PHYSICS FOR A NEW KAON FACILITY AT THE AGS*

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ABSTRACT

A new kaon facility is being planned at the Brookhaven National Laboratory Alternate Gradient Synchrotron. This paper discusses experiments in hypernuclear physics that might be performed at such a facility. Recent results from the Brookhaven hypernuclear spectrometer and elsewhere are presented as an indication of future directions in hypernuclear physics research. Expectations for the performance of the new facility are outlined.

INTRODUCTION

A brief summary of the major experimental results in hypernuclear physics will demonstrate the gaps that need to be filled by further research. Until quite recently all data about hypernuclei came from emulsion experiments. Table I from the review of Pniewski and Ziemska¹ shows the hypernuclear species that have been observed by the emulsion technique. Emulsion experiments, except in special cases, give information only about hypernuclear ground states. A phenomenological analysis of the ground state binding energies by Gal et al.² has defined some of the parameters of the lambda nucleus potential. Two double hypernuclei^{3,4} have been observed, ${}_{\Lambda\Lambda}^6\text{He}$ and ${}_{\Lambda\Lambda}^{10}\text{Be}$. Their binding energies are the only existing data on the Λ - Λ interaction. The first excited states of ${}_{\Lambda}^4\text{H}$ and ${}_{\Lambda}^4\text{He}$ have been measured⁵ by detecting their hypernuclear gamma rays. This data gives information on the spin dependence and charge symmetry of the lambda-nucleus potential. The (K^-, π^-) energy difference technique makes possible the observation of a spectrum of hypernuclear excitations and has been applied by the Heidelberg-Saclay-Strasbourg collaboration⁶ to ${}_{\Lambda}^6\text{Li}$, ${}_{\Lambda}^7\text{Li}$, ${}_{\Lambda}^9\text{Be}$, ${}_{\Lambda}^{12}\text{C}$, ${}_{\Lambda}^{16}\text{O}$, ${}_{\Lambda}^{32}\text{S}$, and ${}_{\Lambda}^{40}\text{Ca}$, formed at small momentum transfer with 2 MeV resolution. The HSS data has yielded a number of interesting results, foremost among them the apparently very small value of the Λ -nucleus spin orbit interaction reported at this conference. At Brookhaven, the collaboration⁷ at the hypernuclear spectrometer has made an intensive study of ${}^{12}\text{C}$ using the energy difference technique. An angular distribution was measured with momentum transfer to the hypernucleus up to 260 MeV/c to permit the excitation of additional hypernuclear states.

Thus, 1) the list of known hypernuclear species needs to be expanded. 2) Observed species are in almost all cases, ground states or excited at small (<100 MeV/c) momentum transfer. 3) The resolution of the present (K^-, π^-) energy difference experiments is 2-3 MeV FWHM. It will be shown below that this is insufficient to resolve many interesting states. 4) Detection of hypernuclear gamma rays can, in principle,

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DISCLAIMER

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Table I. Λ -binding energies of the uniquely identified hypernuclei.

	B_{Λ} (MeV)	Number of events		B_{Λ} (MeV)	Number of events
$^3_{\Lambda}\text{He}$	0.13 ± 0.05	204	$^8_{\Lambda}\text{Be}$	6.84 ± 0.05	68
$^4_{\Lambda}\text{H}$	2.04 ± 0.04	155	$^9_{\Lambda}\text{Be}$	6.71 ± 0.04	222
$^4_{\Lambda}\text{He}$	2.39 ± 0.03	279	$^{10}_{\Lambda}\text{Be}$	9.11 ± 0.22	3
$^5_{\Lambda}\text{He}$	3.12 ± 0.02	1784	$^9_{\Lambda}\text{B}$	7.88 ± 0.15	4
$^6_{\Lambda}\text{He}$	4.18 ± 0.10	31	$^{10}_{\Lambda}\text{B}$	8.89 ± 0.12	10
$^7_{\Lambda}\text{He}$	B not averaged	8+(8)	$^{11}_{\Lambda}\text{B}$	10.24 ± 0.05	73
$^8_{\Lambda}\text{He}$	7.16 ± 0.70	6	$^{12}_{\Lambda}\text{B}$	11.37 ± 0.06	87
$^7_{\Lambda}\text{Li}$	5.58 ± 0.03	226	$^{12}_{\Lambda}\text{C}$	10.76 ± 0.19	4
$^8_{\Lambda}\text{Li}$	6.80 ± 0.03	787	$^{13}_{\Lambda}\text{C}$	11.69 ± 0.12	6
$^9_{\Lambda}\text{Li}$	8.53 ± 0.15	8	$^{14}_{\Lambda}\text{C}$	12.17 ± 0.33	3
$^7_{\Lambda}\text{Be}$	5.16 ± 0.08	35	$^{15}_{\Lambda}\text{N}$	13.59 ± 0.15	14

resolve closely spaced levels. However, distinguishing hypernuclear gamma rays from the background of nuclear gamma rays and deducing a level scheme is a formidable task. Ideally, the gamma rays should be observed in coincidence with a (K^-, π^-) energy difference spectrum of hypernuclear states. The overall efficiency of a gamma-ray detection spectrometer can be roughly 5-10% so that gamma-ray coincidence experiments will require 10 to 100 times the currently available hypernuclear event rate.

Formation of Hypernuclei

The reaction used to form hypernuclei is

where the neutron is bound in a nucleus and the Λ is formed in a hypernuclear orbit. In the (K^-, π^-) energy difference technique, an accurate measurement of the K^- and π^- momenta determines the energy transfer to the nucleus and hence the energy spectrum of hypernuclear states. At 0° for appropriately chosen kaon momentum (~ 550 MeV/c) the reaction can proceed with no momentum transfer to the nucleus. This results in a high probability of forming a hypernucleus and a suppression of the background of quasifree lambda production. However, working at or near the zero momentum transfer condition is not always desirable. At small momentum transfer, the reaction populates preferentially states with the same spin and parity as the target nucleus. In order to understand all the components of the Λ -nucleus interaction and excite the full range of hypernuclear states the formation of hypernuclei at large momentum transfer must also be studied. This is best achieved by observing the pion at large angles with respect to the incident kaon. Cross sections for formation of states involving angular momentum transfer or spin flip are considerably lower than for coherent states produced at zero degrees. Their systematic study will require more intense kaon beams.

The observation of Σ hypernuclear states has been reported at this conference⁸. The existence of narrow Σ hypernuclear states opens a new field of research. The new kaon facility at the AGS will be capable of measuring Σ as well as Λ hypernuclei.

The reaction $K^- + {}^A_Z \rightarrow \pi^+ + {}^A(Z-2)$ can be used to form hypernuclei inaccessible to the (K^-, π^-) reaction. For example, ${}^9_\Lambda\text{Be}$ can be formed using a ${}^9\text{Be}$ target. By comparing hypernuclei formed using the (K^-, π^+) reaction with those formed by using the (K^-, π^-) reaction on the same target charge symmetry in hypernuclei can be tested. The rate of the (K^-, π^+) reaction relative to the (K^-, π^-) reaction is a measure of the importance of two step processes in hypernuclear formation.

Design of a New Kaon Facility

A discussion of a new kaon facility is best approached through an examination of existing facilities. I will describe the hypernuclear spectrometer at Brookhaven (Fig. 1).

The spectrometer utilizes the low energy separated beam I (LESB I) at the AGS. The beam, composed of 8% kaons, is brought to a dispersed focus on the target by a system of dipole and quadrupole magnets

Fig. 1: The configuration of the (K^-, π^-) spectrometer used in this experiment.

(D1,Q1-Q4). Kaon flux on target is $2.4 \cdot 10^4$ /AGS pulse. Multiwire proportional planes P1-P3 define the kaon trajectory. The pion from hypernuclear formation is detected by a similar system mounted on a platform that can rotate up to 35° with respect to the beam direction. Particle identification is made by time of flight between the scintillation counters S1, S2 and S3. A Cerenkov counter CK identifies kaons in the beam and a liquid hydrogen Cerenkov counter CH identifies pions formed in the target. The use of a focussing spectrometer to detect the pion gives good resolution (2.5 MeV FWHM, limited by target thickness effects) at the expense of acceptance (12 msr). A loss of a factor of 10 in K^- flux at 800 MeV/c is suffered in the kaon momentum analyzing section of the spectrometer, primarily due to kaon decay.

A new kaon beam, LESB II, has recently come into operation at the AGS. The K^- flux in LESB II has not yet been measured. The value stated in the design report⁹ is $7 \cdot 10^5$ K at 800 MeV/c for 10^{12} protons incident on the production target. The increased flux relative to LESB I is primarily a result of larger magnet apertures. During normal operation at the hypernuclear spectrometer we have had typically $4 \cdot 10^{12}$ protons on the primary target per AGS pulse. If the beam line of the new kaon facility were to have the same length and aperture as LESB II and, in addition, incorporate kaon momentum analysis, it would represent a hundredfold improvement over the current facility. The beam would have a flux of $2.8 \cdot 10^6$ momentum analyzed $K^-/4 \cdot 10^{12}$ protons. A threefold increase in the solid angle of the spectrometer detecting the pion is feasible. With this vastly increased event rate, a systematic exploration of the hypernuclear periodic table will be possible.

Resolution is intimately connected to flux. Target thickness effects (Landau spread and the difference between K^- and π^- energy loss in the target) are the dominant contribution to resolution in current experiments. The new facility should aim for a resolution of 250 keV FWHM.

Recent Results from the Hypernuclear Spectrometer at Brookhaven

An angular distribution of the states of $^{12}_\Lambda\text{C}$ excited in the reaction $^{12}\text{C}(K^-, \pi^-)$ has been measured⁷ with kaon momentum 800 MeV/c. Figure 2 shows a spectrum taken at $\theta_{K\pi}=15^\circ$ corresponding to a momentum transfer to the nucleus of 210 MeV/c. The lower mass peak corresponds to a binding energy of the lambda of $10.79 \pm .11$ MeV. Experiments using the emulsion technique report¹ a binding energy of $10.76 \pm .19$ MeV for the ground state of $^{12}_\Lambda\text{C}$. This agreement, leads us to identify the lower peak as the ground state.

The higher mass-peak has 11 MeV excitation energy. This peak could correspond to the particle hole configuration $(\Lambda p_{3/2}, np_{3/2}^{-1})$ or $(\Lambda p_{1/2}, np_{3/2}^{-1})$; the former configuration gives rise to a 0^+ and a 2^+ state, the latter to a 2^+ state. (Unnatural parity states are not expected to be excited with significant strength in our kinematic range.) The angular distribution of the peak at 11 MeV (Fig. 3) shows the steep rise in the forward direction characteristic of a coherently produced 0^+ state. However, the shoulder at large angles is interpreted as the excitation of the 2^+ components. Calculations¹⁰ indicate that at 15° the states observed should be predominantly 2^+ . Making the assumption that at 0° we are exciting 0^+ only and at 15° we are exciting 2^+ only

Fig. 3: Angular distributions observed for the ground state of $^{12}_{\Lambda}\text{C}$ and for the peak at 11 MeV excitation. Eye guide curves are shown connecting the points.

we can set limits on the spacing of these states although they are not resolved by our experiment. Assuming that at 15° only one 2^+ state contributes, the 0^+-2^+ spacing is less than 420 keV. Assuming that at 15° the two 2^+ components contribute equal strength, the 2^+-2^+ spacing is less than 800 keV. These limits will constrain the spin dependent parts of the lambda nucleus residual interaction. The above result is an example of structure in the spectra of hypernuclei which is beyond the resolving power of the present generation of experiments.

The existence of core excited hypernuclear states has been predicted.¹¹ These states would consist of a lambda in an s orbit coupled to the excited states of the ^{11}C core. A search was made in the region above the ground state for an event excess using our 15° data. We see no evidence for such states. The total event excess in the region 2 to 7 MeV excitation is $6\% \pm 5\%$ of the ground state strength. This is to be compared with an expectation of two states, one at 3.29 and one at 5.11 MeV excitation with summed strength 33% of the ground state strength. The disagreement between experiment and theory should motivate additional experiments to search for core excited states predicted in other hypernuclei. An experiment detecting gamma rays from the de-excitation of the core in coincidence with a (K^-, π^-) energy difference measurement would be particularly effective in observing these particle stable states. The absence of core excited states at the expected strength may be attributable to uncertainties in the knowledge of the ^{11}C and ^{12}C wave functions or it may signal some more fundamental problem in the theoretical understanding of hypernuclei.

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