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Pioneering Experiment for High Resolution Decay Pion Spectroscopy of Light Hypernuclei at MAMI

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At the Mainz Microtron hypernuclei are produced by (e,e′K) reactions. A dedicated kaon spectrometer located at 0° with respect to the electron beam is used to detect kaons emitted in forward direction thus tagging events involving strangeness production. Excited hypernuclei created in the primary reaction are likely to fragment creating a variety of different light hyperfragments. A large fraction of the hyperfragments is stopped inside the target and deexcites electromagnetically before the decay. Mesonic two body weak decay of these hyperfragments results in mono energetic pions. By measuring the momenta of these pions using high resolution magnetic spectrometers one gains direct access to the ground state masses of the produced hyperfragments. A ground state mass determination with a precision of better than 20 keV/c^2 is expected.

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1. Strangeness in nuclei

As it can be directly observed in the mass differences of non strange mirror nuclei, the strong interaction between protons is different to the one between neutrons. One important motivation to study hypernuclei is the possible difference between the hyperon-proton and hyperon-neutron interaction. A precise spectroscopy of hypernuclei ground state masses can help to measure this difference. Of special interest are here strange mirror nuclei like ${}^{4}_{\Lambda}$H and ${}^{4}_{\Lambda}$He.

1.1 Hypernuclear spectroscopy

To gain further information about the interactions in hypernuclei one needs to measure their masses with high precision. Different spectroscopic methods are available for hypernuclei.

A commonly used method is the missing mass spectroscopy which relies on the initial formation of a hypernucleus. By knowing the momentum of the particle in a primary beam on a fixed target and measuring the momenta of the scattered particles and the associated kaon one can determine the mass of the newly formed hypernucleus. Usually not only the ground state but a variety of excited states can be observed in the missing mass spectrum. Only a small set of hypernuclei can be charted by this method due to the fact that the target isotopes need to be stable. When using *eg.* an electron beam on a natural ^{6,7}Li target one can only measure the mass of the resulting ${}^{6}_{\Lambda}$He and ${}^{7}_{\Lambda}$He hypernuclei, while the ${}^{5}_{\Lambda}$He as well as the ${}^{8}_{\Lambda}$He and the ${}^{9}_{\Lambda}$He hypernuclei are not accessible by missing mass spectroscopy.

Another important spectroscopic method is the gamma spectroscopy. By using high resolution Ge-detectors, precise measurements of the energy differences of several excited states can be obtained. There are no limitations to which hypernuclei can be charted, the only requirement is, that it is produced in an excited state. One drawback of the gamma spectroscopy is, that no access to the absolute ground state mass and therefore the binding energy of the hyperon is feasible.

The decay pion spectroscopy opens the possibility to measure ground state masses of a variety of nuclei with extremely high precision within the same experiment and thus with small systematic uncertainties. This method concentrates on the mesonic weak decay mode of strange nuclei, which is dominant for light hypernuclei. In one of the possible decay channels, the lambda inside the nucleus decays into a proton and a pion, the proton remains in the nucleus and is often bound in the lowest lying state due to the limited amount of available energy, while the pion is emitted. From this two body decay, one can deduce the mass of the decaying hypernucleus by simply measuring the momentum of the decay pion. The only boundary condition is, that the hypernucleus is at rest before its decay.

The decay pion spectroscopy has been successfully performed at the FINUDA experiment at the DAΦNE $e^{+}e^{-}$ collider and decay pion spectra were obtained for ${}^{7}_{\Lambda}$Li, ${}^{9}_{\Lambda}$Be, ${}^{11}_{\Lambda}$B and ${}^{15}_{\Lambda}$N hypernuclei. Due to the detector geometry the momentum resolution for decay pions is limited leading to a hypernucleus ground-state mass resolution of the order of several MeV. Additionally in this experiment the branching ratios for mesonic weak decay $\Gamma_{\pi^-}/\Gamma_{\Lambda}$ and the ground-state spin-parity of the hypernuclei were studied. [2].

	SpekA	SpekC	KAOS
central momentum [MeV/c]	115	125	900
central angle wrt. beam [deg]	90	126	0
momentum acceptance [%]	20	25	50
solid angle acceptance [msr]	28	28	12
dispersive angle coverage [mrad]	±70	±70	±185
non dispersive angle coverage [mrad]	±100	±100	±20
length of central trajectory [m]	10.75	8.53	5.3
first order relative momentum resolution	$< 10^{-4}$	$< 10^{-4}$	$\sim 10^{-3}$
target thickness [μm]		125	
target angle wrt. beam [deg]		54	

Table 1: Important parameters of the experimental set-up. As high precision pion spectrometers, SpekA and SpekC are used because of their good momentum resolution. The KAOS spectrometer is used as a kaon tagger and therefore requires a wide forward angle acceptance as well as a high momentum acceptance.

2. Decay pion spectroscopy at MAMI

Using magnetic spectrometers to measure the momenta of decay pions from electro-produced hypernuclei was first proposed in 2007 at the Jefferson Lab [3]. This method combines the large production yield of the electro-production of hypernuclei with the high resolution of magnetic spectrometers.

In the first pilot experiment at the Mainz Microtron MAMI, $K^+\Lambda$ pairs are produced on a ^{9}Be target by a 1.6 GeV electron beam. By detecting the kaon, reactions involving strangeness production can be tagged. The scattered electron from the reaction is disregarded. With a certain probability the Λ hyperon is captured by the remaining nucleus and forms a highly excited $^9_\Lambda$Li hypernucleus, which due to its high excitation is likely to fragment into a lighter hyperfragment and one or more nucleons or light nuclei. Usually the newly formed hyperfragment deexcites electromagnetically to its ground state before its decay. At this point it is demanded that the hyperfragments are stopped inside the target, so that the decay takes place at rest. If a two body mesonic weak decay occurs, high resolution magnetic spectrometers are used to measure the decay pion momentum from which the ground state mass of the hyperfragment and therefore the binding energy of the Λ hyperon in the nucleus can be reconstructed. A clear identification of kaons in the pioneering experiment was however not possible due to the high flux of background particles in forward direction.

3. Experimental set-up

The electron accelerator MAMI consists of three stages of racetrack microtrons and one stage in the form of a double-sided harmonic microtron [4]. It can deliver a continuous wave electron beam with energies in the range of 180 MeV to 1.6 GeV and currents of up to 100 μA. The beam energy variance is only $\sim$110 keV, which allows a wide variety of high precision measurements.

One of the experimental facilities at MAMI is the A1 spectrometer hall in which three high resolution magnetic spectrometers are operated that can be positioned around solid state, liquid or

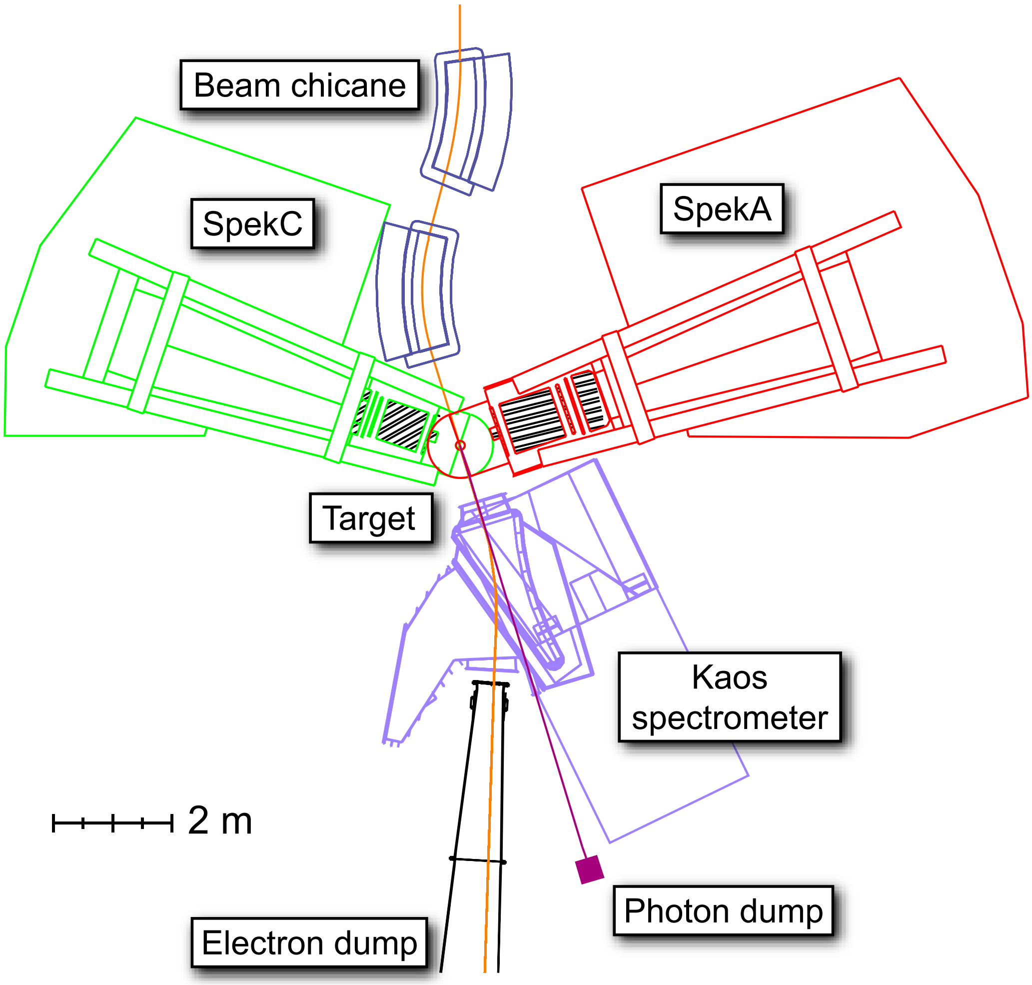

Figure 1: Set-up of the spectrometers for the decay pion spectroscopy. In this figure the electron beam enters from the top. The KAOS spectrometer used as a kaon tagger is placed at a 0° scattering angle. The decay pions can be detected either in SpekA placed at an angle of 90° with respect to the beam or in SpekC at an angle of 126°. In order to guide the excess electron beam onto the existing beam dump two chicane magnets deflect the primary beam before it impinges on the target. A secondary beam dump was build to capture bremsstrahlung photons.

high pressure gas targets at variable angles [5]. They are characrterised by a high relative momentum resolution in combination with relatively wide angular and momentum acceptances as shown in table 1.

With the KAOS spectrometer the A1 spectrometer hall was extended by a short orbit spectrometer dedicated to the detection of charged kaons which serves as a kaon tagger in the proposed experiment[6]. Its single dipole configuration allows to place the spectrometer at a 0° position in beam direction, which is of importance since the cross section for hypernuclei production peaks at forward kaon angles. In this position the electron beam is guided through the magnetic field of the spectrometer after impinging on the target. Positively charged particles are then deflected into a detector assembly consisting of two multi-wire proportional chambers and two time-of-flight

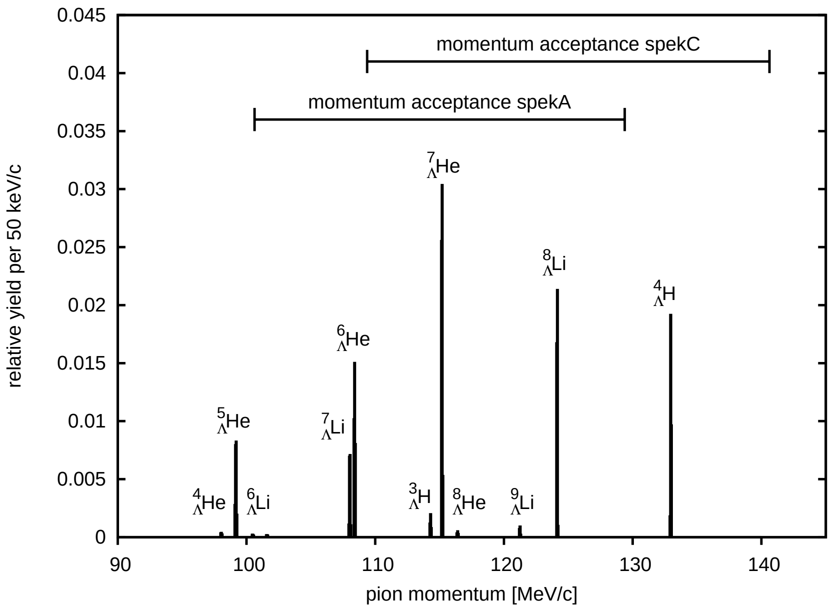

Figure 2: Expected pion spectrum of the experiment performed at MAMI. Since the pions are produced by a two body decay with a long lifetime ($\sim$ 263 ps) narrow peaks are the results which are only broadened by the variation of the energy loss of the low energetic pions inside the target foil. The relative fragmentation yields are taken from a statistical decay model [7]. With the wide momentum acceptances of the high resolution spectrometers it is possible to cover the decay pions of several different hypernuclei in one single experiment while still having a reasonable overlap region.

walls with an aerogel threshold Cherenkov detector in between. For the coincident detection of scattered electrons a detector of scintillating fibres is placed on the opposite side of the dipole. For the present experiment this detector was however not used. Important parameters of the KAOS spectrometer are shown in table 1.

Since the excess electron beam is deflected by the spectrometer, the primary electron beam has to enter it with a non zero angle in order to guide it onto the existing beam dump. Therefore it is directed onto the target with a predefined angle by two chicane magnets in the beamline upstream of the target. This angle has to be correlated according to the magnetic field strength of the spectrometer. For the given field strength of 1.2 T in this experiment, the beam angle was set to 17°. The set-up of the spectrometers and the beamline is shown in figure 1.

For the production of light hyperfragments basically every material can be used as a target, however the background from bremsstrahlung increases with the atomic number. In the studies at Mainz we therefore focus on low Z targets like ^{12}C, ^{9}Be and natural ^{6,7}Li.

Lithium as the lightest of the considered target materials offers the lowest electromagnetic background, the number of available hyperfragments is however small, the heaviest hypernucleus which can be produced is $^{7}_{\Lambda}$He. The main drawbacks of lithium are the difficulties in handling the material. It has a relatively low melting point of only 180.5°C. Since the electron beam deposits several watts of energy on the target foil, it needs to be cooled constantly. Another difficulty in handling it is the high reactivity which causes it to oxidise quickly when in contact with air. On a thin target foil even small layers of oxide can reduce the mechanical stability considerably.

The handling of carbon targets is easy and its heat resistance and stability makes carbon an excellent target for electron beams. On a ^{12}C-target several light hyperfragments up to $^{12}_{\Lambda}$B can be produced. However a major drawback of carbon is the bremsstrahlung background which is considerably higher than for lighter targets.

Beryllium offers a compromise between carbon and lithium. Even though the electromagnetic background is higher than for lithium it is lower than for carbon. The mechanical stability and heat resistance are similar to carbon and sufficient for this experiment. Several hyperfragments up to $^{9}_{\Lambda}$Li can be produced. The toxicity of beryllium does not offer a threat when it is handled carefully.

In this experiment a beryllium target was chosen with a thickness of 125 μm. Even though the probability of the hyperfragment to be stopped inside the target increases with its thickness, it was decided to use a thin beryllium foil, since the spread of the energy loss of the low energetic decay-pions which increases with the target thickness reduces the momentum resolution. This would lead to wider peaks in the pion spectrum and therefore a lower signal to background ratio. To reduce the energy loss variation even further, the target foil was rotated by 54° with respect to the beam, so it is perpendicular to the central trajectory of one of the high resolution spectrometers so the path length of the pion inside the target is minimised.

The expected resulting pion spectrum for this set-up is shown in figure 2. The relative fragmentation yields are taken from a statistical decay model [7].

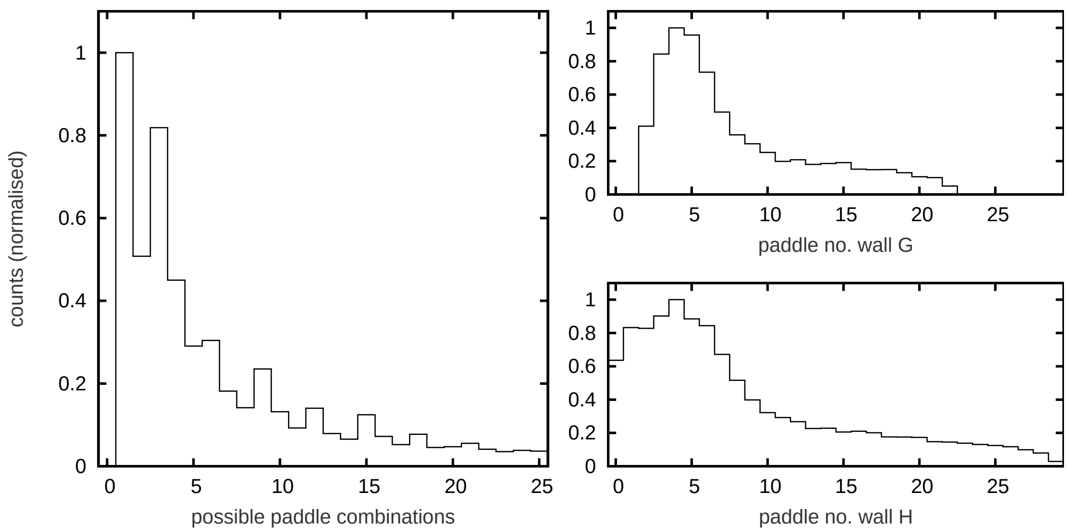

Figure 3: Distribution of particle hits in the two scintillator walls H and G (right). Multiplicity of hit combinations in the walls through which valid tracks can be reconstructed for a beam current of 5 μA (left). Each combination is treated as a possible track in the data analysis in contrast to the standard single track analysis. The fluctuations can be explained by combinatorial effects.

4. Data analysis strategies

The main difficulty in the analysis of the data acquired in this experiment is the high flux of background particles in the KAOS spectrometer. Most of which are positrons produced by pair production of bremsstrahlung photons in the target, but also pions and protons are detected in the spectrometer.

Experiments usually performed by the A1 collaboration, are high precision measurements with limited rates in all detectors. For this reason the analysis software was designed to handle only one particle track per event and spectrometer. In the case of the decay pion spectroscopy, in general several tracks can be found in the kaon tagger for every event. Some of which are caused by background particles, others are spurious tracks. Therefore the analysis code was matched to handle all possible tracks. Figure 3 shows the multiplicity of paddle combinations in the time-of-flight walls through which tracks can be reconstructed which originate in the target. If two neighbouring paddles are hit in one wall, three possible tracks are reconstructed for each hit in the other wall. One track of which leads through each individual paddle and one track crosses both neighbouring paddles simultaneously. This leads to a high number of events where three possible tracks can be reconstructed. Since it is unlikely that all three tracks correspond to real particles, the least probable of these tracks are dropped in a later stage of the analysis.

While analysing the data, the focus lies on the identification of tracks in the KAOS spectrometer that correspond to kaons. If kaons are identified, the narrow peaks from the coincident decay pions should become visible in the momentum spectrum of the high resolution spectrometer. But even if kaons cannot be separated clearly from all other background particles, an event sample

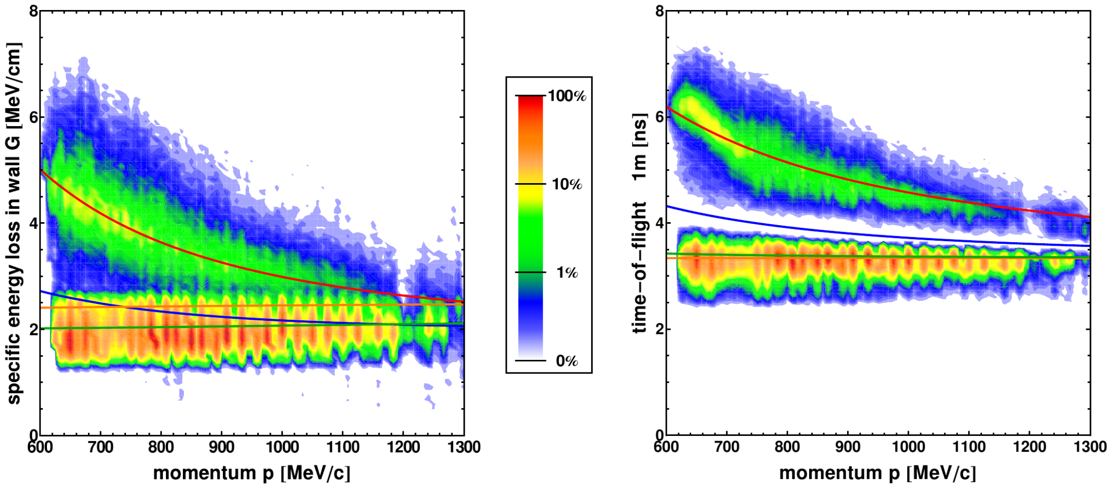

Figure 4: Particle identification in the kaon tagger by energy-loss in one of the scintillator walls (left) and single arm time-of-flight measurement (right) in dependence of the particle momentum. The lines are theoretical predictions for protons (red), kaons (blue), positrons (orange) and pions (green). In both cases the upper band corresponds to protons while the lower band comprises mostly positrons and pions. A clean separation of protons from other particles at least in the low momentum region is possible by each method alone, however the separation of pions, positrons and kaons is not possible even with a combination of both methods.

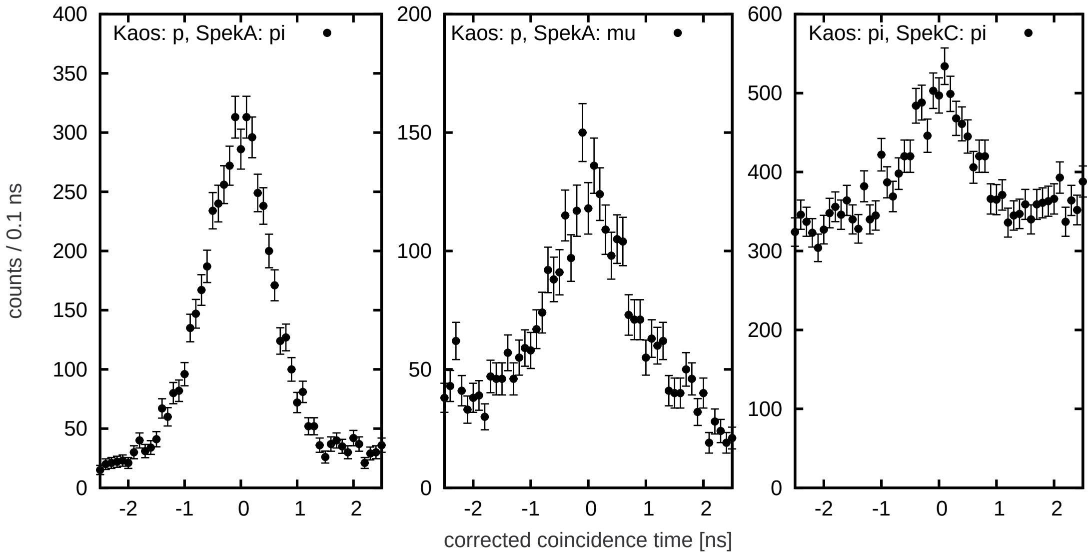

Figure 5: Coincidence time between the kaon tagger and one of the high resolution spectrometers corrected for proton-pion coincidences (left), proton-muon coincidences (center) and pion-pion coincidences (right). The width of the proton-pion coincidence peak is only $\Delta t_{FWHM} = 1.4$ ns. The enhanced background on the left side of the proton-muon coincidence time spectrum can be explained by pions decaying into muons during their flight through the high resolution spectrometer.

enriched in kaons can result in a pion momentum spectrum in which decay pion peaks stick up from the broadly distributed random background. To separate kaons from the background of other particles, several parameters are accessible in the spectrometer data: the single arm time-of-flight, the energy-loss in both scintillator walls, the aerogel Cherenkov information, and the out-of-plane angle of the particle.

Figure 3 shows the particle separation by measurements of the flight time between the scintillator walls in the kaon tagger and the energy-loss in both walls. In both cases protons can be cleanly separated from the background of positrons and pions. A clean separation of pions, positrons and kaons is however not possible with the usage of the KAOS spectrometer information alone.

For identified protons in the kaon tagger one can find coincident pions in the high resolution spectrometer as shown in figure 5, as well as muons originating from the decay of pions close to the target. Since pions can also decay during their flight through the high resolution spectrometer, a tail on the left side of the proton muon coincidence time peak is visible. The contribution of which is however small since the muon has to be emitted in the forward direction in order to be detected in the spectrometer. Even though pions can not be separated from the positron background as easily as protons, pion-pion coincidences between high resolution spectrometer and the kaon tagger can be identified in the coincidence time spectrum as it is also shown in figure 5.

The yield of kaons compared to the background is however so small, that it is not possible to retrieve a clean kaon sample. Therefore the parameters for the kaon identification were deduced from a different experiment in which kaons were clearly identified in the KAOS spectrometer since it was placed at a larger angle and therefore the flux of background particles especially positrons was significantly lower. The according cuts for kaons were then applied to the data acquired in the decay pion spectroscopy experiment. With these cuts the background in the momentum spectrum of the high resolution spectrometer was reduced by several orders of magnitude. However there are no significant peaks visible in the pion momentum spectrum of the data that has been collected up to now.

5. Conclusion and future improvements

The decay pion spectroscopy with high resolution magnetic spectrometers offers a way of measuring the ground state masses of several light hypernuclei in a single experiment. Some of these masses are not accessible by other types of spectroscopy. As the pioneering run has shown, the experiment is feasible but suffers from the huge flux of background particles, mostly positrons, and the resulting random coincidence rate. In order to improve the signal to background ratio one needs to reduce this flux.

One possibility to achieve this is to avoid that positrons enter the detectors by blocking their passage by lead absorbers inside the KAOS spectrometer. Simulations have shown that in the momentum range of 600 to 1200 MeV/c as it was used in the pioneering experiment a lead shield of 50 mm can absorb most of the positrons due to their creation of electromagnetic showers, while kaons in most cases are deflected only by a few degrees. For the placement of the absorbers one has to make a compromise between placing it close to the entrance of the spectrometer thus blocking the particles before they enter any detector but increasing the severity of the kaon scattering, and placing it in the backmost part of the detector assembly where the scattering of the kaons has little effect on the momentum reconstruction but the background particles contribute to the background in most of the detectors. If the absorber is placed inside the magnetic field of the spectrometer, low energetic shower particles leaking through the absorber are strongly deflected and will not hit the detectors.

By choosing a lithium target the positron background can also be reduced due to its lower atomic number. If a natural ^{6,7}Li target is used one looses the possibility to produce some of the heavier hyperfragments. The relative fragmentation yields will however change which might offer the opportunity to study hyperfragments more common in the fragmentation of $^{6}_{\Lambda}$He or $^{7}_{\Lambda}$He than in the $^{9}_{\Lambda}$Li fragmentation.

An alternative possibility to avoid the positronic background is to move the kaon tagger out of the 0° acceptance to a higher angle. Due to the spectrometer design, if it is not placed at 0°, it can only be placed at significant non-forward angles of the order of 30°. The wide angular acceptance will however still enable the detection of particles with scattering angles of down to $\sim$20°. In this kinematical region the Λ-hyperons would be produced with a higher momentum which will reduce the probability of the formation of a $^{9}_{\Lambda}$Li hypernucleus. This momentum can however be transmitted to other nucleons in Λ-nucleon collisions. These nucleons are likely to be emitted from the nucleus instead of the Λ. In this case not an excited $^{9}_{\Lambda}$Li nucleus is formed, but either a $^{8}_{\Lambda}$Li or $^{8}_{\Lambda}$He hypernucleus. The light hyperfragments will still be accessible by their fragmentation.

It is planned to implement these improvements for upcoming measuring campaigns in autumn of 2012.

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