightarrow \Lambda N$ process.

Figure 7. The Σ -nucleus potentials for the isospin $T=1/2$ and $T=3/2$ states in the ΣNNN system calculated by Harada *et al.* [13]. The solid and dotted lines are the real and the imaginary parts, respectively. The potential between a core nucleus and a Σ particle is expressed as $U_{C\Sigma}(R) = U^0(R) + U^\tau(R)(T_C \cdot t_\Sigma)$, in which the second term, U^τ , is the Lane term.

As can be seen in Fig. 6, the bound-state peak rests on a large continuum. The magnitude of this continuum is too large to be explained with the one-step Λ -quasifree process alone. It is likely that we need to take into account two-step processes and other complex processes in such a high-excitation region well above the Λ -production threshold. Since we have no available theoretical models for such processes at this moment, we applied several phenomenological shapes to fit the tail. From these fits we found that the peak position was rather stable, while the peak width was somewhat dependent on the background shapes. Thus, we obtained a binding energy of $4.4 \pm 0.3(\text{stat.}) \pm 1(\text{sys.}) \text{ MeV}$

and a width(FWHM) of $7 \pm 0.7(\text{stat.})^{+1.2}_{-0.0}(\text{sys.})$ MeV. The experimental energy resolution is taken into account in extracting the width.

3. DOUBLE- Λ HYPERNUCLEI

There exist two old emulsion events [14,15] of double- Λ hypernuclei obtained in 1960's. (The identification of one event in Ref. [15] is not convincing.) A recent observation at KEK in 1991 [16], using a hybrid-emulsion technique, reconfirmed the existence of a double- Λ hypernucleus. This time, however, they could not definitely determine the binding energy because of the ambiguity in interpreting the event. Thus, still we do not know whether the Λ - Λ interaction is attractive or repulsive.

Figure 8. Energy spectrum of various $S=-2$ systems: Ξ -hypernuclei and double- Λ hypernuclei, etc.

Also, studies concerning double- Λ hypernuclei have attracted much interest regarding the existence of a predicted stable dibaryon (H). If the mass of the H is smaller than $2M_{\Lambda} - B_{\Lambda\Lambda}$, where $B_{\Lambda\Lambda}$ is the binding energy of two Λ 's in a nucleus, a double- Λ hypernucleus will decay into the H (+residual nucleus) through a strong interaction. Therefore, the observation of the weak decay of a double- Λ hypernucleus excludes the H in that mass

region. In order to produce double- Λ hypernuclei we use Ξ^- quasifree production via the $K^-p \rightarrow K^+\Xi^-$ reaction. Since the reaction is a two-body reaction, it is easy to tag the Ξ^- production by measuring the (K^-, K^+) reaction kinematics. The recoil momentum of the Ξ^- is around 500 MeV/c. The problem is how to put this $S=-2$ particle, Ξ^- , into a nucleus.

The way emulsion people proceeded was to stop the Ξ^- 's onto other nuclei by degrading the energy through thick materials. When a Ξ^- stops, it forms a Ξ^- -atom, and is absorbed via the reaction $\Xi^-p \rightarrow \Lambda\Lambda$. However, in this method, most of the Ξ^- 's produced decay before stopping (mean life of Ξ^- is 1.64×10^{-10} sec.).

In our experiment, BNL-AGS E906, we employ a different process: using the direct production of double- Λ hypernuclei at the (K^-, K^+) reaction point. Since the mean-free-path of the Ξ^- in a nucleus would not be very large, some fraction of the produced Ξ^- would lose energy inside of the nucleus where the Ξ is produced, by knocking out a few nucleons. Then, the Ξ^- could be absorbed via the reaction $\Xi^-p \rightarrow \Lambda\Lambda$ ($Q=28$ MeV). Again, the mean-free-path of the Λ 's is not very large. Moreover, the released energy, 28 MeV, would be compensated if a proton in an α -cluster is involved in the absorption process, because of the large separation energy. This mechanism also enhances the production rate of light double- Λ hypernuclei; such as ${}^5_{\Lambda\Lambda}H$, ${}^6_{\Lambda\Lambda}He$, and so on. Therefore, we can expect formation of highly-excited hypernuclear states with two Λ 's inside. We call these states *double- Λ compound states*. The formation probability of the compound states is estimated to be 0.3–0.9% per (K^-, K^+) reaction for a ${}^{12}C$ target [17], depending upon the strength of the Ξ^- -nucleus potential. The decay process of the compound states is treated in a statistical way, taking into account the different Q -values in various decay modes. A theoretical calculation suggests an $\sim 50\%$ formation probability of ${}^5_{\Lambda\Lambda}H$ and a 10–20% formation probability of ${}^6_{\Lambda\Lambda}He$ from the compound states. Thus, in total, a formation rate on the order of 0.1% is estimated for light double- Λ hypernuclei. This formation rate is not very small, if the high production rate of Ξ^- 's at BNL-AGS is considered, which is $\sim 10^7$ Ξ^- 's for 1000 hours. Therefore, $\sim 10,000$ double- Λ hypernuclei would be produced during ~ 1000 hours.

The identification of a double- Λ hypernucleus is carried out by detecting two sequential weak decays emitting two π^- 's. This is a unique signal of a double- Λ hypernucleus production. For example, ${}^5_{\Lambda\Lambda}H \rightarrow \pi^- + {}^5_{\Lambda}He$, ${}^5_{\Lambda}He \rightarrow \pi^- + p + {}^4He$. A main background process is the free decay of a Ξ^- via $\Xi^- \rightarrow \pi^- + \Lambda$, $\Lambda \rightarrow \pi^- + p$, which would be easily suppressed with decay-vertex cuts. The binding energy of the double- Λ hypernuclei can be determined by precisely measuring the pion energy [18]. For light double- Λ hypernuclei, some have large branches of two-body mesonic decays, in which the pion energy is mono-energetic. In some cases, the pion energy is almost mono-energetic, even for three-body decays, owing to the resonance formation in the final state.

For this purpose, we constructed a cylindrical detector system (CDS) at the BNL-AGS 2-GeV beam line D6. It comprises a solenoid magnet of 5 kG, a cylindrical drift chamber, a cathode-readout Z-chamber, and a cylindrical trigger hodoscope. The CDS covers $\sim 70\%$ of 4π solid angle; the momentum resolution would be better than 3 MeV/c(FWHM) for 100 MeV/c pions, which would enable us to measure the binding energy of double- Λ hypernuclei with better than 0.5 MeV resolution. The CDS was installed in the beam line in April, 1997. We checked the performance of the CDS during the beam time from

Figure 9. Possible scenarios to produce and detect double- Λ hypernuclei.

April to June, 1997, and spent about 1/7 of the approved beam time.

Figure 10 shows some typical events observed in the CDS for the ${}^9\text{Be}(K^-, K^+)$ reaction. The analysis is very preliminary. We will take the rest of the data in 1998.

Figure 10. Typical events observed in the CDS for the ${}^9\text{Be}(K^-, K^+)$ reaction. The event at the top would correspond to a free decay of a Ξ^- , in which the tracks of two π^- 's and one proton are detected.

4. SUMMARY

Studies on new kinds of few-body hypernuclear systems are in progress at KEK and BNL. In particular, the recent rapid increase of the K^- beam intensity at BNL enables us to take high-statistics data on Σ -hypernuclei and to explore $S=-2$ systems, such as double- Λ hypernuclei.

Regarding Σ -hypernuclei, the high-statistics data of E887 and E905 established two important facts:

1. There is no narrow structure in the unbound region;
2. There is a bound state of ${}^4_2\text{He}$ observed in the ${}^4\text{He}(K^-, \pi^-)$ reaction.

Thus, the next question is whether any further bound states of Σ -hypernuclei exist or not. It should be noted that so far we have several high-statistics data which show no peaks in the (K^-, π^+) reaction, and no high-statistics data in the (K^-, π^-) reaction. The E905 data suggest that we need more high-statistics data for other nuclei in the (K^-, π^-) reaction in order to search for any other bound states in light nuclei. The existence of heavy Σ -hypernuclei is still unclear. The accumulation of bound-states data of Σ -hypernuclei would make our prediction more reliable. There is an idea that Coulomb-assisted bound states may exist in heavy Σ -hypernuclei [19].

An experiment (E906) to determine the binding energy of double- Λ hypernuclei is now going to accumulate data with a large solid-angle CDS. If it succeeds, it would be the first glimpse of Λ - Λ interaction, and would put a stringent limit on the H dibaryon mass.

The author would like to thank all the collaborators of BNL-AGS E887, E905, and E906; Drs. R.E. Chrien, R. Sawafta, and T. Fukuda, especially.

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