The status of strange particle physics

A summary of the 9th International Conference on Hypernuclear and Strange Particle Physics

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Abstract. The 9th International Conference on Hypernuclear and Strange Particle Physics was held at the University of Mainz during October 10-14, 2006. Approximately 55 years ago the concept of strangeness as a quantum number, and almost simultaneously, hypernuclear physics was born. A perspective of the status of this field as of 2006 is best achieved by directly reviewing the contributions to this conference as published in this volume. It is impossible to summarize the breadth strangeness in nuclei in a few pages, so that this short review can only present the author's personal flavor on its status at the close of 2006.

1 Introduction

Aside from reports of more recent developments, the conferees were reminded of the contributions of R. H. Dailtz through a Dalitz Memorial Session [1,2]. Dalitz was instrumental in shaping the development of our field, and sadly, died this past year. Among many of his contributions, this author recalls that Dalitz used the new graphic tool that bears his name (the Dalitz Plot) as early as 1959, to predict the existence of the $\Lambda(1405)$ resonance [3].

The conference also reminded all of us that technology in both experiment and theory drives the ability to explore physical processes, and that the exploitation of a new pathway requires the ingenuity of the researchers in the field. Thus, while the last conference in this series was reviewed from the perspective of standing at the threshold of a new generation of activity [4], the summary of this conference is more directed to an evolutionary view of strangeness nuclear physics.

We owe a great debt to Dalitz and to other pioneers who laid the foundation on which our present structures are built. For example, one has only to review the proceedings of the two Brookhaven National Laboratory workshops held in 1973 and 1976 [5] to understand that much of what we now do was conceived many years ago. In fact, it is amazing when one reads papers from these proceedings as to how modern they still appear.

The following sections briefly describe how far we have been able to proceed along paths previously outlined.

2 Facilities

Early experimental techniques used beams of cosmic rays and nuclear emulsion as detectors. These were replaced some 40 years ago by meson beams from proton synchrotrons and bubble detectors. However, emulsion, because of its spatial and energy resolutions, is still an effective detector for special applications, as indeed it was crucial in the most recent determination of the binding energy of double Λ hypernuclei [6].

More recently, modern accelerators and electronic detectors have been exploited to measure experimental quantities in much more detail. For example, results were reported from the Continuous Electron Beam Accelerator (CEBAF) at the Jefferson National Laboratory (Jlab) [7, 8]. The intensity and beam structure of this accelerator allows a new generation of investigations of hypernuclear spectroscopy and elementary electromagnetic production mechanisms.

In addition, the development of a large array of intrinsic germanium detectors having Compton suppression and high count rate capability (*HYPERBALL*) has advanced hypernuclear gamma spectroscopy to a new level of energy resolution [9]. Clearly, evolving technology has richly illuminated the paths that were previously blazed by early researchers in the field.

In fact, since the previous conference in this field, most of the experimental activity has been associated with electron accelerators. At CEBAF hypernuclear spectroscopy is being explored on low to medium A targets with sub-MeV resolution and reasonable production rates [10]. The magnetic spectrometers will be upgraded to increase their acceptance and improve the resolution. In addition to CEBAF, the FINUDA experiment uses an essentially monochromatic beam of kaons from the almost at rest decay, $\phi \rightarrow K^-K^+$. These ϕ mesons are produced by the DAΦNE e^+e^- collider [11,12]. As FINUDA is a large acceptance detector, it can be employed to observe multi-particle decays after K^- capture in a target, and because of its flexibility, it can be used for many types of experiments. DaΦNE will undergo an upgrade, increasing intensity to become an even more valuable tool for strangeness search [13]. Thus the new experiments at FINUDA hope to observe electromagnetic transitions from hyperfragements, and expect production competitive with the Japanese hadron facility which is now under construction.

Spring8 in Japan provides real photons from laser back-scattering on electrons in a synchrotron light ring. These photons have been used for studies of elementary photo- production of hyperons and hyperon resonances [14]. In addition by the time of next conference in this series, MAMI-C at Mainz will have electron beams with energies of 1.5 GeV, and plan to begin a hypernuclear program similar to the one at CEBAF [15].

However, the absence of a hadron accelerator providing intense beams of energetic kaons has been a hindrance to the exploration of experiments involving double Λ systems and Ξ hypernuclei. This deficiency should be resolved by the next conference in this series, as the Japanese Hadron Facility (JPARC) will be in operational [16]. JPARC will provide a high intensity, 50 GeV proton beam, producing intense beams of kaons and pions that will be dedicated to strangeness physics research.

Finally GSI plans a hypernuclear program using heavy ions and anti-ptotons [17]. Hypernuclei produced by heavy ion reactions recoil with sufficient Lorentz boost to allow hypernuclear lifetime and perhaps magnetic moment measurements. Although production of strange systems by anti-proton reactions has been previously limited to hyperon-antihyperon production, it is also potentially possible to produce multistrange hypernuclear systems through nuclear capture of Ξ^- or Ω^- hyperons. Such a program is proposed for initial research after 2010.

In summary, there is no lack of new technologies which could be exploited. Although most of the new facilities are being constructed in Japan or Europe, there should be significant contributions from multi-national collaborations. Thus this resurgence of interest and the new facilities and detection systems, should provide steady, if not spectacular, growth in the field.

3 The $\overline{\mathrm{K}}$ nucleus interaction —strange nuclear structure at high density

At this conference, the topic of K^--nuclear bound states generated the most heat and perhaps a little illumination [18–23]. $\overline{K}$-nuclear bound states were predicted to be bound by 100-200 MeV and to have very narrow widths (less than 50 MeV). This originated from one of two solutions to the K^--atom interaction which was found to be strongly attractive. Of course the atomic system is sensitive only to the tails of the nuclear density, but it was proposed that if a K^- were placed inside a nucleus, the attraction would compress the nuclear medium to high densities creating deeply bound states [20].

Experimental searches for these states originally yielded structure which was attributed to a confirmation of the hypothesis. However, the KEK observation [19] is now believed to be an experimental artifact, and at least a large part of the FINUDA observation must be due to final state interactions [22]. Yet the theoretical prediction of a K^-NN bound state is reasonably robust. The issue now is what is the binding energy and width of such a state?

There have been several more recent theoretical studies [18,23,22], that shed some light on this issue. In one of these, a realistic short range NN potential having a strongly repulsive core was used in a dynamical calculation. It showed that the density saturates at about twice nuclear density, in contrast to the earlier prediction. Also the $\overline{K}NN \rightarrow YN$ absorption precludes narrow states. Another study also concluded that while a K^-pp state may exist, its binding energy should be less than 70 MeV and have a width of perhaps 100 MeV. At present $\overline{K}$ nuclear states are not yet completely understood, but such structures in heavier nuclei are not excluded.

4 Strange nuclear states at low density

4.1 Introduction

Because the Λ nuclear potential is weak, Λ hypernuclei exist at normal nuclear densities. Therefore strange nuclear structures at nuclear densities involve traditional spectroscopy and decay of nuclear states that can be explained by density independent, many-body calculations.

4.2 Λ hypernuclear structure

Mesonic reactions generally convert neutrons into Λ particle-neutron hole states that can be expressed in terms of a superposition of single particle nuclear states resulting in 5-10 MeV spaced $\hbar\omega$ structures. These can be resolved by the 1-2 MeV resolutions of these experiments. However, it is more difficult to extract levels which involve excitations of the nuclear core, or the hyperfine splitting of the $\hbar\omega$ structures.

Electro-production, $(e;e',K^+)$, creates hypernuclear Λ-particle proton-hole states, charge symmetric to those produced by mesonic reactions. More importantly, electro-production has the potential to produce hypernuclear structure with $\approx$ 500 keV or better resolution [24]. Two initial studies were presented at the conference from experiments in Halls A and C at Jlab, and while both experiments have not yet reached their ultimate resolutions, they presently show excitations with resolutions much better than 1 MeV [7,8].

Here it should be pointed out that while the absolute value of the electron beam momentum is not important, it must remain stable during the experimental live-time, which could be on the order of days. This is because the spectra are produced along a locus line in the 2-dimensional space created by the reaction electron and the kaon momenta. A variation of the beam energy or reaction angles shifts this locus, and the energies and widths of the states. Indeed, the intrinsic resolution of the apparatus can vary across the observed spectrum if, as the data is collected, the system is improperly calibrated and un-monitored.

4.3 Hypernuclear electromagnetic transitions

The use of the *HYPERBALL* apparatus to observe electromagnetic, hypernuclear transitions with keV energies has been an outstanding success [9]. Data taken by this apparatus has been previously presented, but analysis of the data continues [25]. The results show a reasonable definition of the Λ nuclear effective potential for p-shell hypernuclei. Within a nucleus, the effective ΛN interaction can be expressed by the form

$$V(r) = V_0(r) + V_s(S_N \cdot S_Y) + V_t S_{12} + V_{ls}(L \times S^+) + V_{als}(L \times S^-) \quad (1)$$

In this expression $S_{12} = 3(\sigma_1 \cdot \hat{r})(\sigma_2 \cdot \hat{r}) - \sigma_1 \cdot \sigma_2$ is the usual spin-tensor operator, and $S^{\pm} = 1/2(S_N \pm S_Y)$ are symmetric and anti-symmetric combinations of nucleon and hyperon spin operators.

When the parameters, $V_0, V_s, V_{ls}, V_{als}, and V_t$ are extracted from the data, the positions of the various levels are found to be the result of cancellations in the summation of the terms. It is then interesting to observe that reasonable results occur for hypernuclei excitations across the p-shell. This builds confidence that the model and the extracted parameters are generally correct. There are still details to resolve, in particular the absence of the ${}^{10}_{\Lambda}$B ground state transition, and the possibility that V_s may vary across the p-shell [25].

In addition to measuring transition energies, *HYPERBALL* can also determine the electromagnetic life-times of some hypernuclear levels. Such measurements can be used to determine the hypernuclear radius, and perhaps with the higher intensities that might be provided by JPARC, a hypernuclear magnetic moment [9]. One notes however, that in the relativistic mean field model, hypernuclear moments are expected to be near their Schmidt limits, so at least a 10% experimental measurement is desired.

Finally, life-times have been measured using using the Lorentz boost in a heavy ion reaction [26], and an a similar experiment has been proposed at GSI as well as a proposal to measure hypernuclear moments [27].

4.4 Non-mesonic weak decay of hypernuclei

After much theoretical and experimental work, the neutron to proton stimulated decay ratio $\frac{\Gamma n}{\Gamma p} = \frac{\Lambda n \rightarrow nn}{\Lambda p \rightarrow pn}$ seems to be resolved The previous difference between the experimental data and theory apparently was due to final state interactions. Primarily this discrepancy was resolved by detecting the two emitted nucleons in back-to-back coincidence, although the theory has been improved to include heavy meson, e.g σ, exchange [28,29].

Still the weak decay asymmetry measurement does not match theory. While experimentally the asymmetry in the non-mesonic decay of ${}^{12}_{\Lambda}$C is nearly zero (perhaps slightly negative), the decay asymmetry of ${}^{5}_{\Lambda}$He is positive. Theory, however, predicts a non-zero, negative value. One notes that the mesonic decay and asymmetry seems to be understood.

This author had thought that the difference between the mesonic and non-mesonic decays could be explained in terms of long range vs short range behavior. If this is not the case, why then does the Δ I = 1/2 rule apply? It is thought that the Δ I = 1/2 rule is due to a dynamical result of meson exchange and cancellation. Something seems to be missing here.

4.5 K^- atomic states

The existing K^- atomic He data is not consistent with charge systematics [30]. A new measurement was reported in which the level shift is smaller, and in better agreement with expectations. The DEAR experiment measured the widths and shifts for atomic levels in K^- hydrogen [31,32]. These provide isospin dependent antikaon-nucleon scattering lengths. However, the DEAR experiment sets limits inconsistent with the K^- deuterium data.

5 Elementary interactions

5.1 Electromagnetic production of strangeness

There is substantial new data from the CLAS experiment at CEBAF, particularly polarization and spin transfer data [33]. Also, much more data is expected from CLAS and LEPS at Spring8 [14]. Together, the photo- and electro-production results favor calculations with non-zero coupling to a D13(1895) resonance. S-channel diagrams are found to be most important at low energy and t-channel/Reggeon exchange dominates when W>2 GeV (*ie* above the resonance region). Importantly, CLAS is providing a consistent data base of production and spin cross sections for analysis.

5.2 Hadronic interactions [34–42]

Also work continues on the extended soft core models which are based on one-boson-exchange and $SU_f(3)$ symmetry [40]. These models show that the Σ-N potential is weakly repulsive for model ESC04 and strongly repulsive for model ESC06.

Such potentials can be used to evaluate the effective hyperon-nucleon potential when the hyperon is embedded into the nuclear medium. However, one must properly include the density dependence and many-body interactions (*eg* $\Lambda\Sigma$ coupling) [34]. At this time a systematic many-body calculation of all the s-shell hypernuclei, including the excited states in the A=4 system, would serve as a calibration of how well both theory and the input potentials can reproduce the data.

A quark model using $SU_f(6)$ symmetry was presented for the NN and YN interactions [39]. The model shows spin and isospin dependence for the ΣN potential, and a shallow pocket at long range for the Ξ nucleus interaction.

6 Multi-strange systems

A contribution to the conference reported that ${}^{4}_{\Lambda\Lambda}$H was bound, but a similar test calculation did not did not bind ${}^{3}_{\Lambda}$H [43]. This leaves the result uncertain. On the other hand a previous calculation did not bind ${}^{4}_{\Lambda\Lambda}$H. Interest remains as the ${}^{4}_{\Lambda\Lambda}$H system is important as potentially the least bound double Λ system. A previous experiment that claimed the observation of ${}^{4}_{\Lambda\Lambda}$ is probably incorrect as was shown by a reanalysis of the data. Double Λ hypernuclei exist, but will require intense K^- beams for their investigation.

However, bound Ξ hypernuclei have yet to be observed, although in light systems they are are predicted to be bound by about 6 MeV with sufficiently narrow widths that a spectroscopy is possible [44]. Again, intense K^- beams are required for their investigation.

In addition, there has been no evidence for the H particle either below or above the $\Lambda\Lambda$ threshold in experiments looking at both production and decay channels [45]. The latest experiment shows only evidence for final state interactions.

At higher temperatures, a coalesce model can be applied in relativistic heavy ion collisions to predict the formation of hyperons and and light hypernuclei [46]. The model allows the residual baryons in the central rapidity region to cool thermally, collecting those that have sufficiently low momentum and spatial separation within an appropriate phase space. Just how applicable this process is to the study of strange, and in particular multi-strange, nuclear systems is not so clear.

It was pointed out in reference [47] that due to the possible strong $\Lambda - \Xi$ attraction proposed by the NSC97 model, the S = -3 hypernuclei ${}^{6}_{\Lambda\Xi}H$ and ${}^{6}_{\Lambda\Xi}He$ may provide the onset of Ξ stability in nuclear mater. This observation, and the sign of the ΣN potential is relevant to the composition of neutron stars [48,49]. However, input to these models requires knowledge of the poorly known hyperon-baryon potentials.

As a final comment, strange nuclear physics provides the possibility of extracting the hyperon-N interaction at normal nuclear densities, and this information can serve as a normalization point to extrapolate the $SU(3)_f$ interaction to the matter-densities found in neutron stars.

7 Summary

Hypernuclear Physics is more than nuclear physics revisited. It can illuminate features that are obscured in conventional nuclear systems, and it offers a selective probe of the hadronic many-body problem. All the conferees look forward to increased activity as the new facilities allow expansion of experimental activity into multi-strange nuclear systems.

Finally, it is the reviewer's task to thank the participants for their careful preparations and presentations to this conference. You have helped to make it a rewarding experience. I also must especially thank the organizers, students, assistants, and the University administration at Mainz. You have provided an excellent environment for our conference and for enlightened discussions. I hope to see all of you again in 2009.

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