Can we produce hypernuclei without recoil at COSY?

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Introduction

Strangeness in nuclear systems has been of interest since long time. The question of medium modifications of strange hadrons in nuclear matter is a popular keyword. Another point of interest related to that are hypernuclei. Here a Λ or a Σ hyperon is bound in a nuclear potential.[1] The modification of the Λ lifetime and decay ratios in a heavy nucleus have already been a subject of studies also at COSY [2]
A very successful story was and still is the spectroscopy of single Λ hypernuclei in counter experiments with the kinematical trick of close to recoilless (K^-, π^-) strangeness exchange reactions with large forward cross sections of about 10 mb/sr.
All high statistics counter experiments with hypernuclei so far were done with secondary beams of K^- mesons [3], [4], [5] or even π^+ mesons [6] They all suffer however from the problem of comparatively miserable beam quality: At best some 10000 K mesons per second are available, contaminated by much more pions in general, emitted into order of 100 π mm mrad emittance with duty factors around 0.1 with targets of big size and more than g/cm^2 thickness.
These experiments all need sophisticated spectrometers already for the incoming K-mesons.

If it were possible to study hypernuclei at COSY using the extremely high quality proton beam we might open a new and very rewarding field of physics here. It should be particularly interesting to produce and tag well defined hypernuclear states. The very small target volumes would be a great advantage for observing their further decays. Some points of interest are:

- Hypernuclei allow seeing shell model aspects in their cleanest approach.
- there is still debate if there are also Σ bound states [7], [8]
- the ΛN spin-orbit splitting is small.[9] Why that, and what about ΣN spin orbit splitting?
- is a hyperon in a nuclear potential completely free of Pauli blocking effects or are there blocking effects on the level of quarks,
- what can one learn from the modification of hyperon lifetimes and decay branching when they are bound in different nuclei?
- the weak lambda decay shows the lambda polarization. How is it related to the strange quark polarization or the polarization of the hypernucleus,
- there are observable gamma transitions between bound hypernuclear states
- out of small targets the decay products, mesons, nucleons and fragments may be identified,
- etc.

Recoilless production

If one wants to study the fate of strange hadrons in nuclear matter under cleanest conditions, one has to ensure a “cold” situation during production. The strange hadrons must have about zero relative energy with respect to the residual nuclear system.

A well-known and very effective way to achieve this is the trick with recoilless kinematics in the production. The direct strangeness exchange reaction

$$K^- + n \rightarrow \pi^- + \Lambda$$

can have Λ momenta around zero for K-meson momenta around 530 MeV/c. This reaction can proceed on a neutron in a nucleus and the resulting Λ is then embedded in the nuclear surrounding with minimal disturbance. This was proposed long ago [10], [11] and used at CERN [3], [12], BNL [13] and at KEK [14] with big success.
The transition from initial to final state depends on a folding integral with a momentum transfer dependent factor

$$<\Psi_f | \exp(-iqr) | \Psi_i>$$

Clearly for q=0 the exponential factor becomes 1 over the full range of the integration and the transition strength concentrates on few, target like states in the exit. With rising q and larger angles $\Delta L > 0$ transitions appear and distribute the transition strength over more, and more complex states shown in fig. 1 [12]

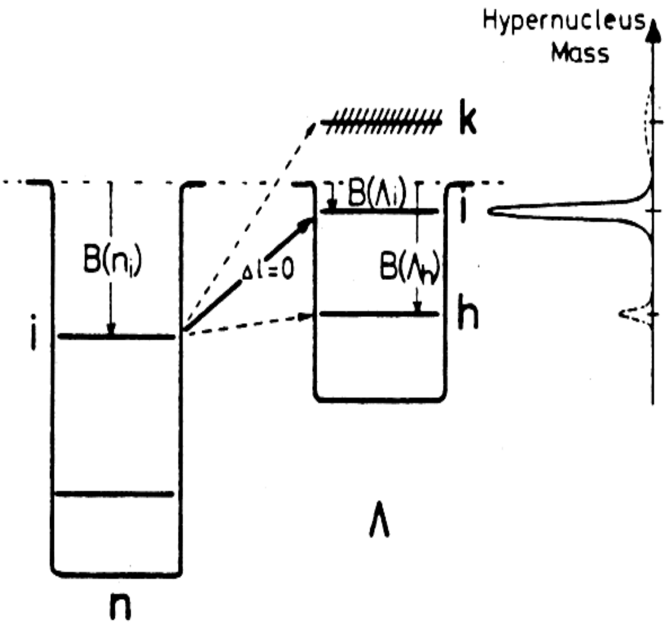

Fig. 1
Schematic spectrum of hypernuclear states built upon a neutron hole in state i = (n,l,j). For small Λ recoil the quasi- elastic transition $n_i \rightarrow \Lambda_i$ dominates and quasi-free satellite states, $n_i \rightarrow \Lambda_h$ or $n_i \rightarrow \Lambda_k$, are weak. The level spacings reflect the different Λ binding energies. On the right side a spectrum is indicated as measured with a ^{12}C target.[9]

We can assume a reaction mechanism with a single particle embedded in a nuclear core. With an oscillator model one can estimate the transition probability from a target nucleon state i = (n,l,j) to a Λ state with the same target like quantum numbers (nuclear Debye-Waller factor)

$$P_{i\rightarrow i} = \exp(-(2n_i + 1) E_{recoil}/D) \qquad (1)$$

Here n_i is the oscillator quantum number, $E_{recoil} = q^2/2m$ the recoil dependent energy of the built-in system and D the oscillator constant. [15] The total production probability of target like hypernuclear states will be a folding over this recoil energy dependent transition probability. One still needs to determine the distribution of low momenta (energies) for the built-in strange object. This is a question of kinematics and reaction mechanisms. The recoilless spectra found experimentally on ^{12}C and ^{16}O targets support this simple picture.[9]

Recoilless production with proton beams

Reaction mechanisms

At COSY we might take advantage of recoilless kinematics as well, if we create a strange hyperon (S = -1) at rest in a nucleus with an incoming proton. An S = 1 K meson has to be made as well then in associated production. An overall recoilless reaction of this type, which leads to a hypernucleus at rest, is kinematically possible. An example is:

$$p + A_{target} \rightarrow {}_{\Lambda}(A\text{-}1)_{hypernucleus} + \{ p + p + K + \varepsilon\} \qquad (2)$$

For simplicity we interpret the outgoing three particle system $\{ p + p + K + \varepsilon\}$ as a quasiparticle with its internal excess energy ε as parameter between 0 and the maximal possible cm excess energy in the reaction of eq. 2.
In more detail, the reaction mechanism can be assumed to be a spectator core R at rest. In its vicinity a reaction sequence occurs on two active nucleons. One is kicked out in a direct, strangeness producing reaction; a second one is converted to a low energy hyperon, which interacts strongly with the core R. This is shown in eq. 3

$$p + \{N + N + R\}_{target} \rightarrow \{ R + \Lambda \}_{hypernucleus} + \{ p + p + K + \varepsilon\} \qquad (3)$$

The outgoing quasi particle $\{ p + p + K + \varepsilon\}$ can carry away momenta close to the beam momentum and its four vector, if determined with sufficient precision tells the excitation energy of the hypernuclear state.

Evidently there is an underlying still simpler reaction mechanism (without the nearly passive core R)

$$p + \{ N+ N \}_{target} \rightarrow \Lambda + \{ p + p + K + \varepsilon \} \qquad (4)$$

or an even more reduced picture, assuming the injection of 177 MeV excitation energy (mass difference of Λ and p) without recoil into a nuclear medium.

$$p + N \rightarrow \{ 177\ \text{MeV}_{,\ S=-1,\ z=0\ \text{or}\ -1}\} + \{ N + N + K^{0\ \text{or}\ +} + \varepsilon\} \qquad (5)$$

Now excess energy, strangeness and charge are created like a particle, without transfer of momentum. This is a fast, direct knock out reaction. It might be seen as a far off shell anti-kaon production, analogous to the on shell reaction $pp \rightarrow K^- K^+ pp$ studied at COSY11.[16] There is no problem to describe such a far off shell process correctly in relativistic kinematics.In contrast to the πN case where there are no baryonic states with masses below $m_n + m_\pi$ there are the ground state hyperons Λ and Σ with masses below $m_\Lambda + m_K$. A "medium modification" of the anti kaon mass in a nucleus down to 177 MeV would create degeneracy with hyperons in nuclei. Due to the negative parity of the K meson a $\Delta L = 1$

transition would be needed. If on the other hand a $\Delta L = 0$ transition would be found, then the "177 MeV" object would not be an off shell K meson.

If the relative energy in the "quasi particle" is fixed for example **ε = (100) 200 MeV**, then "magic", recoilless kinematics happens in forward direction always for the same beam momentum **P_{magic} = (2920) 3270 MeV/c** independent on the mechanisms in eq 2 to 5 above. This is due to the fact that the magic beam momentum P_{magic} depends especially on mass differences ($m_{tgt} - m_A$) and not on individual masses.

$$(P_{magic})^2 = \{ \left((m_{beam}^2 + m_{out}^2) - (m_{tgt} - m_A)^2 \right)^2 - 4\, m_{beam}^2\, m_{out}^2 \} / (4\, (m_{tgt} - m_A)^2 \}$$

The reaction kinematics related to the three reaction mechanisms is shown in Fig.2. for an outgoing quasiparticle *{ N + N + $K^{0\ or\ +}$ +100MeV}* and "magic" beam momentum. Independent of the reaction mechanism (with the exception of small changes by binding energies or isospin dependent masses) there is zero momentum on the anti strange objects at zero degree.

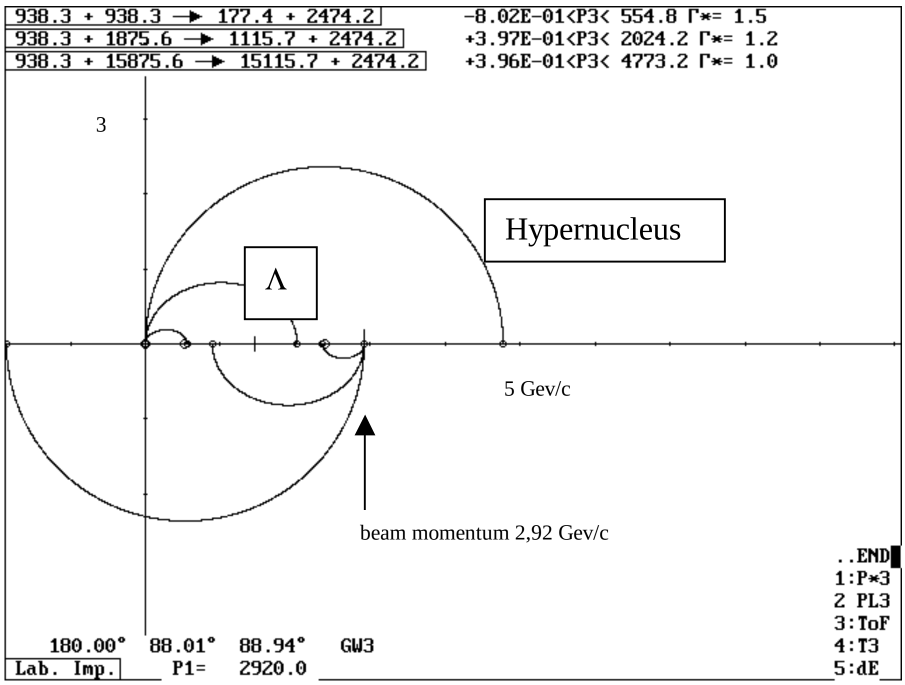

Fig. 2
Polar diagrams of lab momenta of outgoing particles in proton induced reactions with magic beam momentum, according to reaction eq. 3 (heavy target → hypernucleus - N), eq.4 (2N → Λ) and eq.5 (N → "$177_{s,z}$"). Momenta of the antistrange systems are shown in the upper half. They reach zero. The outgoing quasiparticle { N + N + $K^{0\ or\ +}$ +100 MeV} is always the same and its momentum distribution is in the lower half. It reaches beam momentum at zero degree with very different cm momenta for different target masses.

The fact that recoilless kinematics can also be achieved in endothermic reactions instead of exothermic (case of $K^- + n \rightarrow \pi^- + \Lambda$), was suggested some years ago.[17] As applications were mentioned pionic atoms, η mesons in nuclei, the injection of 300 MeV into nuclei for recoilless Δ production or even cool production of 1S holes in nuclei. This idea was one of the motivations to make COSY. [18] Recoilless production of pionic atoms has been established meanwhile in (d,^{3}He) reactions and is now the basis of a very successful research program at GSI. [19], [20] For recoilless Δ production exists an accepted COSY GEM proposal [21]

Reaction rates

Fig 3 shows the kinematics for proton-induced Λ production according to eq. 4 with different values for the excess energy ε in the outgoing quasiparticle. The largest ellipsoids correspond to ε= 0. No momenta outside of these lines can occur. The steps in ε are 100 MeV up to 400 MeV.A beam momentum of 3270 MeV/c is chosen which is recoilless for ε= 200 MeV.

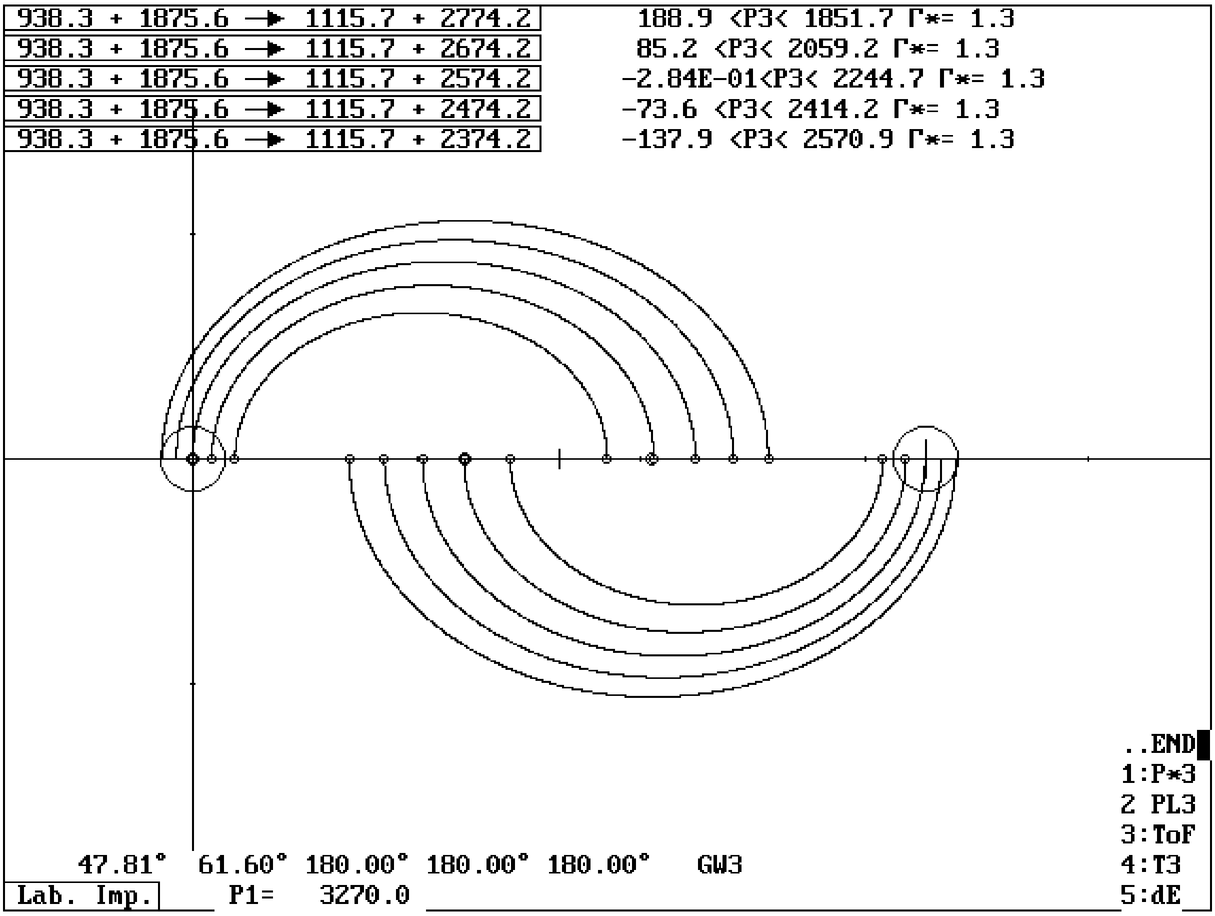

Fig. 3

Polar diagrams of the outgoing momenta in the process p + d → Λ + { p + p + K + ε }. The Λ momenta are in the upper half, the quasi particle momenta in the lower half. The biggest contours are related to an excess energy ε = 0. The smaller contours are related to 100 MeV steps in ε up to 400 MeV. Relevant for recoilless production are only momentum vectors within the circles of 140 MeV/c radius around zero and beam momentum. The lowest quasiparticle momentum still reaching the circle is 3136 MeV/c. The excess energy there is ε = 350 MeV. Its subsequent decay protons have the maximum possible angles of all cases and can never go beyond 38^0 in the lab system.

The circles around zero momentum and beam momentum have 140 MeV/c radius. They contain this fraction of the events where the lab energy of the Λ is less than 8.5 MeV. From this sample **target like** hypernuclear states may be created with a **fusion probability** of about $\mathbf{10^{-1}}$, according to eq. 1 (with n_i =1, D = 10 MeV)

In the circle around beam momentum are the interesting momenta of the related outgoing quasiparticle. Only those have to be accepted by the detector system. They have maximal

forward momentum and only small angular spread. Consequently the decay products (two protons and a K meson) have smallest possible angular spread. This helps to increase the acceptance.
In Fig 4 the fraction low energy Λ with momenta <140 MeV/c is shown as it results from a Monte Carlo calculation of the reaction eq 4 with a deuteron target. No further assumption about reaction dynamics was made. No Fermi momentum distribution between the two target nucleons or two step effects in the reaction are considered which might reduce the result or final state interactions between nucleons / hyperons which might enhance it.

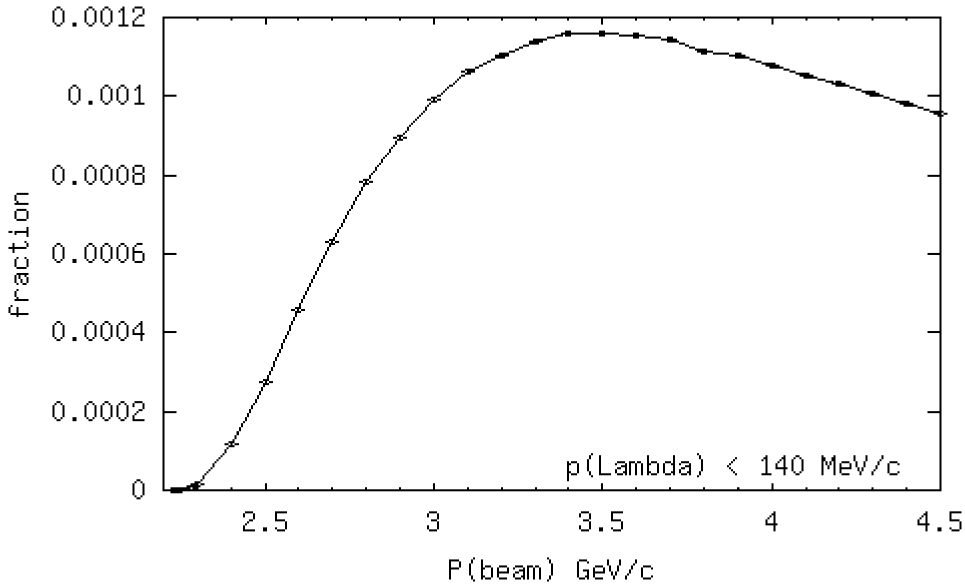

Fig. 4
Monte Carlo result for the fraction of Λ particles with lab. momenta <140 MeV/c in $p + d \rightarrow \Lambda + p + p + K^0$ as function of the beam momentum.

For beam momenta above 3000 MeV/c according to fig 4 a **low energy fraction** (Λ with <140 MeV/c) of about **10^{-3}** is expected.
The total cross section for $p + \{ N+ N \}_{target} \rightarrow$ anything is about 80 mb. The partial reaction cross-section for $p + \{ N+ N \}_{target} \rightarrow \Lambda + \{ p + p + K + \varepsilon \}$ should be at least like the 20 μb found at 3 GeV/c for $p + p \rightarrow \Lambda + p + K$.[22] or in other words at least a **branching ratio of 2.5 10^{-4}** of all p+2N reactions.
For a heavy target A the effective deuteron number will be (at least) about one. The total p+A cross section however will be about 0.5 $A^{2/3}$ 80 mb. For oxygen: $A^{2/3} = 6.4$ and the branching ratio for narrow hypernuclear states has still to be divided by 3.2.

Taking this together we may expect
a branching ratio of >2.5 10^{-4} of all p+2N reactions **leads to ΛppK.**
a fraction of >10^{-3} of them has low enough Λ energy
the fusion probability of those into narrow hypernuclear states is >**10^{-1}**
on a nucleus A the branching ratio has still to be **divided by $A^{2/3}$**

For $p + {}^{16}O \rightarrow {}^{15}_{\Lambda}C + p + p + K^+$ we expect as a result narrow hypernuclear states with a branching ratio of about 10^{-8} or a cross section of about 2 nb.

Experimental clarifications

COSY11

In order to proof that bound states are populated with the new production mechanism one needs 10 MeV resolution and one should reach 1 MeV resolution for a subsequent spectroscopy program.
COSY11 is the only set-up which may have at present the necessary resolution to allow a glimpse on bound hypernuclei at COSY. In the reaction $p + p \rightarrow K^- + p + p + K^+$ at a total excess energy ω_{exc} = 17 MeV above threshold, K^- masses are reconstructed with < 2 MeV fwhm resolution and a cross section of 2 nb is found. [16] The resolution in COSY11 scales with $(\omega_{exc})^{1/2}$. In hypernuclear production according to eq 2 with a 2920 MeV/c beam there is ω_{exc} = 1100 MeV. The scaling factor is $(1100/17)^{1/2}$ = 8 and we expect in the worst case a resolution of < 16 MeV fwhm. The missing mass spectrum of the hypernucleus is made from the measured four vectors of p, p and K^+ like in the elementary experiment.

With nitrogen or oxygen in the cluster target we want to search for

$$p + {}^{14}N \rightarrow {}^{13}{}_{\Lambda}B + p + p + K^+ \qquad \text{or} \qquad p + {}^{16}O \rightarrow {}^{15}{}_{\Lambda}C + p + p + K^+$$

The oxygen reaction ends up with a particularly simple configuration. Eight neutrons close up the $P_{1/2}$ shell and for the six protons the $P_{3/2}$ shell is filled. One can expect that the reaction strength concentrates to only few lines mostly with the Λ in a P state with about zero binding energy.
For hypernuclei we expect 2nb production cross section like in the elementary p+p reaction [16] which gave 60 events in a two weeks run.
Two facts however will reduce the observable hypernuclear events compared to the elementary ones:

the 3 body coincidence acceptance for outgoing $p + p + K^+$ which **is ~ 10^{-3} in** the elementary reaction at 17 MeV excess energy will be lower because of higher excess energy. The acceptance shrinks slower than $(\omega_{exc})^{-1/2}$ That makes a factor >1/8 in reconstructed events.
Fig 5 shows outer limit contours for possible K^+ and proton momentum vectors from the decay of forward quasi particles (see fig. 2) and how they overlap partially with the grey acceptance region. In the horizontal plane the acceptanc is not modulated and quite large. Most of the losses come from the low vertical aperture.

the target thickness may have to be less oxygen nuclei per cm^2 than there were protons per cm^2 in the elementary reaction studies. If one can make the same number then certainly good stochastic cooling is needed in order to compensate the stronger multiple scattering and absorption effects in the Z = 8 target.

We conclude that it is not sure that one can identify hypernucleus production in COSY11 in the present state of the art. We would expect to collect in a two weeks run about 10 events in a narrow target like state and additional events in satellite states at mostly higher energy but also in the ground state (ΔL = 1 transition into $1S_{\Lambda}$)

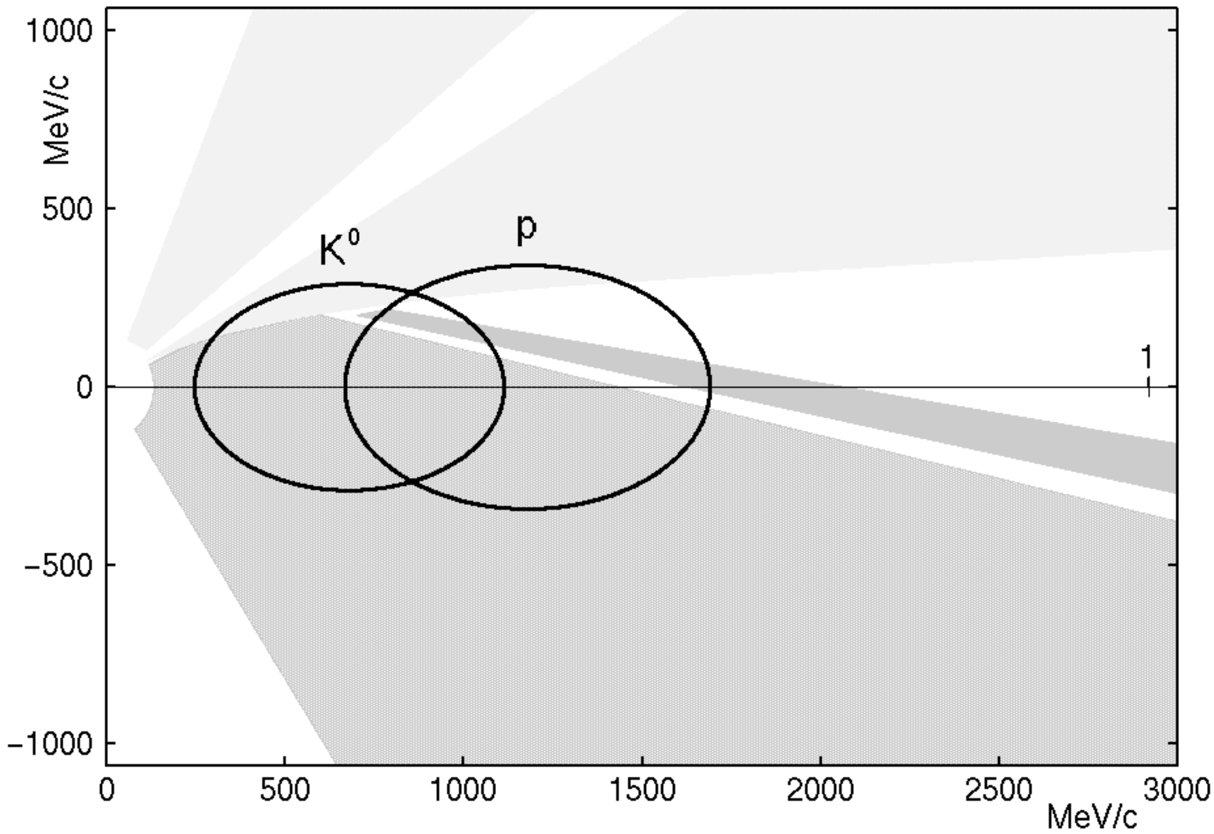

Fig 5
Acceptance of COSY 11 in longitudinal/horizontal momentum plane (grey regions) Also shown are the maximal contour lines for K^+ meson momenta and proton momenta coming from the decay of the quasi particle { p + p + K^+ + 100 MeV } as it comes with a beam momentum of 2970 MeV/c and hypernucleus production

With complex nuclear targets there will be always strong background from non-strange break-up into 3 or more charged tracks including pions, nucleons and fragments.
COSY11 with its comparatively good resolution provides the chance to study the spectral distribution of background evnts in the phase space region where the hypernuclei appear.

TOF

A direct way to learn about the relevant partial cross section for low energy Λ production at the magic momentum is to study the reaction

$$p + d \rightarrow \Lambda + p + p + K^0 \qquad (6)$$

with a beam of 3270 MeV/c (excess energy 306 MeV). This can be done with very large acceptance and kinematically complete at TOF over the full phase space. The phase space occupation in the vicinity of zero Λ momentum (compare fig. 4) can then be determined precisely by extrapolation
From TOF data we know that the cross section for $p + p \rightarrow K^+ + p + \Lambda$ is >20 μb at 2850 MeV/c (excess energy 170 MeV) and the missing mass resolution for the Λ is 20 MeV

fwhm.[22] On a deuteron we can expect a similar cross section for the reaction of eq. 6 and a Λ missing mass resolution also in the 20 MeV region.
The TOF acceptance is without holes up to $\theta > 60^0$ in the 3m version with Quirl, Ring and Barrel. The two prompt protons and the decay protons of the Λ from reactions like in eq 6 have >90% chance to be simultaneously detected in TOF. Should one of the protons be slow or go backward then the K_s decay tends to have particularly favourable high forward momentum. There are always still over constraints.
The delayed decay signatures either $K_s \rightarrow \pi^+ + \pi^{--}$ (BR = 69%, 50% of the K^0 are K_s) or $\Lambda \rightarrow p + \pi^{--}$ (BR = 64%) or in most of the cases both in coincidence provide a very selective trigger and a drastic reduction of all nonstrange background contaminations. The decay geometries act as decay spectrometers and allow determining independently the K and/or Λ four vectors.

As a by-product this measurement of $p + d \rightarrow \Lambda + p + p + K^0$ will also give good and complete data on the quasi free reaction

$$p + \text{“n”} \rightarrow p + \Lambda + K^0$$

with well determined spectator protons over a wide momentum range. The precision in this channel is particularly high with TOF because in a large fraction of the events two delayed decays can be used for kinematical reconstruction and over constraints. Also information on spectator protons with lowest possible energy will not be lost.

Possible consequences

If we find indications that recoilless selective population of hypernuclei is feasible at COSY then big efforts for necessary improvements are justified.

In the near future TOF will be upgraded to better resolution, trigger efficiency and insensitivity of meson decays
- by the straw tracker which is presently developed
- by an optimised start region

Very big improvements for the TOF luminosity and event purity can be expected from the pre cooled, halo free beams which were recently made for the first time.
One should check if these new conditions are already opening a chance to study hypernuclei.

COSY11 could of course go on if it is capable to resolve already hypernuclear states and collect reasonable rates.

On an intermediate time scale it seems necessary to build a WASA or CRYSTAL BARREL type detector.
- a system with full acceptance and high resolution magnetic analysis of charged tracks
- and a full acceptance shower detector around, allowing for precise neutral particle reconstruction
- the inner part for charged particles must be a good decay spectrometer as well (like in TOF).

Such **a full acceptance, charged and neutral particle spectrometer** is in any case that what is missing at COSY for everything and possibly for hypernuclei.

Requests

We ask for **1 week** beam time at **COSY11** in order to study at 2930 MeV/c on a oxygen (or nitrogen) cluster target the background situation in the region where the recoilless production of $^{15}{}_{\Lambda}C$ (or $^{13}{}_{\Lambda}B$) hypernuclear states occurs.

We ask for the permission to study during **1week** in addition to a hyperon beam time at **TOF** the reaction pd→ΛppK^0 at 3270 MeV/c, preferentially with TOF in its 3m version.

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