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Recent Experiments in Novel Nuclear Excitations at the BNL AGS

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Abstract:

Recent experimental work at the AGS dealing with unusual nuclear excitations is summarized. Three examples are given: the deexcitation of Λ hypernuclei by γ transitions, the production of Λ hypernuclei by the (π^+, K^+) reaction, and the search for η -nuclear excitations. The status of each field and the implications of the research for nuclear theory are discussed.

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"Novelty is of all things the best loved." Ovid.

Nuclear systems examined with hadronic probes at high energies can be expected to reveal properties which are largely inaccessible to more conventional, lower energy probes. The novel nuclear excitations available to such probes give us a singular insight into nuclear interactions.

At Brookhaven, the Medium Energy Group has performed a number of experiments in recent years which have improved our insight. A summary of these would include Exp. 773--A Search for the Strangeness = -1 Dibaryon, Exp. 774--A Search of Σ -Hypernuclear States for Lithium and Carbon Targets, Exp. 781--The Observation of Hypernuclear Spin-Flip Gamma-Rays, Exp. 798--The Production of Hypernuclei by the (π^+, K^+) Reaction, Exp. 828--A Search for Eta-Excitation in Nuclei, and Exp. 835--Total Kaon Cross Sections and Quark Deconfinement. The constraints of space-time do not permit a detailed summary of all this work; I shall instead select three experiments--781, 798 and 828--where in the past year considerable progress has been made and the goals of these efforts have been attained.

1) 781--The Observation of Hypernuclear Spin-Flip Gamma-Rays

In spite of diligent research on Λ hypernuclei over the past decade, very little quantitative information exists on the Λ nuclear, or Λ 2-body spin-dependent interaction. They are known to be much smaller than their nuclear counterparts, but their strengths remain unobserved.

The nuclear information on these spin splittings comes almost exclusively from S and P shell hypernuclei. If we start with a P-shell target and form a p-shell hole and an s-shell Λ in a $\Delta l=1$, $P \rightarrow S$ transition, then one has for the nuclear Hamiltonian

$$H = H_{\text{core}} + H_{\Lambda} + V_{\text{int}}$$

and V_{int} is calculated using a 2-body interaction summed over all the core nucleons. The S-shell core contribution contributes a constant term V_0 and

$$V_{\Lambda N} = V_0 + V_{\sigma}(r) \vec{S}_N \cdot \vec{S}_{\Lambda} + V_{\Lambda}(r) \vec{l}_{\Lambda N} \cdot \vec{S}_{\Lambda} + V_N(r) \vec{l}_{\Lambda N} \cdot \vec{S}_N \\ + V_T(r) [3(\vec{\sigma}_N \cdot \vec{r})(\vec{\sigma}_{\Lambda} \cdot \vec{r}) - \vec{\sigma}_N \cdot \vec{\sigma}_{\Lambda}].$$

The terms above are referred to as the spin-spin term (Δ), the Λ spin-orbit (S_{Λ}), the nuclear-induced spin orbit (S_N) term, and the tensor (T) term. To first order, the energy of the hypernuclear state is a linear function of these 5 terms, with coefficients that can be determined from a shell-model calculation with realistic wave functions. The energy levels can be compared to experiment, which given the accuracy of the calculation, can be used to check both the parameters of the two-body potential, and the accuracy of the shell-model representation of P-shell nuclei.

One may divide the possible radiative transitions into two classes according to the above Hamiltonian: one class involves transitions between the core levels, in which the Λ plays the role of a spectator. The second involves transitions between members of spin multiplets which involve alternative spin couplings of the Λ to the core. The former category of transitions was observed in our earlier Exp. 760 using sodium iodide detectors. The latter transitions, the spin-flip M transitions, give more direct information on the spin-dependent parameters Δ , S_{Λ} , S_N , T, whose measurement formed the goal of Exp. 781. Two evaluations of these spin-dependent parameters are available in the literature: one due to Dalitz and Gal [1] (1978) and the second due to Millener, Gal, Dalitz, and Dover [2] (1985). The latter

parameters, based on a more comprehensive experimental input, generally predict smaller spin-multiplet spacings. Millener et al. predict a ground-state multiplet spacing of ≈ 190 keV for $(2^- \rightarrow 1^-)$ in $\Lambda^{10}\text{B}$ and ≈ 82 keV for $(1^- \rightarrow 0^-)$ in $\Lambda^{16}\text{O}$. In each case the predicted production cross section is 50 $\mu\text{b/sr}$ and in the oxygen, it is independent of level order.

The analysis of Exp. 781 is now virtually complete, and I report here the conclusion: there is no γ -ray transition observed in the range 80 keV to 1000 keV from $\Lambda^{10}\text{B}$. Figures 1 and 2 show the expected numbers of observed events and the experimental sensitivity for the $\Lambda^{10}\text{B}$ sample against γ -ray energy. The sensitivity is defined as that cross section which would be obtained by assigning all observed events in a resolution width (here FWHM = 6 keV) to the signal. Figure 2 shows that a transition of 50 $\mu\text{b/sr}$ would be clearly observable above background. None is seen down to a level of ≈ 10 μb at 100 keV, and even less at higher energies. $\Lambda^{16}\text{O}$ will show a similar result, except there the lower energy bound for an observable result is not quite established as yet. This result suggests that the spin-spin parameter is too large, or that the spin orbit is too small; their difference largely determines the splitting.

It should be emphasized that the non-observation of the spin-slip transition in Exp. 781 is a strong statement: the experimental sensitivity of that experiment is quite adequate to observe the predicted γ ray. The smallness of the spin-flip transition energy suggests that its observation will be impossible for P-shell hypernuclei (with the possible exception of $\Lambda^7\text{Li}$). Before leaving this topic, I wish to refer to a candidate line near 160 keV previously cited as a possible hypernuclear transition. This "line" has been discarded as a fluctuation because of its unacceptable time distribution, which rules it out as a hypernuclear transition. One other

possible candidate is observed at a 3σ confidence level near 491 keV. It lies well below the predicted 50 $\mu\text{b/sr}$ level at 8 $\mu\text{b/sr}$, and in any event a 3σ fluctuation out of a spectrum of 160 resolution widths (1000/6) is not a rare event, $(.9987)^{160} = 0.812$.

The future for γ -ray experiments from (K^-, π^-) reactions is therefore not bright. Perhaps more attractive is the possibility of $(\pi, K\gamma)$ reactions and/or the observation of intershell E-1 transitions; i.e., P $\rightarrow$ S transitions which are observable in principle across the whole periodic table.

2) Exp. 798--The Production of Hypernuclei by the (π^+, K^+) Reaction

It has long been the dream of the nuclear physicists to produce the ideal nuclear probe--a probe that allows examination of the nuclear structure without modifying it. The problem of examining deeply-lying states of nuclear systems is closely related to the search for such a probe. The Λ particle is a good candidate for examining the single particle structure of nuclei since, for the Λ , all possible nuclear orbitals are unoccupied.

The (π^+, K^+) reaction has been demonstrated to be successful in placing the Λ in deeply-lying nuclear orbitals for quite heavy hypernuclei. The feasibility for a P-shell target was demonstrated by Milner et al. [3] in Exp. 759, and recently extended to beyond the P-shell ($A=28$ and 89) by the collaboration of Exp. 798 [4].

The experimental parameters of the Exp. 798 test, done with the LESB-1 channel and Moby Dick spectrometer tuned for the (π^+, K^+) mode of operation, are shown in Table I. For ^{13}Co , ^{51}V , ^{40}Ca , and ^{89}Y targets a 6 mm lucite Cerenkov detector, placed just downstream of the target, vetoed beam pions which did not interact in the target. The pions interacting with carbon nuclei in the Cerenkov detector provided a simultaneous measurement of energy and resolution for these targets. A resolution of 2.5 MeV was achieved. The

typical experimental spectra are shown for ^{28}Si and ^{89}Y in fig. 3. The ground state cross sections, as calculated from DWIA, are in good agreement with experimental results.

From these data the binding energies of the s, p, d, f, and g single-particle states are well fit [4] to a potential of the form

$$-V(r) = V_1 f(r)$$

where $V_1 = 28 \text{ MeV}$, and $f(r) = [1 + \exp(r-c)/a)]^{-1}$

with $c = r_0 A^{1/3}$, $r_0 = 1.128 + 0.439 A^{-2/3} \text{ fm}$,

as shown in fig. 4. These binding energies provide a "textbook" (the quote is from ref. 5) example of single particle structure in nuclear physics, and illustrated the utility of the Λ as a probe of deeply-lying shell model orbitals.

One important question has to do with the spreading and escape widths which result from the coupling of these single particle excitations with the dense background of hypernuclear excitations. The obvious importance of these widths are easily demonstrated by comparing fig. 3 to fig. 5. It is clear that the experimental resolution does not adequately account for the broadening of the π, K lines and that a spreading width must be involved. These spreading and escape widths, while smaller than the single-particle spacings, are clearly of the same magnitude as the resolution widths. We have therefore to admit the fact that improved spectrometer resolution will not be useful to sharpen the observed separation between the single particle states. In this regard, however, the situation is exactly the same as in nuclear physics.

The γ -ray spectroscopy of heavy hypernuclei remains an unexplored field. If we admit the likelihood that ground-state spin-dependent multiplet

spacings are so small as to be essentially unobservable, we are left with either observation of the transitions between core states, whether collective or single particle in nature, or of intershell γ transitions. The $P \rightarrow S$ and $D \rightarrow P$ transitions will be observable in principle in most hypernuclei. Rosina [6] has pointed out the usefulness of observing such transitions, and their competition with nucleon emission, to fix the precise parameters of the Λ potential well. For heavy hypernuclei, where the (π, K) cross sections become small, the population of deeply lying states by nuclear Auger emission after formation of the substitutional states in the (K, π) reaction may offer the only way of examining nuclear structure. It would indeed be exciting to view the effect of the presence of the Λ on nuclear collective motions. These studies will play an important role in future hypernuclear spectroscopy.

3) Exp. 828--A Search for Eta-Excitation in Nuclei

The eta (η) meson is a pseudoscalar meson member of the $SU(3)$ octet containing pions and kaons. It is closely related to the π^0 meson, with whom it shares identical quantum numbers of spin, parity and charge-parity, differing from the π^0 in isospin ($I=0$ for the η) and in quark content. The η has a mass about 400 MeV heavier than that of the π^0 , and this mass is ascribed to its large $(s\bar{s})$ component.

While bound nuclear mesonic states have often been suggested, none has ever been observed. Several suggestions of the existence of η -bound states have been published [7-8]. Stimulated mainly by the work of Liu and his co-workers, a search for such excitations was undertaken at the AGS, using the (π^+, p) reaction. The $N\text{-}\eta$ channel of the $N^*(1535)$ resonance is known to be attractive and it dominates η production near threshold. Liu predicts nuclear bound η states for mass numbers larger than $A=10$, with widths which increase with binding energy and A ; for $A=16$, the expected width is near 10 MeV.

The calculated total cross section for η production in the (π^+, p) reaction peaks near 740 MeV/c. The differential cross section for S-state η -mesic nuclear production peaks near $\theta_{\text{LAB}} = 15^\circ$, and for ^{16}O the cross section is predicted to be highest; hence ^{16}O is the ideal target for the search.

The experiment was carried out with the Moby Dick spectrometer at the Low-Energy-Separated Beam I at the AGS at an increasing pion momentum of 800 MeV/c, near the optimum as predicted by Liu. Using the program RAYTRACE, momentum coordinates could be calculated with the highest precision for the spectrometer. Figure 6 shows a $^{12}\text{C}(p, p')$ spectra taken as a resolution test; the figure indicates a FWHM total resolution of $2.4 \text{ MeV}/c^2$, which is more than adequate for the η search. For cross section calibration and for determination of the momentum acceptance of the spectrometer, the $^1\text{H}(\pi^+, p)\pi^+$ reaction was used at $P_{\text{beam}} = 525 \text{ MeV}/c$. In this reaction the backward scattered proton is near 700 MeV/c, which is the desired setting for the (π^+, p) reaction on nuclei. To span the mass region of interest, we choose to look at targets of lithium, carbon, oxygen (in water), and aluminum. Lithium was expected to yield, according to theory, a null result. To cover a sufficiently broad momentum region, three different spectrometer settings--657, 700, and 740 MeV/c--were selected at $\theta_{\text{LAB}} = 15^\circ$, and the results were pieced together using the spectrometer acceptance function of fig. 7.

The results [9] are shown in the composite fig. 8. These spectra bear a strong resemblance to recent (p, p) data published by Garreta et al. [10], who were attempting to observe possible $\bar{p}$ nuclear states. The search for an η state is complicated by the presence of the large proton background due to the π^+ -induced continuum processes which result in proton ejection. The data for these four targets can be fit with a Maxwellian continuum function over this

range; however, below the point corresponding to the η -production threshold (denoted by an arrow) one sees clear evidence of an increase which is undoubtedly attributable to η production. An η nuclear bound state would be expected (for carbon, oxygen, and aluminum) near the position of the arrow. None is seen.

An expanded scale for oxygen, showing the position and size of the expected η state predicted by Liu, is shown in fig. 9. Also shown there is a calculated η quasi-free spectrum, calculated assuming an effective member for η 's, $(N_{\text{eff}})=1$. Our statement of experimental sensitivity is the following: we would have seen a peak of one-third the size predicted at a confidence level of 3σ ($P = 0.9987$). Either the predicted widths are underestimated, or the predicted cross sections overestimated, or both, by a combined factor of at least three.

The size of the pion-induced inclusive proton continuum observed is much larger than that given in ref. 6. However, the observed continuum has been calculated by Divadeenam and Ward [11] using a standard Intranuclear Cascade (INC) Model code. Their result for aluminum is shown in fig. 10 and is in good agreement with experiment. For lithium, carbon, and oxygen, the INC calculation ranges from 10% to 30% lower than the data. Considering the simplicity of the INC Model, this may be regarded as adequate agreement.

Future Plans

In closing this report, it is appropriate to look forward to expected progress in the next five years. Our immediate goal is to complete a search for an $S = -1$ dibaryon by combining results from (K^-, π^-) on deuterium with (K^-, π^+) on ^3He . This experiment should be finished by early 1989. In about three years a high-intensity ($>10^6$) separated kaon beam line operating near 2.0 GeV/c will be complete and ready for double-strangeness studies through

the (K^-, K^+) reaction. This line will also provide pions useful for (π^+, K^+) and for $(\pi^+, K^+ \gamma)$ studies. The AGS will thus continue to serve as a valuable bridge to the era of the proposed kaon factories.

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Table I. Target Parameters.

Target	Thickness (g/cm ²)	$\langle P_{\pi} \rangle$ (MeV/c)	Run Time (hrs)	π^+ Intensity/ Spill at Target
¹² C**	2-4	1031.4-1034.4	13.5	0.2-1x10 ⁷
⁹ Be	2.35	1034.7	27	2x10 ⁶
¹⁶ O***	3.0	1033.5	43.4	2x10 ⁶
²⁸ Si*	4.0	1033.3	73.3	2x10 ⁶
⁴⁰ Ca*	4.13	1033.3	109.5	0.2-1x10 ⁷
⁸⁹ Y	3.95	1033.7	88	1x10 ⁷
⁵¹ V	3.48	1024.6	23	1x10 ⁷
# ¹³ C**	2.0	1032.0	23	1x10 ⁷

*natural target; **scintillator live target; ***H₂O target; P₀ for kaon spectrometer = 700 MeV/c; $\theta_{lab} = 10$ deg; #run in tandem with ⁵¹V, benzene live target (¹³C₆H₆) with 1.4 g/cm² teflon window on either side.

Figure Captions

- Fig. 1 Expected number of counts in a 6 keV resolution width for the $2^- \rightarrow 1^-$ $^{10}_\Lambda\text{B}$ ground state multiplet.
- Fig. 2 The experimental sensitivity for Exp. 781. This sensitivity is the observed counts, converted to a cross section, in 6 keV intervals.
- Fig. 3 Experimental (π^+, K^+) spectra for ^{89}Y and ^{28}Si (from ref. 4).
- Fig. 4 Single-particle binding energies for hypernuclei. The open circles are data from Exp. 798; the closed triangles are calculated in ref. 5.
- Fig. 5 A calculated (π^+, K^+) spectrum for $A=89$.
- Fig. 6 A resolution test for the Moby Dick Spectrometer.
- Fig. 7 The momentum acceptance function for Exp. 828.
- Fig. 8 The (π^+, p) spectra obtained for Exp. 828.
- Fig. 9 The (π^+, p) spectrum for ^{16}O near the eta threshold. The dashed line is the extrapolated continuum fit, and the solid line includes an eta quasi-free contribution. The eta-bound state signal is shown dotted.
- Fig. 10 An INC Model calculation for ^{27}Al (from ref. 11).

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FIG 4

FIG 5

FIG 6

FIG 8

FIG 8

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