From Nuclei to Hypernuclei: A Retrospective View of Medium Energy Physics at Brookhaven

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A new frontier in physics originated with programs at two Brookhaven National Laboratory facilities—the Cosmotron and the Alternating Gradient Synchrotron. The development of this frontier over a half century is described, as it turned from conventional nuclear physics to the hypernuclei and the study of strange matter.

The early history of Brookhaven Laboratory, founded in 1947, shows how research was developed at the two major facilities, the Graphite Research Reactor and the Cosmotron. The primary reason advanced for the foundation of BNL was in fact the ability to construct major facilities beyond the ability of individual academic institutions to support such devices [1].

One of the first and most visible of the BNL research staff was Donald J. Hughes. Hughes became well-known for his research on slow neutrons and his application of reactor neutron sources to topics in both nuclear and material sciences. His book on "Pile Neutron Research" became a standard in the field and was widely circulated in the US and elsewhere. Hughes made extensive use of the reactor, but he was also interested in expanding the range of his neutron research to include high energy neutron interactions. Hughes attempted to span an energy range extending from "cold" neutrons (neutrons of energies less than 0.025 electron volts) to neutrons in the billion electron volt range. It was symptomatic of his broad research interests that even with very slow neutrons, he was exploring areas which we today assign to the realm of hadronic interactions. His famous work on the neutron-electron interaction, for example, was motivated by the desire to explore the role of meson exchange in nuclear forces[2].

To obtain a source of high energy neutrons, Hughes conceived using the process of neutron-proton charge exchange, which was a way of transferring charge from a high energy proton to a neutron. The inverse effect would then be used to detect the neutron after it engaged in some nuclear scattering process to be studied.

It is interesting to quote from Hughes' initial ideas presented in a memo dated 1956 to then Lab director Leland Haworth[3]. "...the motivation being experiments at high energy on the nuclear radius... they would show how adequate current nuclear modes are for high energy interactions, as stressed in a talk given here by (Roy) Glauber. The measurements we have made with zero energy neutrons give a nuclear radius distinctly larger than the electromagnetic radius... whereas the few experiments done with high

energy neutrons show no difference. An explanation is that the nucleus contains a shell of neutrons outside the protons." Neutron halos are a hot topic even today, some 50 years later.

Fig. 1 D. J. Hughes (1960)

Fig. 2 Harry Palevsky (1968)

It was that desire to reach for the fundamentals which motivated these physicists. As we learned later, the naïve belief that the low energy understanding of nuclear phenomena could be extrapolated to high energies was confounded, time and again, by the undreamt of complexities of the real world. Some will argue that this naïveté is still with us today. Be that as it may, with this naïve belief, Hughes turned his attention to the Cosmotron.

The first step in this scheme was to mount a test experiment at that accelerator, which the Hughes group attempted to do, starting in 1956 with the construction of a high pressure gas Čerenkov detector. His colleague, Harry Palevsky, who joined Hughes at BNL— and was entrusted by Hughes to carry on the detailed tasks of directing the specific experiments Hughes wanted to see done— was given the job of preparing the instrumentation for the Cosmotron

Unfortunately this scheme was interrupted twice, first by a serious fire at the Cosmotron in 1957, and then by Hughes' unexpected death in April, 1960. It was left to Palevsky to pick up the pieces left by Hughes and to direct the group's activities at BNL. These were many and various, including continuation of neutron scattering and resonance studies at the BNL graphite reactor and at the NRU reactor at Chalk River, the building of instruments for the newly-conceived High Flux Beam Research Reactor, the expansion of neutron data compilation activities started by Hughes with the famous "Barn Book", and moving forward with the Cosmotron effort.

This was indeed a daunting set of tasks for Palevsky, and the ability to carry them out was a source of concern for the BNL management. Fortunately for BNL, Harry surprised many with his keen instinct for pursuing interesting physics problems and for his leadership ability. Palevsky, however, was not Hughes, and his interests started to diverge from the paths that Hughes wanted to pursue.

The Cosmotron feasibility experiment[4] – a measurement of the (n,p) charge exchange cross section at 2 BeV (nowadays we use GeV, instead of BeV)— was carried out under Harry's personal direction, but with active help from all of us. The key detector in this experiment was a high pressure CO₂ threshold Čerenkov detector, one meter in length

and 10 cm in diameter, designed by Harry. It operated at 40 deg C, with a pressure of up to 82 atm. We always regarded this device with awe; I remember vividly the explosion of a filter, for gas impurity removal, attached to its filling pipe.

Two experiments were ultimately done, and the results determined the backward value of the (n,p) cross section at 1-3 GeV; they showed that the charge exchange reaction has a significantly narrower angular distribution than that of the (p,p) elastic process. That experimental result, along with work of Manning at the Rutherford Lab, stimulated theoretical work [5] to explain the result. While the cross section leading to forward-going protons could not be interpreted as single pion exchange, theorists showed how absorptive processes in the entrance and exit channels could reproduce the Cosmotron result. However, their consistent predictions of a secondary spin-flip peak at larger angles was contradicted by the data. The BNL result has never been explained. As we shall see, time and again, the simple picture failed, and a more complicated interpretation led nowhere.

Fig. 3 np charge exchange

Fig. 4 Deuteron Production

While those experiments proved practical, they also demonstrated to Palevsky that there was a rich field of high resolution nuclear spectroscopy to be mined using high energy protons as nuclear probes. The sources for these high energy protons were accelerators like the BNL Alternating Gradient Synchrotron and the newly-conceived Los Alamos Meson Physics Facility. Harry moved aggressively to use the Cosmotron for experiments using protons as probes of nuclear structure. For that purpose, he hired a bright young graduate of the University of Illinois, Joe Friedes, to carry on that program. Friedes did that with energy and great skill.

Friedes had little interest in pursuing studies with high energy neutrons, but he was quite interested in probing nuclear structure with high energy protons. Together with students Gerry Bennett and Dick Sutter from Stony Brook, recent graduates Duane Simpson and Tom Emerson from Gerry Phillips' group at Rice, George Igo from Los Alamos, and

Sandy Wall of Maryland, Palevsky and Friedes carried on experiments on helium and other targets at the AGS. They were aided by close cooperation by theorists such as W. Czyz from Warsaw and Colin Wilkin from Oxford.

These events signaled the birth of Medium Energy Physics in the United States. The brief period between 1963 and 1968 resulted in doctoral dissertations for students from Stony Brook, and University of Maryland. These experiments were the first at GeV energies to achieve the resolution to separate successfully the elastic and inelastic scattering on light nuclei [6]. It was initially hoped that hadronic scattering would reveal nucleon-nucleon correlations, as the momentum transfer corresponds to a scale below 1 Fermi. Large numbers of knock-out deuterons were apparently produced from a series of p-shell targets, and a back-scattered deuteron peak was produced from protons scattered from helium. This kind of result stimulated expectations of interesting experiments at the generation of pion factories which were coming into being.

The theorists pointed out, however, that life isn't that simple; final state interactions obscure the apparent simplicities of high-energy hadron probes. As Gerry Brown quaintly observed in 1967, "It looks like nature really has built a rather intricate fence around the nucleus, to prevent us from looking directly at correlations sitting there." [7]. It is another example of the difficulty in extending simple low-energy concepts to the higher energy regimes.

While the Cosmotron program was showing encouraging results, the BNL management was committed to upgrading the AGS to achieve higher intensity levels, and at the same time, budgetary increases were starting to assume more modest increments than were provided to the scientists of the 50's and 60's. In any event the Cosmotron was closed and the ongoing studies sacrificed to the burgeoning AGS program.

With the close-out of the Cosmotron, Palevsky made an effort to carry on the proton scattering program at the Princeton-Penn Accelerator, and at the Berkeley Bevatron. This effort faltered because of the closing of the former, and reduction of effort at the latter, facility. The departure of a sizable fraction of the BNL group in 1968 to form a private business enterprise ended this phase. This departure was triggered by Palevsky's failure to secure tenure for Friedes, who became discouraged with his situation and the laboratory, and who opted for a career as an entrepreneur. Using a clever idea for direct recording of analog voice signals on a digital computer disk, due to an idea of Dick Sutter, a voice response company called Periphonics was formed. The four original partners, Friedes, Sutter, Simpson, and Emerson were joined by Julian Sandler to form the company, based on a patent awarded to Sutter, Simpson, and Emerson. With an infusion of cash due mainly to Palevsky, Friedes left to work exclusively at Periphonics. Thus ended the first phase of medium energy physics, just at the time of the start of the program of research at the Los Alamos Meson Physics Facility—LAMPF. The installation of the high resolution spectrometer, the HRS, was triggered by the BNL program.

The next chapter in the history of medium energy physics at BNL was the start of a hypernuclear research program, in which one could create nuclear states with the introduction of hyperons into a nuclear medium. This had its origins in the sabbatical year spent by Harry Palevsky at CERN in 1971-72. He noticed there were two collaborations, spearheaded by Povh at Heidelberg and Bressani at Torino, actively attacking the strangeness exchanging (K^- , π^-) reactions at the CERN PS.

The fact that the incorporation of hyperons—that is baryons with strange quarks—in the nuclear medium could lead to novel nuclear excitations had been known for some time from emulsion and bubble chamber experiments. It was not until the 70's, however, that instrumental developments permitted the full exploitation of this field. There was at the same time, the theoretical impetus of Lipkin's suggestion[8] that strangeness-exchange would show the presence of a strangeness analog state, similar in concept to the isobaric analog state of ordinary nuclear physics.

The decades following the 60's witnessed very active programs in hypernuclei by groups working at CERN, AGS, and KEK, along with continued interest by emulsion groups in Poland, UK, and Japan. A veritable explosion of theoretical activity accompanied these efforts; the interaction of theory and experiment proved stimulating and beneficial to the field. An important by-product was the training of many new scientists from the USA and elsewhere, especially from Japan.

A document key to the initiation of the BNL program was the Summer Study of 1973[9]. It is interesting to read this document even in the present day, as it presents a thoughtful summary of the field and its potential. The topics addressed include a) the spin structure of the hyperon-nuclear interaction and especially the Λ -nucleus spin-orbit splitting, b) $\Sigma - \Lambda$ mixing and the role of 3-body forces in the nuclear medium, c) the use of γ -ray spectroscopy in hypernuclei, d) weak decay—both mesonic and non-mesonic, e) charge symmetry breaking and the role of isospin in hypernuclei, and f) the search for doubly-strange hypernuclei. Among others, Feshbach at this meeting emphasized the usefulness of hyperons as tracers, able because of lack of Pauli repulsion to probe regions of high nuclear density. In only one major area—that of the usefulness of the (π^+, K^+) reaction—did that summer study fail to foresee the future.

One other prescient aspect of that document which is worthwhile quoting is the after-dinner address by Maurice Goldhaber. He closed by saying, "The field we have been discussing here falls between two others, low-energy and high-energy physics. The responsible agencies and the scientists must watch that this field does not fall into a budgetary gap."

After developing interest in the United States, and convincing BNL-AGS management to invest in facilities to explore this area, Palevsky moved rapidly to initiate a series of experiments designed to elucidate the properties of nuclei containing one or more hyperons. He hired a Columbia graduate, Morgan May, to assist in the preparations for the hypernuclear program. That program has been the principal effort of the BNL Medium Energy group through to the end of the 20th century.

The Brookhaven effort attempted to exploit the stimulating issues raised by in-flight experiments of Povh and Bressani and their collaborators at the CERN-PS. These included identifying p and s states of hypernuclei through angular distributions, looking for Σ -hypernuclei, observing radiative transitions among hypernuclear levels, studying strangeness-changing weak decays, initiating dibaryon searches, using associated production to supplement the tool of strangeness exchange, exploring η production, and extending the field to include multi-hyperon systems.

The first step was to set up a focusing spectrometer system placed on a rotatable platform obtained from the Cambridge Electron Accelerator, called Moby-Dick (presumably because of its size). Moby-Dick was installed at the AGS-LESB1 beamline previously

designed by John D. Fox. This line was chosen in preference to the more newly-developed LESB2, in spite of the larger flux allegedly available there.

The Moby-Dick spectrometer, along with other instrumentation, was assembled to carry on the research. An evolving collaboration was formed, of whom the most active members were Princeton, Houston, Carnegie-Mellon and MIT in the USA. The first BNL results were published in 1979, and they showed the effectiveness of Moby-Dick in obtaining the angular distributions for substitutional and non-substitutional states, corresponding to $\Delta L=0$ and 1 for ^{12}C [10].

Later on, the collaboration was strengthened by an infusion of an international contingent, mainly with students from Japan— KEK, Tokyo, Osaka, and Kyoto. The BNL effort also benefitted in a very important way from the input of BNL Theory group, principally Carl Dover, John Millener, Tony Baltz, and Sid Kahana, who brought in many other theorists from around the world. The close relationship between experimentalists and theorists was one of the strengths of the BNL Physics Department.

Fig. 5 The Medium Energy group in 1981

During a period of about five years before the first experiment, there had occurred a gradual deterioration in Palevsky's health, leaving to others the task of carrying on the day-to-day work. This culminated in his retirement in 1981. It was in May of that year that I formally assumed the group leadership.

A very important contributor to the instrumentation development was Phil Pile, who joined the group in 1983, and who was primarily responsible for three innovations. He first developed a fast, high-rate, drift chamber design, benefitting in part from Charpak's work, but also from our own studies of rate effects. The high rates led to the growth of spectacular "whiskers" on the sense wires. Their elimination through careful control of the solvents and adhesives used in construction was an important step forward. The second was a shortening of Moby-Dick by elimination of the first QDQ elements, replacing

them by using tracking through the last bend in the LESB1 beamline. Finally, he was responsible for the design of the D6 line, which produced a 1.8 GeV/c beam of unmatched intensity and purity.

It is of interest to examine the list of AGS proposals on strange nuclear physics. Most of them were carried out by the BNL group in collaboration with universities and other institutions, both in the US and elsewhere. The enumeration in the appendix to this paper presents that list[11].

Experiments 646, 728, and 746 were strangeness and charge exchange studies with the 3-MeV resolution Moby-Dick spectrometer assembled at BNL. They were the first to exploit angular distributions to separate the s- and p-shell states and to place a significant limit on the nuclear spin-orbit splitting, while E752 attempted to confirm CERN and KEK reports of narrow Σ states in the continuum. The latter subject represented a major and continuing world-wide effort. The history of this saga was covered in detail in ref. [12], which explains the pitfalls and difficulties of the search. It was only recently, in two AGS experiments, E887[13], and E905[14], that the issue of narrow Σ states in the continuum was put to rest.

Kaon and pion scattering studies were initiated in E692, and later measurements on total, elastic, and inelastic kaon scattering were made in E835 and E874. These experiments demonstrated a clear medium effect on kaon interactions in the nucleus.

One of the areas heretofore ignored in hypernuclear spectroscopy was initiated with experiments E758 and E790, which were decisive in showing the single particle states of the Λ hyperon in hypernuclei. This was done by using associated production in place of strangeness exchange in producing hypernuclei. Here it is important to acknowledge the contributions of LANL's Arch Thiessen, who originally suggested the practicality of the technique, and of Carl Dover, who developed the theory along with Ludeking and Walker.

Fig. 6 Carl Dover (1984)

The usefulness of γ -ray techniques was shown in E781, which first used radiative transitions to set new limits on spin-orbit splitting. E781 also demonstrated the role of the Λ in stabilizing the nuclear system. The application of γ detection, combined with angular distributions for separation of subshell components, was a feature of the recent E929 experiment, confirming the smallness of the spin-orbit splitting. While E781 also attempted

to use intrinsic germanium detectors in strangeness exchange reactions, their successful application was left to the KEK work using the (π, K) technique. However the attempt continues at the AGS with E930, which will seek to identify a tensor component in the effective interaction in the p-shell nucleus ${}^{16}_\Lambda\text{O}$.

Experiment 759 started a new generation of weak decay studies with a study of ${}^{12}\text{C}$, and then later, in E788, to ${}^4_\Lambda\text{He}$ and ${}^5_\Lambda\text{He}$. The interplay between mesonic and non-mesonic decays, and their branching ratios, has revealed details on the weak interaction Hamiltonian, sensitive to the short range portion of the hyperon-nucleon interaction. Those studies continue with E931, yet to be run.

Perhaps the most interesting aspect of the strangeness program involves multiple nuclear strangeness—either in Ξ , $\Lambda\Lambda$ hypernuclei, or dibaryons. It has long been speculated—actually since the suggestion of Bodmer[15]—that matter at extreme densities would collapse to its most stable form, which would be strange matter. Inasmuch as it has been shown that pion condensates are unlikely to occur in extreme stellar matter and that kaon condensation is more likely, there continues to be theoretical interest in experimental evidence for strange matter, whether baryonic or dibaryonic in form.

A suggestion, in fact, that $S=1$ dibaryons might exist comes from the famous deuterium threshold cusp, or “demon deuteron” reported by CERN. A fruitless search for $S=1$ dibaryons was made in E820; a byproduct, however, of that search, was a measurement of the cross section of a two-step reaction. This type of reaction, involving charge exchange in the intermediate step, was suggested as a possible route to multiple strangeness correction. The cross section, however, reported by E820, was disappointingly small.

By far the most interest was stirred by Jaffe’s suggestion for production of a stable (against strong decay) neutral dibaryon containing 6 quarks of the lowest mass flavors. The suggestion ultimately resulted in the construction of a 2.0 GeV/c kaon beam optimized to search for that dibaryon—the “H”—by producing Ξ -hyperons in the (K^-, K^+) reaction on hydrogen, and capturing them on deuterium to give a neutron-tagged H. Experiment 813, which has just been submitted for publication, reports a null result for that search, as do several other attempt, such as E836, with varying sensitivities.

One exciting prospect which points to a non-null finding, however, is the search for $\Lambda\Lambda$ hypernuclei of E906, which observes a pair of successive weak decay pions, signaling two changes of the strangeness quantum number. The suggestion of E906, reported at this conference, that there exists a large production of $\Lambda\Lambda$ hypernuclei, makes the existence of an “H” in the nuclear environment implausible.

As I look back on the 40 years of Medium Energy physics effort centered at the BNL facilities, I consider that one of my most important accomplishments was the training of more than 40 students who learned the techniques of nuclear and particle physics research here at BNL, and especially those sent by our Japanese collaborators. It may be that their contributions will have a continuing impact far into the future of strange particle physics.

Fig. 7 J. Nakano and S. Ajimura presenting retirement scrolls to R. E. Chrien (1998)

I have presented here a retrospective view of the BNL medium energy program. We stand at an interesting juncture in the history of this research, a time when several crucially important problems in the study of hypernuclei are within the practical reach of present and newly-planned facilities. We await their solutions in the next millenium.

APPENDIX

BNL-AGS Medium Energy Proposals with Strangeness (1974-1998)

- **E646 Hypernuclear Spectroscopy of States Formed by the Coherent Interaction of K^- with Nuclei**
1 Mar 74
H. Palevsky, spokesman. Actually run 4-5/78;10-11/78;3/79
First hypernuclear physics proposal at AGS; slated for C4 line (LESB1) and Moby Dick Rotatable Spectrometer stand procured from Cambridge Electron Accelerator
- **E692 Measurement of $K^\pm$ Elastic Scattering from Selected Nuclei at 800 MeV/c**
1 Sept. 75
P. Barnes, B. Wharton. Actually run 12/78, 2/79
First study of K^+ as a nuclear medium probe
- **E728 Extension of E646 to $(K, \pi^\pm)$ Reactions and a Search for Σ Hypernuclei**
1 Dec. 76
H. Palevsky. Actually run 10-11/79
First attempt to employ both charge and strangeness exchange at the AGS; search for bound Λ -N system.
- **E746 Spin and Isospin Effects in Light Hypernuclei**
16 April 79
H. Palevsky. Actually run 3-4/80, 6-7/80
Classic angular distribution study of $^{13}_\Lambda C$ to determine nuclear spin-orbit splitting
- **E752 A Search for Sigma Hypernuclear Levels in $^{16}_\Sigma O$ using the (K^-, π^+) Reaction**
26 Dec. 79

E. Hungerford. actually run 11-12/80; 5/81

Reported peaks in continuum for ${}^6\text{Li}$ target.

- **E758 The (π^+, K^+) Reaction: A New Tool for the Study of Hypernuclear Structure**
1 March 1980
H. Thiessen. Actually run 2-3/83.
First (π^+, K^+) experiment and observation of particle-hole excitations in carbon. A major step forward; this was suggested by Thiessen and developed theoretically by Dover et al.
- **E759 Weak Decay of p-Shell Lambda Hypernuclei**
1 January 80
P. Barnes. Actually run 4-5/83
First in-flight hypernuclear weak decay experiment at AGS; direct lifetime measurement in carbon.
- **E760 Spin Dependence of the Lambda Nucleus Interaction Determined by Observation of Hypernuclear Gamma Rays**
15 April 80
M. Deutsch. Actually run 5-6/82
First observation of radiative transitions in p-shell hypernuclei from in-flight kaon capture. Demonstration of Λ stabilizing effect. Set new limits on spin-orbit splitting.
- **E773 A Search for $S=-1$ Dibaryon States in the Λp Missing Mass Spectrum Near the ΣN Threshold in the Reaction ${}^2\text{H}(K^-, \pi^-)\Lambda p$**
13 Sept. 82
H. Piekarczyk. Actually run 3-4/85; 5-6/86
First of searches for dibaryons using strangeness exchange reactions. Particular attention to the region of the cusp at Σ threshold.
- **E774 A Search for Σ Hypernuclear Levels in ${}^4\text{He}$**
9 April 82
E. Hungerford, R. Hayano. Actually run 5/85; 4-5/91
Targets of both ${}^4\text{He}$ and ${}^3\text{He}$ examined. Later included an attempt to verify bound state reported in KEK stopped kaon experiments. Last runs of this experiment were the first to use Moby Dick in the LESB2 C8 line
- **E781 Spin Dependence of the ΛN Interaction Determined from the Observation of Hypernuclear Gamma Rays**
10 Sept. 82
Deutsch, May. Actually run 1-4/84; 6/91; 6/92
First attempt at in-flight kaon capture with high-resolution Ge detectors; established feasibility of technique; later used NaI to detect P to S shell radiative decay in ${}^{13}_\Lambda\text{C}$.
- **E788 Four Fermion Weak Interaction and the Decay of ${}^4_\Lambda\text{He}$ and ${}^5_\Lambda\text{He}$**
12 Sept. 83
P. Barnes. Actually run 1-3/90
- **E798 Study of Strangeness in Nuclei by Use of the (π^+, K^+) Reaction**
13 Sept. 84
J-C. Peng, P. Pile. Actually run 1-2/87
Classic study of the π^+, K^+ with targets from Be to Y; led to reviews of single particle structure by Dover, Millener, and Gal.
- **E813 Search for a Strangeness -2 Dibaryon**
31 Jan. 85
Barnes, Franklin. Actually run 4-6/91; 5-7/92; 6-7/93; 1-5/95
First use of the 2.0 GeV/c beamline with incorporation of KEK separator technology; beams of excellent purity and intensity. This experiment was severely hampered by neutron background.

- **E820 Search for a $S=-1$ Dibaryon in the Mass Region 2050-2130 MeV Using the Reaction ${}^3\text{He}(K^-, \pi^+)nD_s$**
 19 Sept. 85
 H. Piekarz. Actually run 1-2/89
This was the last nuclear experiment using Moby Dick at LESB1; published first result showing two-step (K^-, π^+) process
- **E829 Search for a $S=-1$ Three-body Bound System**
 24 Jan. 86
 T. Kishimoto. Actually run 2/89
- **E835 Kaon-Nucleus Total Cross Sections and Partial Deconfinement in Nuclei**
 1 May 86
 E. Piasetzky, R. Chrien. Actually run in 5/87; 2/88; 3-4/90
This experiment set a precision record for K^+ total cross sections and started a series of studies on nuclear medium effects with a K^+ probes at the LESB2 beamline
- **E836 Search for a Strangeness -2 Dibaryon Using a ${}^3\text{He}$ target**
 7 May 86
 Barnes, Franklin. Actually run in 5-7/94
An alternate method for H production by direct (K^-, K^+) production and did not require neutron detection as in E813
- **E874 Kaon-Nucleus Quasielastic and Elastic Scattering**
 24 Jan. 91
 Peterson, Hungerford, Chrien. Actually run in 6-7/92; 6-7/93
Decisive demonstration of medium effects in kaon scattering
- **E885 An experiment to Detect $\Lambda\Lambda$ Hypernuclei**
 16 Jan. 92
 Franklin, May, Davis. Actually run in 4/94; 3-6/96
As in E813, neutron background too large to allow $\Lambda\Lambda$ identification from the neutron signal
- **E886 Search for New Particles in Nucleus-Nucleus Collisions**
 16 Jan. 92
 Imai, Pile. Actually run 4-5/92; 8-9/93
2 GeV/c beam line used as a mass spectrometer to separate exotic nuclei
- **E887 Do Narrow Σ Hypernuclei Exist?**
 17 Jan. 92
 Sawafta, Hicks. Actually run 5-6/94
At long last, CERN Be report of narrow states was checked. No narrow states were found in ${}^6\text{Li}$ or ${}^9\text{Be}$.
- **E905 Search for a Σ Hypernuclear Bound State in ${}^4\text{He}(K^-, \pi^\pm)$ Reactions**
 30 Sept. 94
 T. Nagae. Actually run 3-6/96
Confirmed the bound state in ${}^4\text{He}$ claimed previously at KEK
- **E906 Experiment to Detect Double- Λ Hypernuclei by Observing Characteristic π -Mesonic Decays**
 3 Oct. 94
 Fukuda, Chrien, Rusek. Actually run 4-5/97; 10-11/98
Apparent copious production of $\Lambda\Lambda$ hypernuclei
- **E907 Investigation of Light Hypernuclei Using the (K^-_{stop}, π^0) Reaction**
 3 Oct. 94
 E. Hungerford, J-C. Peng. Actually run 5-6/96; 4-5/97; 6-7/98

- **E929 Spin-orbit Splitting of Single Λ State by the $^{13}\text{C}(\text{K}^-, \pi^+ \gamma)$ Reaction**
1 Sept. 96
T. Kishimoto. Actually run 6/97; 9-10/98
- **E930 The High-Resolution γ Spectroscopy of Hypernuclei using a Large-Acceptance Germanium Detector**
1 Sept. 96
H. Tamura. Actually run 12/98
- **E931 A Study of the $\Delta I=1/2$ Rule in the Weak Decay of S-Shell Hypernuclei**
1 Sept. 96
Hungerford, Dehnhard, Zeps. Actually run 11-13/98
These two experiments, E930 and E931, have not completed their assigned run times.

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