ISSN 1330–0016
CODEN FIZBE7

STRANGE NUCLEAR PHYSICS – A BRIEF STATUS REPORT

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Received 11 January 1999; Accepted 12 July 1999

This paper briefly reviews the present status of strange nuclear physics. Recently, significant progress has been made. One example to be discussed is a new, electroproduction experiment which offers the possibility of obtaining Λ hypernuclear spectra with at least a factor of 3 better resolution than previously. However, many different experiments have an impact on a broad spectrum of problems from weak interactions to astrophysics. Although in this short paper it is not possible to cover many topics in depth, sufficient information is provided so that the interested reader can obtain all of the most relevant material.

PACS numbers: 21.80.+a, 25.20.-x UDC 539.126

Keywords: strange nuclear physics, Λ hypernuclear spectra, high resolution

1. *Introduction*

A brief review is given of the present status of the field of strange nuclear systems, followed by an outline the most promising areas for future research. As this may be of most interest here, we will comment in particular on the upcoming electromagnetic experiments which will provide substantial new information.

While this field is some 45 years old, it has progressed relatively slowly, mostly due to the lack of appropriate experimental facilities. However, in recent years, the implementation of magnetic spectrometers coupled with intense, energetic beams of pions, and kaons, has accelerated the investigation of light-mass Lambda and Sigma hypernuclei [1], i.e. nuclei which contain one Λ or Σ hyperon. These experiments have demonstrated that a Λ particle essentially retains its identity in a nucleus, and opened a spectroscopy based on a new hadronic symmetry, strangeness [2]. Thus, a hypernucleus can be viewed at some level of approximation as a collection

[1] Supported in part by the US DOE

of baryons having both isospin and strangeness symmetries [3], and if the Λ retains its identity within a nucleus, it resides, as an identifiable particle, deeply within the nuclear interior [4].

Experimentally, several ground and excited states, particularly of the 1p-shell hypernuclei, have been identified [1], and a few electromagnetic transitions between these states have been measured [5]. Here, one should note that a free Λ decays with a meanlife of 2.6×10^{-10} s, and although this is not the dominant decay mode of heavier hypernuclei, it does mean that such systems have long lifetimes compared to both the strong and electromagnetic interactions. On the other hand, narrow (≤ 2 MeV), Sigma-nuclear states are not observed to exist [1] due to the strong interaction of the Σ hyperon with the other nucleons via the Σ N $\rightarrow \Lambda$ N reaction. Unfortunately, then, a spectroscopy of Σ-nuclear systems is not possible.

Much less is known about cascade or multi-hyperon hypernuclei [6]. A few emulsion events have been interpreted as multi-strange nuclei, but accelerator-based counter experiments have not been successful in observing the creation of such systems. However, the search for multi-strange systems is extremely important, as at somewhat higher than normal densities, it is generally believed an equal mixture of strange and non-strange baryons forms the lowest energy configuration. This means that neutron stars, for example, should really be called strange objects [7].

In the future, electroproduction of hypernuclei promises to provide a new, high-precision tool to study Λ-hypernuclear spectroscopy, with resolutions of several hundred keV [8]. In addition, the study of electromagnetic decays of hypernuclear levels using large solid-angle Ge-detectors, should help to define the spectra of the lighter Λ hypernuclei [9]. It is also possible that more intense beams of kaons and heavy-ions, coupled with new detection technologies, may provide the means to detect multi-hyperon hypernuclei [10]. Finally, although there have been a few previous experiments, the study of the weak decay of Λ hypernuclei provides a high momentum process which probes, at short distances, the interior environment of a nucleus [11]. Such information about static behavior deep within a nucleus is essentially impossible to obtain by other means.

To conclude, it is of little interest to extensively reproduce nuclear structure with hyperons, but strangeness in nuclei can provide a unique tool to study many aspects of the hadronic many-body problem. Thus, by a selective choice of experiments, one can illuminate specific issues in hadronic systems which would be difficult to study by other means. We briefly discuss a few of these below.

2. Search for a consistent set of effective p-shell parameters

Spectroscopy of lambda hypernuclei has identified a number of hypernuclear states in the 1s- and 1p-shells, and at least the major shell structures of heavier systems. Indeed, analysis of these shell-model levels has shown that at least the major shell structures can be reproduced by a universal, density-dependent Wood-

Saxon potential (see Fig. 1), confirming the single-particle behavior of a Λ within a nucleus [3,12]. Note, in this figure A is the mass number of the core nucleus. This encourages a more detailed analysis of specific states in the 1s- and 1p-shells.

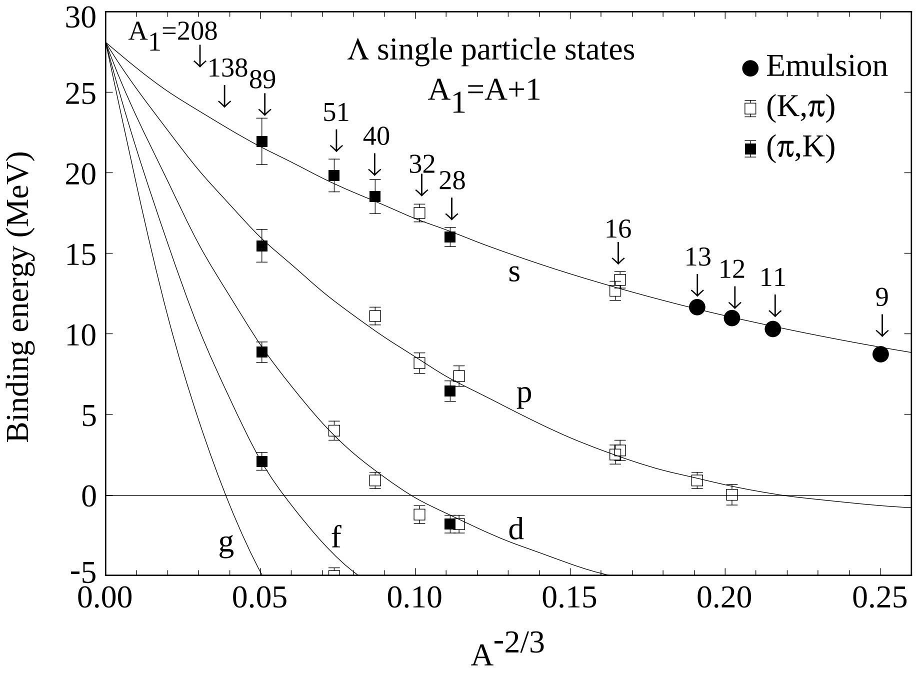

Fig. 1. The binding energy of various hypernuclear shells as a function of $A^{-2/3}$.

The 1s- and 1p-shell states have been analyzed to obtain a parameterization of the effective Λ-Nucleus interaction [13]. This parameterization is obtained from a general two-body Λ-Nucleon potential of the form:

$$V(r) = V_0(r) + V_S\vec{\sigma}_1 \cdot \vec{\sigma}_2 + V_T S_{12} + V_{LS}\vec{L} \cdot \vec{S}^+ + V_{ALS}\vec{L} \cdot \vec{S}^- \, .$$

where S_{12} is the usual spin-spin tensor operator, and $\vec{S}^{\pm}$ represents $1/2(\vec{\sigma}_1 \pm \vec{\sigma}_2)$. The effective Λ-nucleus interaction generated by the above form results in one radial integral which can be incorporated into the potential strengths. This produces a set of constants multiplying the various operators analogous to those defined above. Thus one finds a central, V_0, spin-spin, V_0, tensor, V_T, spin-orbit, V_{LS} and a anti-symmetric spin-orbit, V_{ALS}, parameter. The best values [13] for this parameter set are given in Table 1. One important result of this and previous analyses is the small values for the spin coupling components of the potential. However, contrary to expectation, it has not really been possible to find a consistent set of parameters which can be used to predict all the observed states in the 1p-shell, as the parameters in Table 1 were obtained by ignoring the p-shell binding energies and allowing a change of the spin-spin strength between the s- and the p-shells.

Parity conservation prevents a long-range, one-pion-exchange component in the Λ-N interaction, but higher-mass meson and two-pion exchange compete to create the effective potential. This provides a mechanism to couple an intermediate Σ propagator to the interaction diagrams, and since the long-range component of the force is suppressed, virtual Σ coupling and three-body interaction terms can be significant [14]. This also means that the effective Λ-nucleus potential would be strongly state dependent, since the Σ-N two-body potential depends on spin and isospin, perhaps explaining why the above parameterization fails.

TABLE 1. Parameters for the effective Λ-nucleus potential in the 1p-shell (in MeV*).*

Central	Spin-spin	Tensor	Symmetric spin-orbit	Anti-symmetric spin-orbit
30.	0.3	0.02	-0.02	-0.1

If all this is true, then we may have a clear indication of the need to involve a 3-body nuclear potential. It also means that the strong charge symmetry breaking observed in $A = 4$ hypernuclei, is a state dependent effect, present in all hypernuclear systems. Additional data, particularly the measurement of level splittings through the detection of transition gamma rays, should lead to confirmation of this effect.

3. New reactions

Both (K^-, π^-) and (π^+,K^+) reactions have been previously used to study hypernuclei. The (π^+,K^+) first explored at BNL [14], has been particularly effective, populating deeply bound states in heavier hypernuclei. However, the best resolution obtained for this spectroscopy is about 2 MeV (FWHM) on a C target [16]. The resolution degrades as the target mass increases due to multiple scattering and energy straggling.

Recently, an experiment has demonstrated that the ($K^-_{\rm stopped}, \pi^0$) reaction [17] can also be used. This reaction replaces a proton, instead of a neutron, by a Λ, and thus can produce hypernuclei, charge symmetric to those previously studied. Mirror hypernuclear pairs can be used to study charge-symmetry breaking, and perhaps by comparison of mirror pairs, extract a hypernuclear radius. In a stopped K reaction, the contribution of the beam to the energy resolution is removed, so by observing the decay of the π^0 into two photons, thick targets may be used as the π^0 energy is obtained from the opening-angle geometry, not from calorimetry. It is estimated that a resolution of about 1 MeV can be obtained. For example, Fig. 2 shows the resolution from a recent calibration measurement [18] of the $K^+_{\rm stopped} \to \pi^0\pi^+$ decay. Analysis of data taken on the $^{12}C(K^-_{\rm stopped}, \pi^0)^{12}_{\Lambda}B$ reaction are now proceeding [18].

There is the expectation that electromagnetic production of hypernuclei, (e,e'K$^+$), which also exchanges a proton for a Λ, will provide much more precise studies of hypernuclear structure. Initial experiments in the light systems could reach resolutions between 600 to 700 keV, at least a factor of 3 better than the best resolution achieved with hadronic beams. In addition, the intensity and small dimensions of the electron beam require very small targets (mg of material) allowing the study of almost any separated isotope. It is also possible that with a future, dedicated kaon spectrometer, resolutions could reach the 200 to 300 keV range.

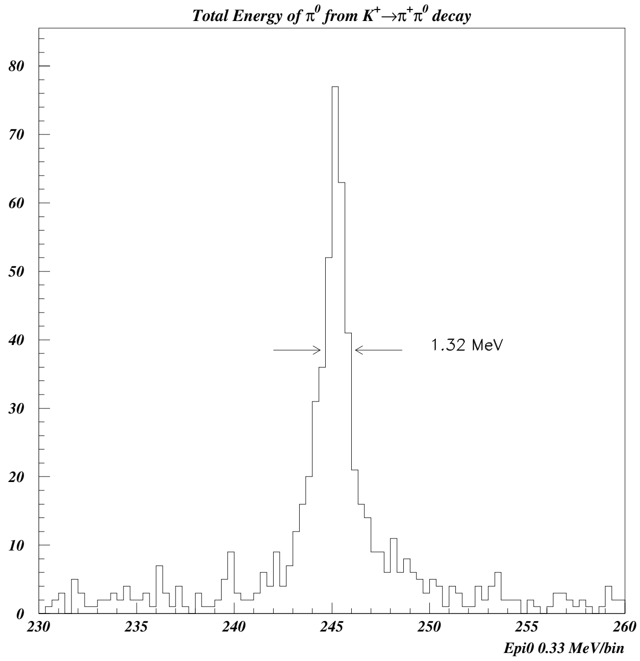

Fig. 2. A spectrum of π^0 from the decay, $\mathrm{K}^+ \to \pi^0\pi^+$, showing the NMS resolution.

An experiment [19] will be mounted at the Jefferson Laboratory in approximately one year to obtain the first precision spectra using the (e,e'K$^+$) reaction with several p-shell nuclear targets. This experiment will employ, for the first time, zero degree electron-tagging, which allows low luminostiy and extremely good resolution. It is expected that the resolution will be about 650 keV, dominated completely by the resolution of the existing Kaon Spectrometer. Future experiments are proposed to measure spectra in s-d shell nuclei.

4. *Weak decay of Λ hypernuclei*

A free Λ decays by pion emission. However, in a hypernucleus, this decay channel is Pauli blocked, and the four-fermion weak-process, $\Lambda\mathrm{N} \to \mathrm{NN}$ dominates. The non-leptonic, strangeness-changing weak decays of free kaons and hyperons are found to be enhanced when the change of isospin is 1/2. This observation is generalized into the "$\Delta I = 1/2$" rule, which states that the non-leptonic decays of all strange hadrons proceeds through $\Delta I = 1/2$ amplitudes [20]. However, there is no universal explanation for this apparently universal rule, and most likely the effect is due to complicated dynamics in the decay process [21]. In fact, the rule may be associated only with long-range pion interactions.

Non-mesonic decays occur through either the proton, Λp $\rightarrow$ np, or neutron, Λn $\rightarrow$ nn, stimulated decays. Because there are spin-isospin correlations between the constituents of light hypernuclei, the $\Delta I = 1/2$ rule makes specific predictions about the neutron to proton stimulated decay ratios. In general, the neutron stimulated decay is calculated to be much smaller than proton decay, but experimentally, although statistics are poor, the rates are found to be equal if not larger for neutron decay [22]. Thus one finds in particular the $^{13}\mathrm{S}_1 \rightarrow {}^{13}\mathrm{D}_1$ tensor transition, which is open only to proton decay because the Λ and interacting nucleons are in the 1s-shell, is expected to dominate the long-range, pion-exchange component of the interaction [24]. Therefore, simple calculations based only on π and ρ exchange exhibit the dominance of proton decays as discussed above. If the experiments are correct, the physics requires an understanding of short range, perhaps quark, effects [23], but certainly precision measurements of the partial decay rates on non-mesonic hypernuclear decays are needed.

A test of the $\Delta I = 1/2$ rule is in progress at BNL. As the experiment is difficult, the results will not be available for some time.

5. *Multi-strange nuclear systems*

From the point of view of the conventional many-body problem, a study of the hyperon-hyperon interaction is important, and this can only be done within a multi-strange hypernucleus. One is reminded here of the recent attempts to find the H dibaryon [25], whose absence in the experimental data must be telling us something about hyperon-hyperon interactions. Of course a direct study of hyperon-hyperon scattering would be extremely valuable, but because these particles have very short lifetimes, this is impossible. Still, there are emulsion events which have been interpreted as either cascade or double-Lambda hypernuclei. These events, if interpreted correctly, do give a well depth for the $\Lambda - \Lambda$ potential [26], but the interpretations are open to debate. Clearly, much more experimental information must be obtained on his subject.

One of the most interesting results of theoretical studies on multi-strange systems is that strange nuclei with $S \approx A$ could be stable with respect to both the strong and weak interactions. This would occur at somewhat higher than nuclear matter density, but if true, some neutron stars might evolve into strange stars composed of nucleons, hyperons, and leptons, or perhaps even into a "soup" of unconfined up, down and strange quarks. The only way to expermentially investigate such systems is to use collisions of relativistic heavy ions, but to date no evidence of these so called "strangelets" has been found. Such collisions do apparently produce an excess of strange particles, so the experimental observation of strangelets may only require finding a sufficiently sensitive experiment.

6. Conclusion

The physics of strangeness in nuclei is not merely an extension of convential nuclear physics. As examples: we expect to find new degrees of freedom, providing new types of states which allows us to expand our understanding of the hadronic many-body problem. The weak decay of hypernuclei introduces a four-fermion weak vertex, which is only present in these decays. It provides information on both the parity conserving as well as the parity non-conserving weak amplitudes. Given that these decays occur locally within the nucleus, it provides a probe of the nuclear interior. Finally, multi-strange nuclear systems are extremely interesting, as they may be the true ground state of neutron stars. Therefore, as new beams and apparatus become available, this field will continue to expand.

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STRANA NUKLEARNA FIZIKA – KRATAK PREGLED

Kratko se raspravlja o stranoj nuklearnoj fizici. Nedavno je načinjen važan napredak. Primjer koji se raspravlja je novo mjerenje elektrotvorbe koje pruža mogućnost za dobivanje Λ hiperjezgri s razlučivanjem boljim barem tri puta od dosadašnjih. Međutim, mnoga se različita mjerenja sučeljavaju s nizom teškoća od slabih međudjelovanja do astrofizike. Ovdje se ne raspravljaju podrobnije mnoge teme, ali se izlažu podaci kojima se može dobiti najveći dio povezane građe.