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Statistical decay of hyperfragments

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Combining the unique features of the hypernuclear electro-production mechanism and the high precision in magnetic spectroscopy, the proposed E-08-012 experiment at Jefferson Lab, Virginia, and the scheduled hypernuclear experiment at MAMI, Germany, focus on the high-resolution spectroscopy of weak two-body decay pions from hypernuclei. These experiments will provide insight on a wide range of light hypernuclei via the production of hyperfragments from ^{9}Be, ^{6,7}Li and ^{12}C targets. In the present work we explore the production of Λ-hypernuclei following the micro-canonical break-up of an initially excited hypernucleus which is created by the electro/photo-production reaction. Finally the model is used to predict the pionic decay spectra and relative fragmentation yields for the hypernuclear experiment at MAMI.

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1. Introduction

Since the first discovery of hypernuclei some fifty years ago in cosmic ray emulsion studies, hypernuclear physics, especially with Λ-hypernuclei, has been used as an important way to extend the investigation of ordinary nuclear physics pertaining only nucleons (protons and neutrons) to a new dimension with a new degree-of-freedom, towards a unified description of the baryon–baryon interaction and structures of baryonic matter. A substantial gain in knowledge has been achieved by continued experimental and theoretical efforts. However, problems remain and can only be resolved by better precision, new techniques, new findings/discoveries, and improved theoretical understanding. One should note that none of the current leading YN models consistently agrees with experimental results for all measured few-body systems in terms of Λ binding energies of ground states and first excited states.

Extended theoretical and experimental investigations on more complicated hypernuclear structure in a wide range of charge (Z) and mass (A), different production mechanisms, and decays, are intended to understand the nature of the YN interactions and, in particular, the role of the Λ-hyperon, with its known features in free space, in the strongly interacting many-body medium. The study of light Λ-hypernuclei plays a crucial role in hypernuclear physics. Appropriate models for the ΛN and Λ-nucleus interactions must be able to describe optimally the Λ binding energies and separations of the ground state and the low lying excited states as well as their spin/parity. Th questions in theory are on the depth of the current theoretical understanding of the YN interaction and the reliability of current few-body calculations. A fundamental YN interaction model was constructed based on our understanding of the NN interaction and the extremely limited YN scattering data. It relies on structure studies of the $A \sim 5$ hypernuclei to verify its correctness.

The most influential data for $A \sim$ 3–5 systems came from emulsion experiments. In terms of the experimental data, one question is the reliability of the emulsion data analysis, given the level of complications in terms of calibration and event recognition. Emulsion results are the only available information on the ground state Λ binding energies for most of the few-body hypernuclei as well as some of the p-shell hypernuclei which could not be produced directly by other production mechanisms in the past. Until now, the ground state Λ binding energies of most of the light hypernuclei ($A \leqslant 15$), except the drip line hypernuclei, come primarily from emulsion measurements of decades ago. Poor statistics and insufficient energy resolution made it impossible to carry out more detailed studies by emulsion experiments. The ground state spin/parity of many light hypernuclei is either not known or unconfirmed. Many puzzles remain unresolved. For instance, only 16 events were recognized and assigned to be from the ${}^{7}_{\Lambda}$He hypernucleus but are spread over various excited energies, *i.e.* no distinct peak could be seen. Thus, the ground state Λ binding energy could not be given by emulsion data until the recent observation of the ground state in the directly electro-produced missing mass spectroscopy from the E01-011 (HKS) experiment at JLab [1]. However, no low lying excited states were seen. Therefore, the debate about the existence of hypernuclear isomeric states continues.

All the important observations of the excited states of light hypernuclei have come from high resolution γ-transition spectroscopy, especially the measurements achieved in recent years by the Hyperball program with experiments done at KEK-PS and BNL-AGS, see e.g. [2]. With excellent energy resolution, the observed transitions provide valuable information on hypernuclear structure leading to understanding of the spin dependent terms of the Λ-nucleus interaction. Most of the observed transitions appear surprisingly well described by simple shell model configurations. However, the latest results from $^{10}_{\Lambda}$B and $^{11}_{\Lambda}$B indicate that problems remain; something new must be added, and additional information that may have to come from different observations is clearly needed. It is unclear if current puzzles arise from the existence of isomeric hypernuclear states that have never been clearly identified or whether the spin order assignment for the ground states is incorrect.

One clear disadvantage for the γ-spectroscopic program is that no ground state Λ binding energy could be determined. On the other hand, limited by the primary production reactions, either (K,π), (π,K), or (γ,K), only a handful of light hypernuclei could be produced and studied, far fewer than in emulsions which utilize weak and other observable decays from various subsequent fragmentations (hyperfragments) from initially produced hypernuclei.

Missing mass spectroscopy experiments were developed based on modern accelerator and counter technologies. They have significant advantages in terms of production rate, statistics, and the capability of observing states with a Λ-hyperon in various orbits in a large mass range. In addition, governed by the difference in momentum transfer, related to the formation probability, production reactions can selectively produce hypernuclei with different spins. Although the resolution has been greatly improved from a few MeV (experiments at CERN, BNL, and KEK) to a few hundred keV (experiments at JLab) [2], which enables one to measure deeply bound configurations with various spin-orbits and shell levels with improved binding energy precision, the resolution is still not sufficient to resolve the issues associated with ground-state doublets, low lying states separated only by a few hundred keV, and to confirm the spin order, which is quite essential. Discrepancies between experiments on missing mass spectroscopy and theory in terms of binding energies and cross sections are commonly seen. Overall, experimental data on Λ-hypernuclei from emulsions, γ-spectroscopy, and missing mass spectroscopy has led to significant gains in knowledge of baryon with strangeness in the nuclear medium, thus beginning to uncover the secret of the YN interaction. However, some key ingredients appear still missing or undetermined. Theoretical studies have emphasized the importance of ΛΣ-coupling and ΛNN three body forces. They remain to be investigated in light hypernuclear systems which may not be produced easily by conventional primary reactions. Therefore, new findings and high precision data on key light hypernuclei are critically needed.

Since the 1970s, the development of the translational invariant shell model in an attempt to interpret substitutional hypernuclear states (core particle hole — Λ particle) has led to an important prediction: large yields of hyperfragments. When the mass of a hypernuclear state lies above a certain nuclear breakup threshold, the system breaks up into a lighter hypernucleus plus nuclear fragment(s). This mechanism has been successfully used to produce hypernuclei that are not easily produced directly from primary reactions.

On the other hand, it also means that a variety of light hypernuclei can be formed from the Λ quasi-free continuum following strong nuclear cascade processes, *i.e.* Λ recapture followed by nucleon emission or fragmentation, including drip line hypernuclei. The quasi-free Λ can be viewed as a Λ hyperon that strikes the residual nucleus in either a “virtual” process or a real rescattering process from an independent target nucleus. It is a rich source for light hypernuclei with wide range of (Z,A). Accessing them directly from the continuum by using the currently available

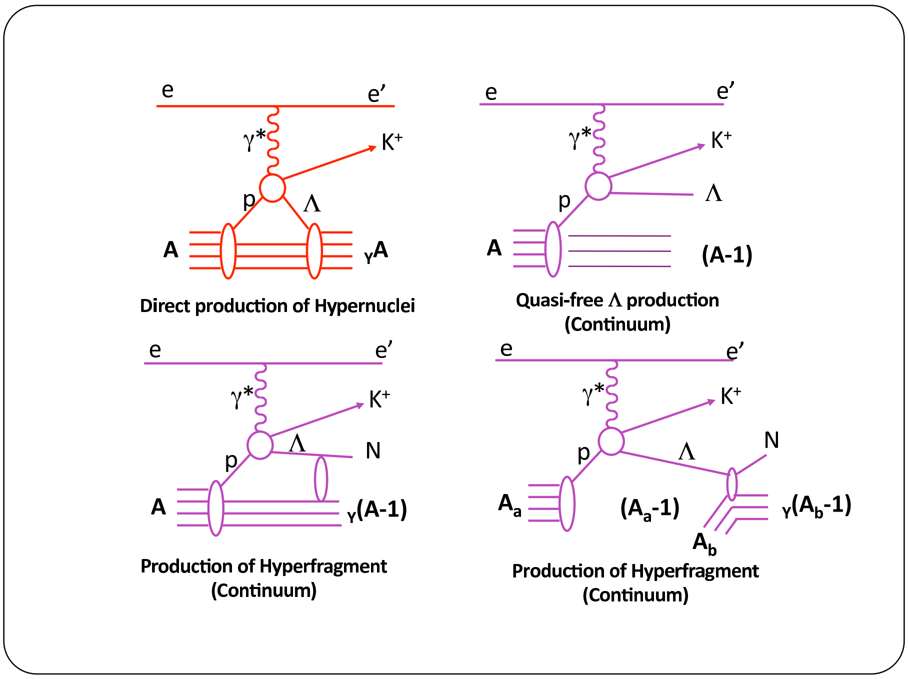

Figure 1: (a) Electroproduction of a bound hypernucleus; (b) A real quasi-free process in which the residual nucleus can be treated as a spectator; (c) A "virtual" process in which a Λ is considered to be "recaptured" to form a lighter hypernucleus while the excitation energy is released by ejecting nucleon(s); and (d) A real Λ re-scattering process off an unrelated target nucleus which forms a hyperfragment (a light hypernucleus) while releasing nucleon(s) or nuclear fragment(s) similar to (c).

experimental techniques and facilities is either impossible or extremely difficult. Therefore, it has been ignored, except for a few applications in experiments that study hypernuclear weak decays. The only way to access these light hypernuclei, primarily their ground states, from the primarily produced continuum is through mesonic weak decay ($\Lambda \rightarrow \pi^- + p$) inside the nuclear medium, which has an energy release below that due to Fermi motion. This in-medium decay features high sensitivity to the spin/parity structure and dynamics of the ground state hypernucleus, and thus may provide crucial information that we do not have yet. However, high resolution and high initial yield of the continuum are the keys to studying π^--spectroscopy from the continuum.

2. Continuum phase of hypernuclei as a rich source for a variety of hypernuclei

The hypernuclear continuum refers to the production of a quasi-free Λ in the continuum energy phase with respect to the residual nuclear core in a two body frame work. Using Λ electro-production , the production of a hypernucleus or a free Λ is illustrated by diagrams in Fig. 1.

The process as shown in Fig.1(a) is the well known one which has been used by the JLAB Hall A and C experiments to measure the mass spectroscopy of bound hypernuclei electro-produced by the primary A(e,e'K$^+$)$_\Lambda$A reaction. By absorbing the virtual photon on one proton from the target nucleus, the K+ and Λ are associatedly produced. A bound hypernucleus is formed by coupling the Λ back to the residual core with various level and spin/parity configurations. Some well defined unbound states with sufficiently narrow decay widths may also be formed appearing above but close to the Λ particle emission threshold in the continuum region. This is similar to production by the (π, K) reaction in which the elementary electro-production is replaced by the strong strangeness associated production reaction or by the (K, π) reaction which replaces it with the strong strangeness exchange reaction. These different production reactions provide selectivity with respect to the spin configurations of the produced hypernuclei because of differences in momentum and angular momentum transfers to the Λ. All current experimental investigations on spectroscopy of hypernuclei use these types of processes, depending on the facility.

The other three processes all contribute to quasi-free production. In mass spectroscopy they cannot be distinguished but form a summed distribution of masses or excitation energies starting from the Λ particle emission threshold with respect to the ground state core nucleus. This energy spectrum is more forwardly peaked and less pronounced when the reaction has small momentum transfer to the Λ, but broadened, strongly produced, and extended up close to about 400 MeV in excitation energy above threshold when reactions with large momentum transfer are used, such as (e,e'K^+) at JLAB, (π, K) at BNL and KEK, or (K_{stop}, π) at FINUDA. However, they are rather different in terms of the final state produced since two of them can actually create a variety of lighter hypernuclei or hyperfragments. For the case as shown in Fig. 1(b), the process represents free Λ production from nuclei. This production contributes no physics to hypernuclei and can be described well by Plane Wave Impulse Approximation (PWIA) calculations in which the Λ is treated basically as a free particle taking most of the momentum transfer from the primary reaction while the residual core is simply a spectator. This free Λ decays via the well known weak (ΔS=1) mesonic modes: $\Lambda \rightarrow \pi^-$ + p (64%) or π^0 + n (36%).

Other than the final state, the case shown as (d) in Fig. 1 is just a part of the case (b) in the overall contribution to the quasi-free mass distribution; thus, they cannot be distinguished and separated in terms of PWIA calculations.

In contrast in the sense of the final state, in the processes shown in Fig. 1(c) and (d) the Λ interacts either with the residual nucleus in a "virtual" process or with an independent target nucleus in a real re-scattering process. A significant portion of these reactions can result in production of hyperfragments or lighter hypernuclei by emitting nucleon(s) or a light nucleus (d, t, ^{3}He, α, or others) or combinations. Since a Λ lives long enough (decaying only weakly) while the reaction process is rather fast, the final state light hypernuclei may be reached in multiple steps through a cascade process, i.e., a sequence of break ups. About 60 MeV above the Λ emission threshold, almost all channels for possible light (below target mass A) hypernuclei are open, i.e., the energy is above all the break up thresholds. Therefore, the continuum is a rich source of a variety of hypernuclei, or hyperfragments which have been known for a long time, including those held important but which have not been seen and thus remain undiscovered by other means [3]. For example, it has been known that a Λ increases the binding of nuclear cores which may be unbound and unstable; the neutron drip line may thus be increased. Study of highly neutron rich hypernuclei and a search for heavy hyper-Hydrogen were suggested even at early stage of hypernuclear physics [4] and their importance has been continuously emphasized [5, 6]. They may hold the answers to questions about the role of Λ-Σ mixing [7] and the existence of long-lived isomeric states. The hyperfragment process from the continuum may become an effective source to access these important hypernuclear isotopes.

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Only limited Λp scattering data exist, primarily the total cross sections that do not adequately constrain potential models [8]. Thus, precise predictions of the cross sections for hyperfragment production or for formation of lighter hypernuclei by Λ scattering off nuclear targets cannot be made reliably at the present time. However, study of lighter hypernuclei produced by the breakup of heavier hypernuclei (above nuclear break up thresholds) has already used. As one of the examples, ${}^{5}_{\Lambda}$He (used recently to study extensively the non-mesonic weak decay) is commonly produced from the breakup of ${}^{6}_{\Lambda}$Li which is first produced by primary reaction, since no ^{5}Li or ^{5}He targets are available as direct production targets. More significantly, the ground states of many light p-shell hyperrnuclei, which could not be directly produced by primary reactions, were measured in emulsion by recognition of certain decay modes. On the other hand, light hypernuclei, such as ${}^{3}_{\Lambda}$H, ${}^{4}_{\Lambda}$H, and ${}^{5}_{\Lambda}$He, were found as hyperfragments from a wide range of nuclear targets (Li, Be, C, N, O, Ca, Ag, and Br) [9]. However, none of the past and current experiments can really utilize the rich continuum. Nevertheless, from the limited experimental information it is believed that roughly 10% of all quasi-free products from primary reactions convert into hyperfragments or lighter hypernuclei following the processes in (c) and (d) as shown in Fig. 1, in which the process (c) is considered dominating.

3. Statistical decay model

For light nuclei with mass numbers $A \leq 13$, even a relatively small excitation energy may be comparable to their binding energy. In the following we therefore assume that the principal mechanism of de-excitation is the explosive decay of the excited nucleus into several smaller clusters. To describe this break-up process and in order to estimate the population of individual excited states in single hypernuclei, we have developed a statistical decay model which is reminiscent of the Fermi break-up model [10, 11]. We assume that the nucleus decays simultaneously into cold or slightly excited fragments [12]. In the case of conventional nuclear fragments, we adopt their experimental masses in ground states, and take into account their particle-stable excited states. For single hypernuclei, we use the experimental masses and all known excited states. For double hypernuclei we apply theoretically predicted masses and excited states [13, 14].

In the model we consider all possible break-up channels, which satisfy the mass number, hyperon number (*i.e.* strangeness), charge, energy and momenta conservations, and take into account the competition between these channels. Since the excitation energy of the initially produced double hypernuclei is not exactly known, we performed the calculations as a function of the binding energy of the captured Λ-hyperon. Calculations were performed for several stable secondary targets, ^{9}Be, ^{6,7}Li and ^{12}C, which lead to the initial production of excited states in single hypernuclei. Figs. 2,3,4 show the relative hypernuclear fragmentation yields from ^{7}Li, ^{9}Be, and ^{12}C targets as a function of the excitation energy as predicted by the statistical decay model.

4. Model predictions for the hypernuclear experiment at MAMI

At the Mainz electron accelerator MAMI, a hypernuclear decay pion experiment is scheduled in the A1 spectrometer facility for Summer 2011. In this experiment, the electron beam of 1500 MeV energy will be incident on a ^{9}Be target, electro-producing quasi-free hyperons in the

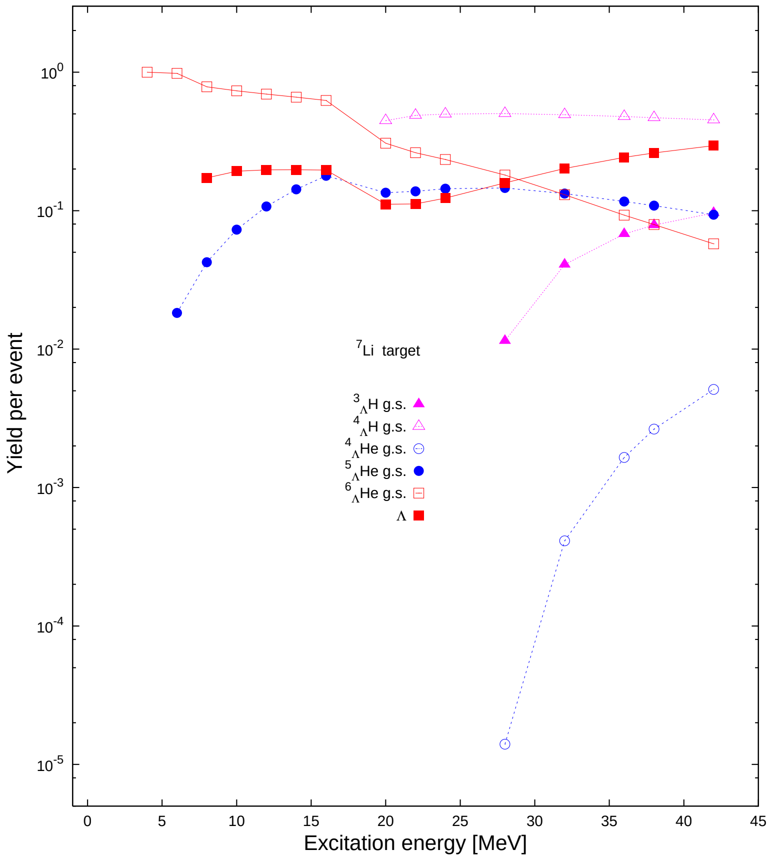

Figure 2: Relative hypernuclear fragmentation yields from ^{7}Li target as a function of the excitation energy as predicted by the statistical decay model.

continuum in association with a charged kaon emitted dominantly in forward direction with respect to the beam. These kaons will be tagged by the KAOS spectrometer and coincident pions from the weak decay of the hyperfragments can be detected by the high-resolution spectrometer C under backward angles. Details of the experimental set-up are given in Table 1. Spectrometer C utilizes a quadrupole–sextupole–dipole–dipole magnet combination achieving a large acceptance and high resolving power. The central optical axis of the spectrometer will be normal to the target plane so that the energy-loss uncertainty of the decay pions will be minimized. The KAOS spectrometer has been operated since 2008 in strangeness electro-production experiments.

In the quasi-free electro-production process on light targets the excitation energies available for the formation of hyperfragments are in the range of 10–50 MeV, according to measured missing mass distributions at Jefferson Lab [15].

The estimate for the formation probability of a initially excited $^9_\Lambda$Li* has large uncertainties that come from the unknown binding process of the quasi-free produced Λ-hyperons to the core nuclei. The formation depends very much on the transferred momentum to the hyperon. The kinematics of the hypernuclear experiment at MAMI, however, is comparable to the kinematics at the proposed

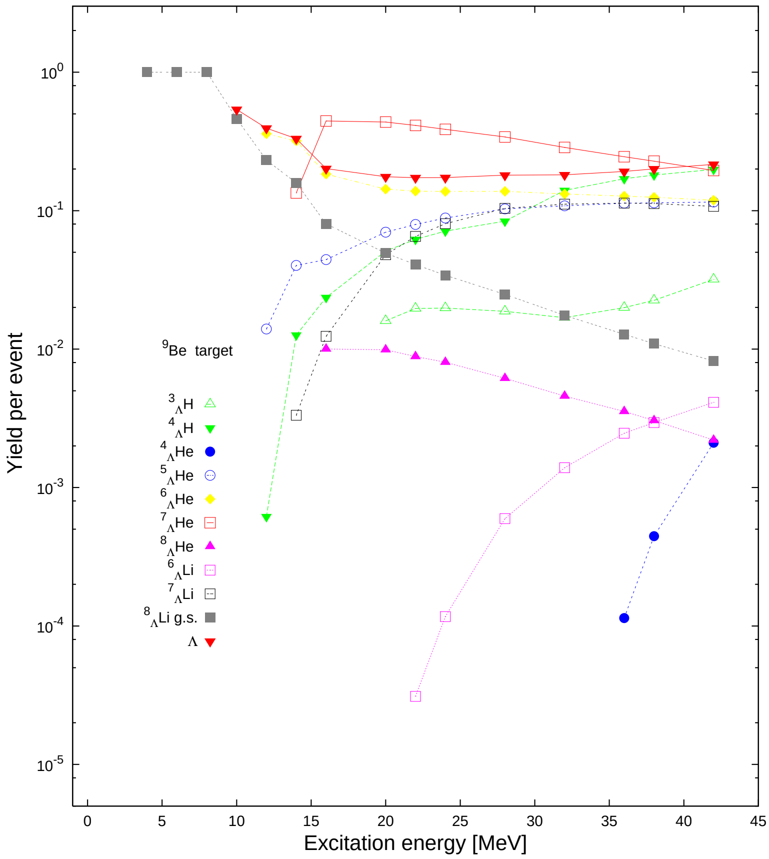

Figure 3: Relative hypernuclear fragmentation yields from ^{9}Be target as a function of the excitation energy as predicted by the statistical decay model.

JLab experiment. If the momentum transfer is large compared with typical nuclear Fermi momenta, the hyperon will emerge from the nucleus. One possibility to model the formation process is the introduction of a sticking probability as for example in [16], assuming harmonic oscillator wave functions for the bound hyperon. For the estimate of a minimum formation probability, the sticking probability was modelled with an exponentially falling dependence on the momentum difference between hyperon and nuclear core including the Fermi Gas distribution of the nuclei. The minimum was found to be $\varepsilon \geq 0.002$; Ref. [17] gives a maximum estimate of $\varepsilon \leq 0.2$.

For the estimate of the fragmentation yield following the initial formation in the ^{9}Be target, the results from the statistical decay model were used. The largest predicted yields for small excitation energies were found for $^{7}_{\Lambda}$He hyperfragments and free Λ-hyperons with $\sim 20\,\%$, and $^{8}_{\Lambda}$Li, $^{6}_{\Lambda}$He, $^{4}_{\Lambda}$H hyperfragments with $\sim 10\,\%$ respectively. The total probabiltity for an initially excited $^{9}_{\Lambda}$Li* to de-excite into hyperfragments is $\varepsilon_{frag} \sim 0.7$.

For the detection of the hyperfragments via their decay products, they need to be stopped inside the target. Fig. 5 shows the probability of different hyperfragments to be stopped as a function of the ^{9}Be target thickness. The initial momenta are predicted by the model and are of the order of

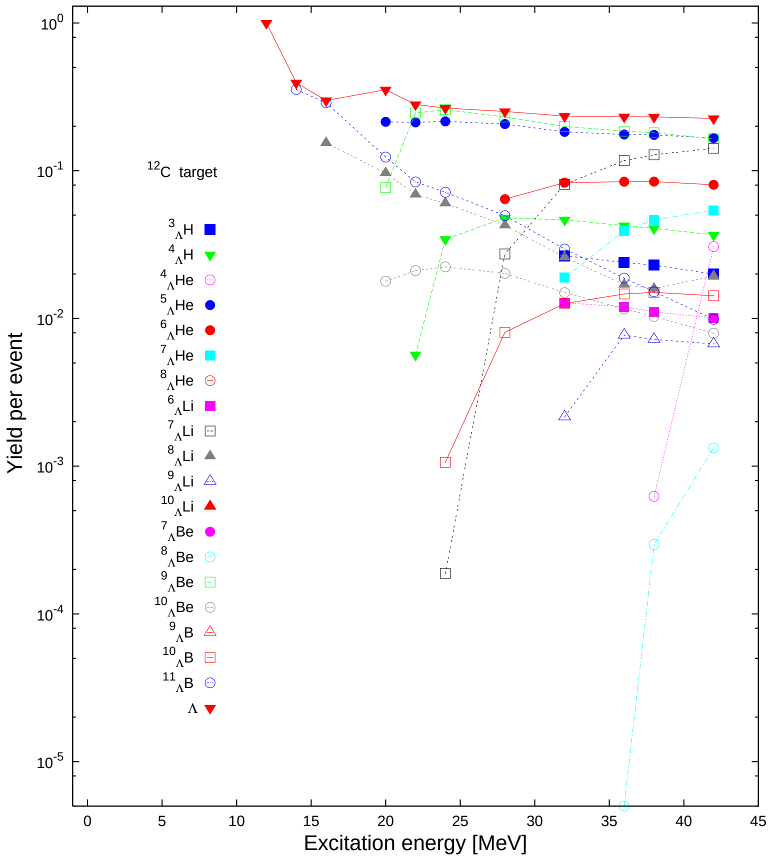

Figure 4: Relative hypernuclear fragmentation yields from ^{12}C target as a function of the excitation energy as predicted by the statistical decay model.

100–300 MeV/c. It is seen that most hyperfragments with charge numbers $Z > 1$ are stopped in thin targets of thickness 100–500 μm. For hydrogen the increase in stopping probability is 30 % in that range. The maximum probability is limited by surface losses. The decay pions have a discrete momentum lying in the range $\leq$ 133 MeV/c and will leave the target. Fig. 6 shows the predicted line shapes and relative yields of the pions from the two-body weak decay of hyperfragments stopped in a ^{9}Be target. The monoenergetic lines are broadened by the energy straggling inside the target material. The average stopping probability of the hyperfragments in a 125 μm thick target for which the decay pions are inside the spectrometer momentum acceptance is $\varepsilon_{stop} \sim 0.87$. It is assumed that pions are emitted isotropically within a mean life time of $\tau \sim 200$ ps. The pion detection efficiency in spectrometer C is given by the efficiency of the drift chambers for minimum ionizing particles, 98 %.

The pionic decay yield was estimated from (i) the elementary reaction kinematics and cross-sections, (ii) the statistical decay model for the fragmentation probabilities, (iii) the stopping probabilities for the hyperfragments, (iv) the two-body decay branching ratios, and the spectrometer acceptances, efficiencies, and particle survival fractions. To calculate the rate for elementary $K\Lambda$

Table 1: Experimental set-up of the scheduled hypernuclear decay pion experiment at the Mainz Mictrotron MAMI. For the forward-angle kaon tagging the KAOS spectrometer is used, for the backward-angle pion detection spectrometer C (SpekC) of the A1 spectrometer facility [18] is used.

	SpekC	KAOS
central momentum (MeV)	120	900
central angle wrt beam (°)	126	0
momentum acceptance (%)	25	50
solid angle acceptance (msr)	28	12
dispersive angle acceptance (mrad)	± 70	± 185
do. (°)	± 4.0	± 10.6
non-dispersive angle acceptance (mrad)	± 100	± 20
do. (°)	± 5.7	± 1.14
length of central trajectory (m)	12.03	5.3
first-order momentum resolution	$< 10^{-4}$	$\sim 10^{-3}$
target thickness (μm)	125–500	
target angle wrt beam (°)	54	

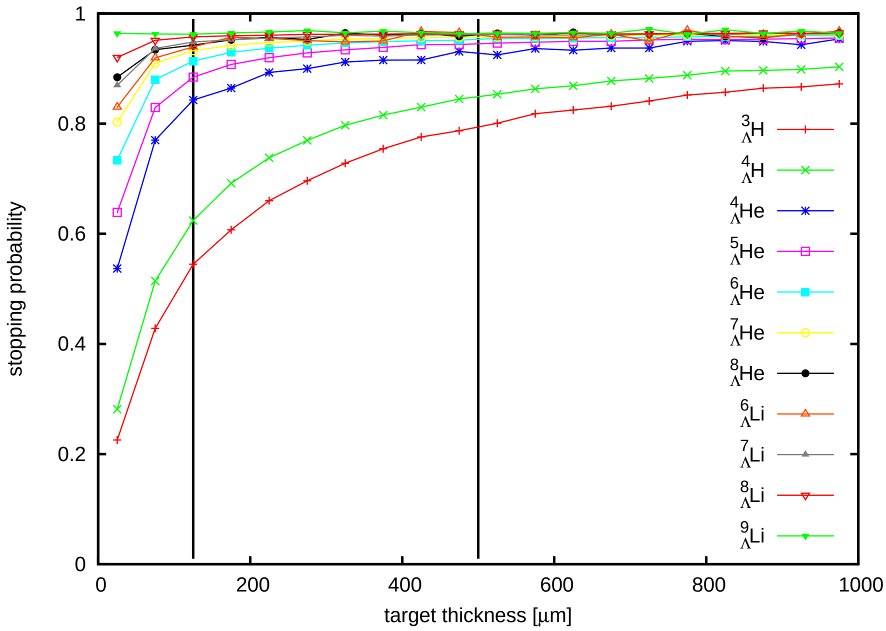

Figure 5: Stopping probability of hyperfragments as a function of the ^{9}Be target thickness. The vertical lines indicate the target thickness range available at the hypernuclear experiment at MAMI. Most hyperfragments with charge numbers $Z > 1$ are stopped in thin targets of thickness 100–500 μm.

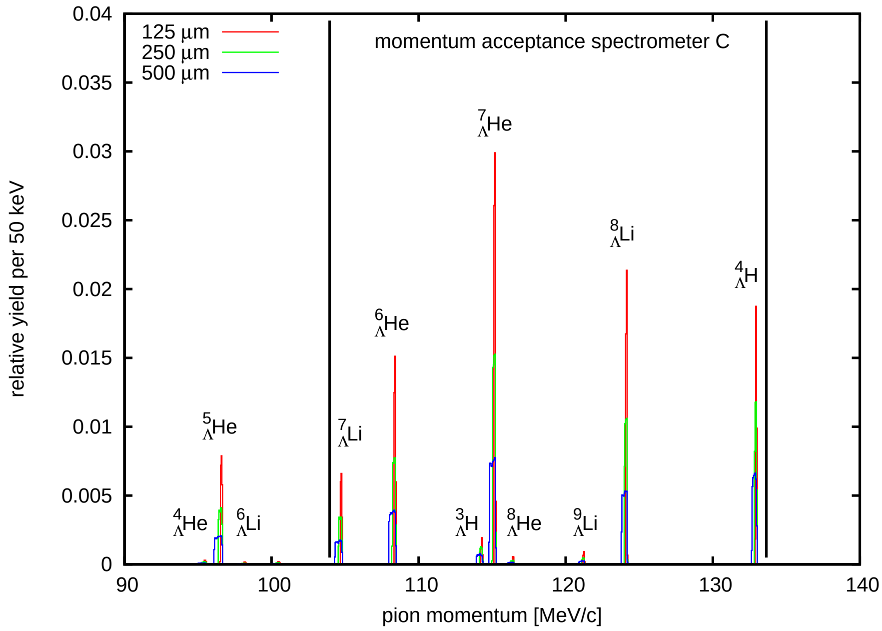

Figure 6: Relative yield of charged pions from the two-body weak decay of hyperfragments stopped in a ^{9}Be target as a function of its thickness. The monoenergetic lines are broadened by the energy straggling inside the target material. The momentum resolution of the spectrometer is better than the bin width and the vertical lines indicate the momentum acceptance of the spectrometer around (120 ± 15) MeV/c. The yield calculations are based on the statistical decay model and include the pionic two-body decay branching fractions.

electro-production at small kaon angles, $\theta < 30^\circ$, the experimental data for the differential cross-section of $0.2\,\mu\text{b/sr} < d\sigma/d\Omega < 0.35\,\mu\text{b/sr}$ was used [19]. From the total cross-section inside the KAOS spectrometer acceptance and the target density the rate of kaons per μA of beam current is estimated to be $R/I \sim 160$–280 Hz$/\mu$A. For a central trajectory length of $L_K = 7$ m including the penetration of all time-of-flight and Cherenkov detectors in the KAOS spectrometer and a typical 850 MeV/c kaon momentum, the kaon survival fraction evaluates to $\varepsilon_{survK} = \exp(-L_K/\beta_K\gamma_K\tau_K c)$ = 0.3, where τ_K is the kaon life time at rest of 12 μs and β_K, γ_K are the kaon Lorentz factors. The branching fractions for the pionic two-body decay mode of the light hyperfragments are of the order of $\Gamma_\pi/\Gamma_\Lambda \sim 0.2$–$0.3$ and the pion survival fraction in spectrometer C is $\varepsilon_{surv\pi} \sim 0.2$. With the given spectrometer acceptances and efficiencies the daily coincidence rate for the hypernuclear experiment at MAMI is calculated to be 0.4–55 hyperfragments/day/μA. In the real experimental conditions we will have three sources of background: i) promptly produced pions; ii) decay pions from quasi-free produced Λ-hyperons and three-body decays of hyperfragments; iii) accidentals.

5. Conclusions

In this paper the role of high-resolution decay pion spectroscopy for light hypernuclei is discussed. The physics subjects which can be investigated by means of decay pion spectroscopy include for example the study of YN interactions. A micro-canonical decay model is used to describe the break-up of an excited hypernucleus after the absorption of a Λ-hyperon. For different targets nuclei, fragmentation yields were predicted.

The main goal of the Jefferson Lab proposal E-08-012 and the scheduled hypernuclear experiment at MAMI is to to carry out decay pion spectroscopy from light production targets like ^{6,7}Li or ^{9}Be and to precisely measure binding energies and life-times of produced light hypernuclei and hyperfragments. The model is used to predict the pionic decay spectra and relative fragmentation yields for the kinematics and the setup of the hypernuclear experiment at MAMI.

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