High resolution spectroscopy of deeply-bound pionic Sn atoms (S236)

Study of pion mass & pion decay constant in nuclei

&

Search for □/□-mesic nuclei (S214)

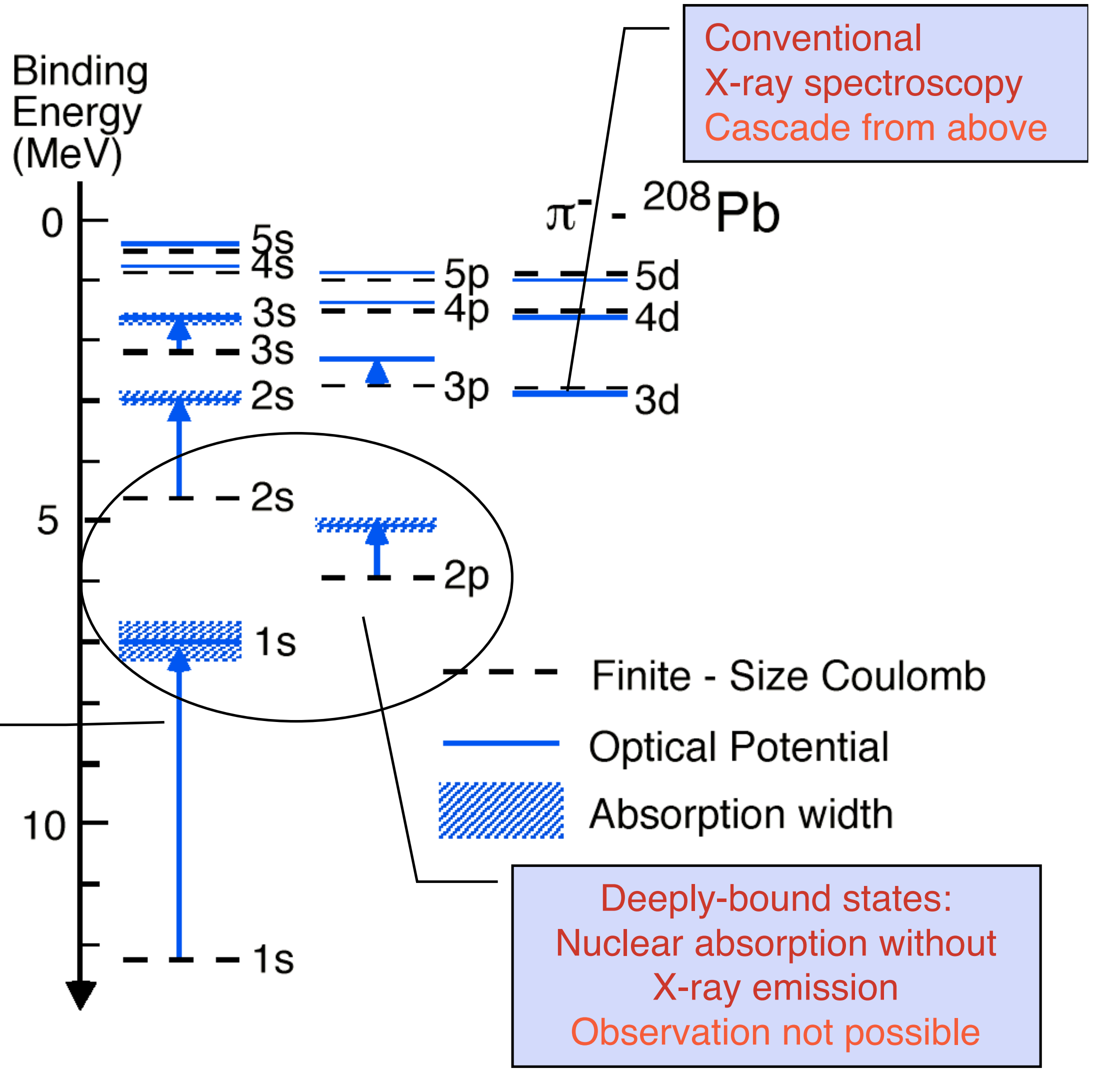
R.S. Hayano

CERN/Tokyo

For Tokyo - GSI - Münich - Jülich collaboration

What are deeply-bound states?

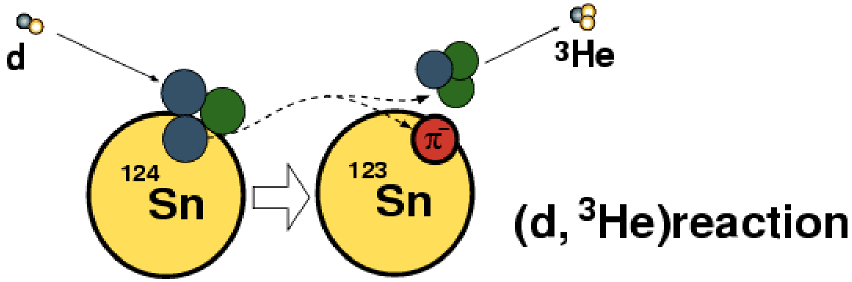
- States cannot be populated by the conventional X-ray deexcitation.
- Pion partially in the nucleus, but width < level spacing



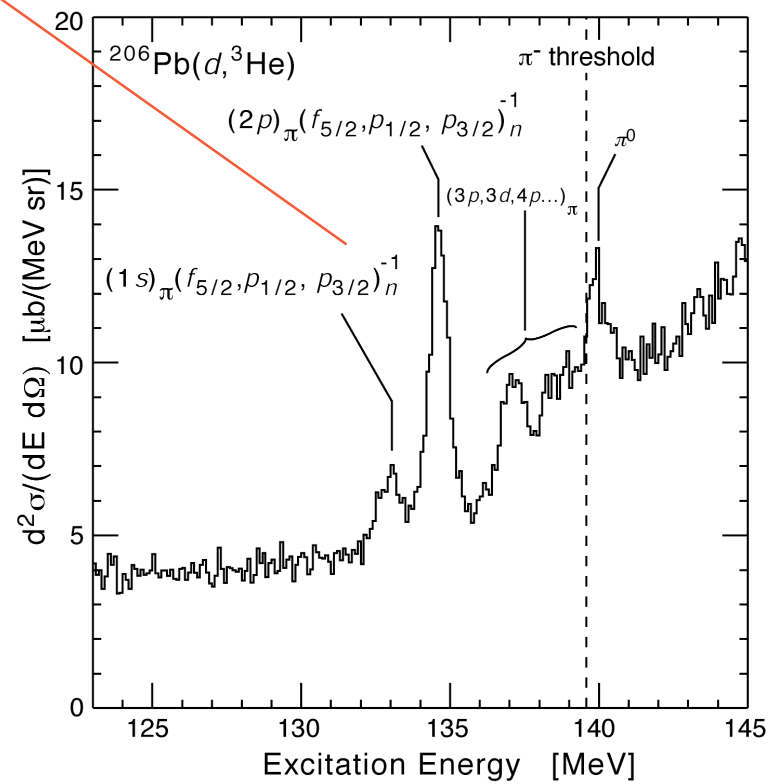
1s-state shift
= pion mass shift

What do we measure & what do we learn?

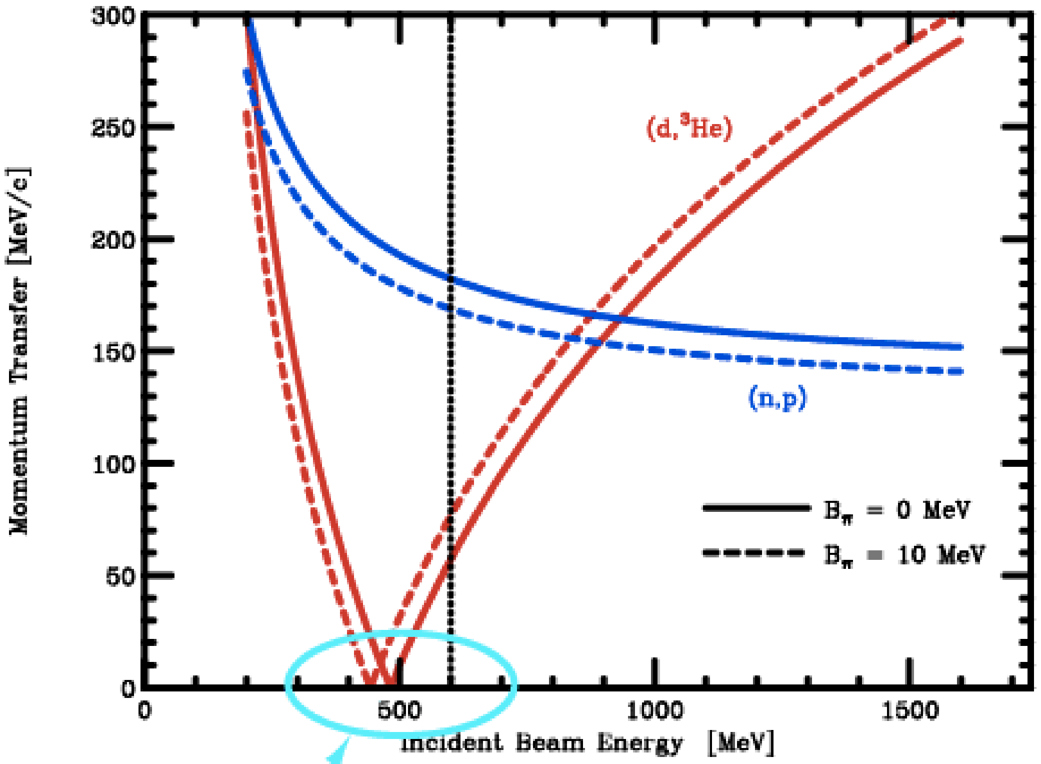
- Pionic 1s states produced by the (d,^{3}He) reaction @ T_d ~ 500 MeV (peaks in the Q-value spectra)
- Peak analysis → strong int. shift & width → pion mass modification in nuclei **(established in S160)**
- Recent theory by Weise et al., isotope shift → f_π modification (order parameter of chiral symmetry) in nuclei **(S236 motivation)**



π–transfer reaction
(charge exchange reaction)



Recoilless



recoilless condition

$\Delta q \sim 0$ -> $\Delta l = \Delta q \times s \sim 0$

(d, 3He) reaction

'magic' momentum

→ recoilless condition

→ ⊿l ～ 0

Large cross section

Deeply-bound meson-nucleus states

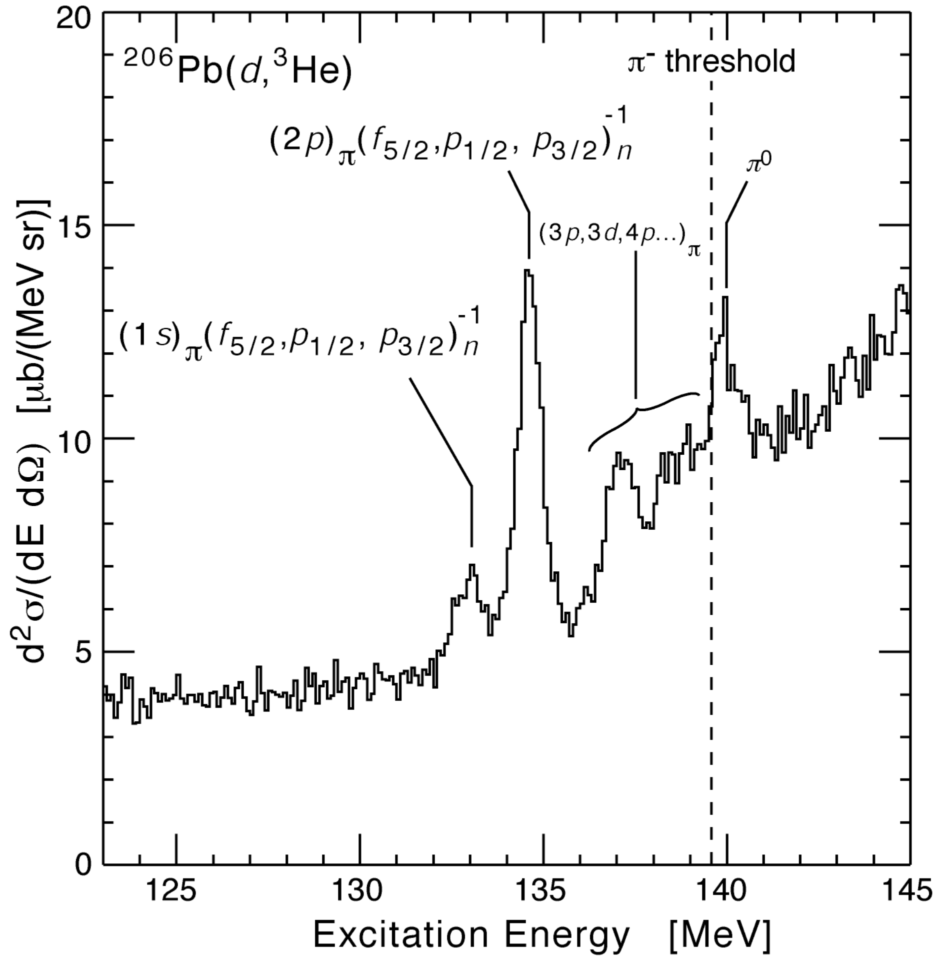
using recoilless (d,^{3}He) reactions

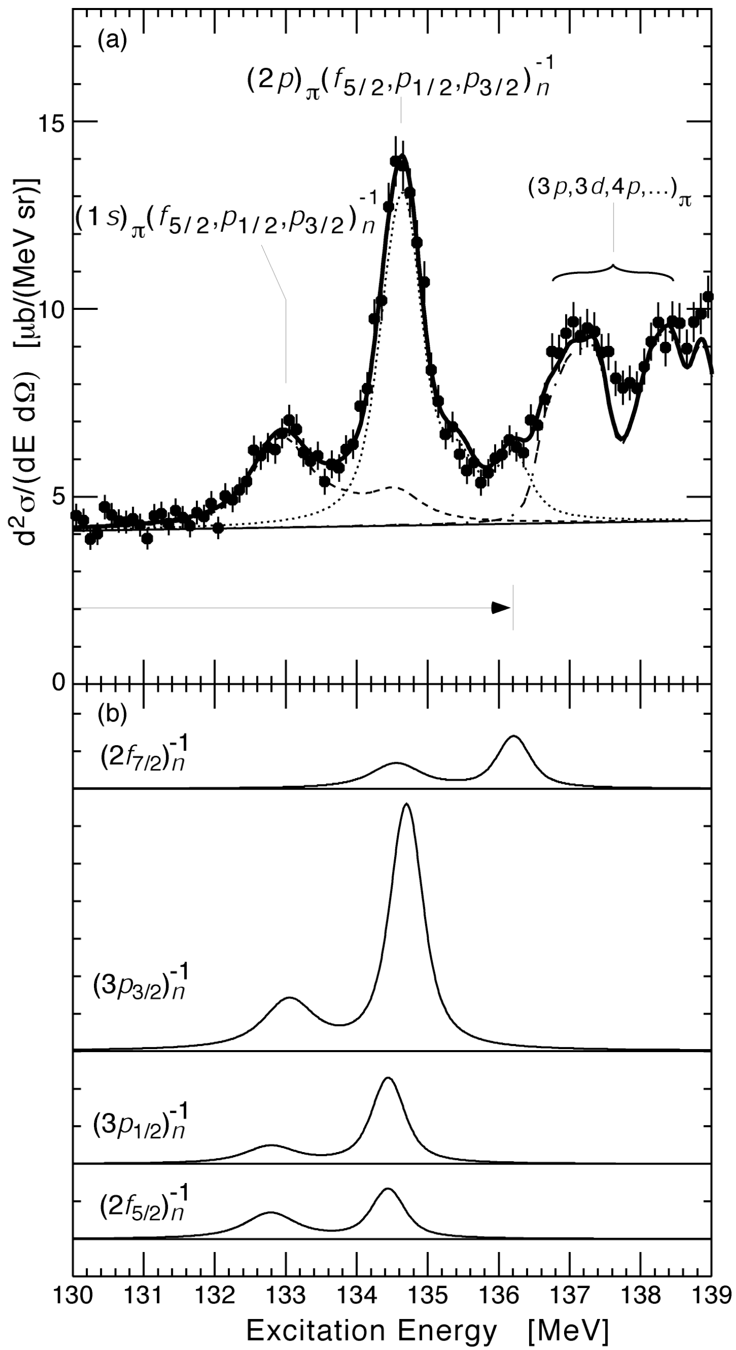
- GSI S160/S236 experiment:
  - discovery of the π^- ^{207}Pb 2p peak
    - H.Gilg et al., Phys. Rev. C62 (2000) 025201
    - K. Itahashi et al., Phys. Rev. C62 (2000) 025202
  - observation of the π^- ^{205}Pb 1s peak
    - K. Itahashi et al., Phys. Rev. Lett. in press
  - further systematic studies using Sn targets ^{116}Sn, ^{120}Sn, ^{124}Sn
    - Extract b_1 (isotope effect), and study the possible f_{π} modification effect
    - Data taken, analysis in progress

1s peak clearly observed in ^{206}Pb(d,^{3}He)

H.Geissel et al., PRL in press

Pion mass ~ 26 MeV heavier at nuclear center





Physics Motivation of S236:
Isotope shift → f_π modification → chiral condensate

Local (s-wave part) of the Optical potential ~ mass shift

$$U_1(r) = \underbrace{\varepsilon_1 b_0 \rho(r)}_{\text{isoscalar part}} + \boxed{b_1}\underbrace{\{\rho_n(r) - \rho_p(r)\}}_{\text{isovector part}} + \varepsilon_2 \mathrm{Re}B_0 \rho^2(r)$$

$$\varepsilon_1 \equiv 1 + \frac{\omega}{M} \qquad \varepsilon_2 \equiv 1 + \frac{\omega}{2M}$$

This contains interesting physics (Weise et al.)

Determine b_1 (isovector part),

& compare with b_1^{free}

⇒ Sn isotope Targets

$^{116}\mathrm{Sn}$ $^{120}\mathrm{Sn}$ $^{124}\mathrm{Sn}$

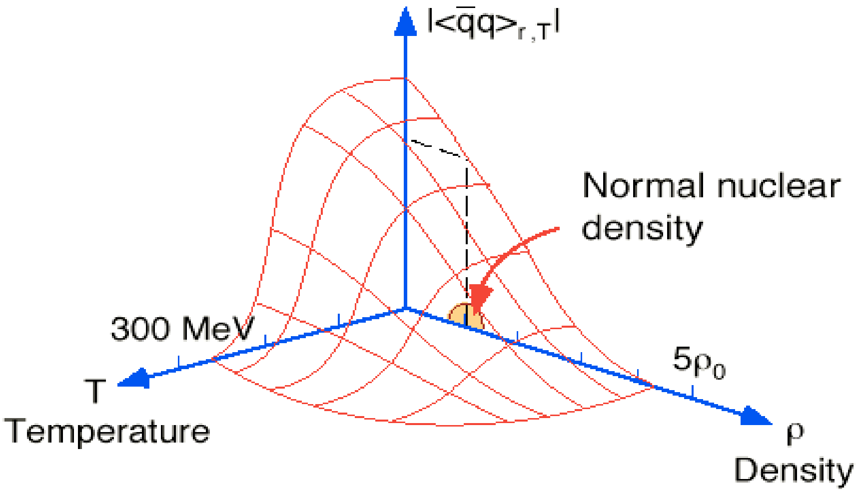
b_1, f_π, chiral condensate, etc.

- b_1 vs f_π (Tomozawa-Weinberg)

$$b_1 = \square \frac{1}{4\square(1+m_\pi/M)}\frac{\square}{2f_\pi^2}$$

- f_π vs Chiral Condensate (Gell-Mann-Oakes-Renner)

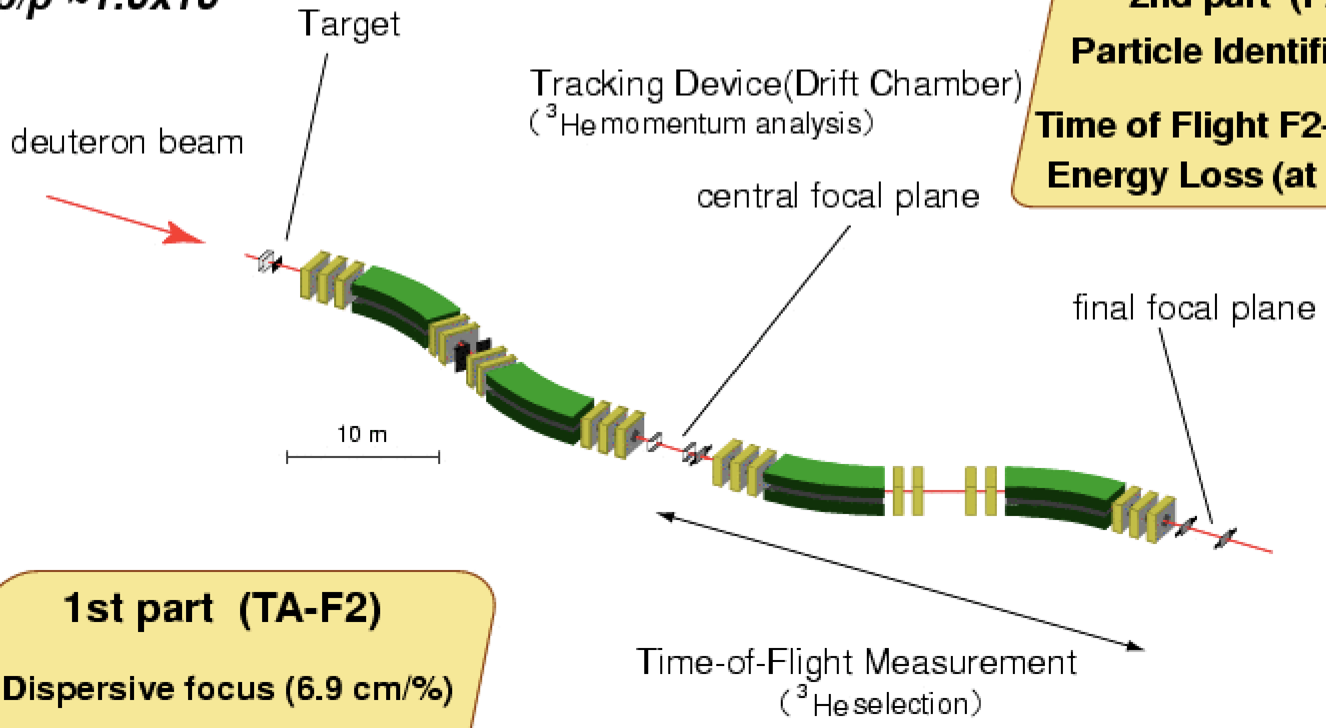
$$m_\pi^2 f_\pi^2 = \square \frac{m_u + m_d}{2}\left\langle \bar{u}u + \bar{d}d \right\rangle$$



Experimental Setup

FRS spectrometer

1.5 mm strip
Sn 25mg/cm^2
dp/p ~1.0x10^{-5}



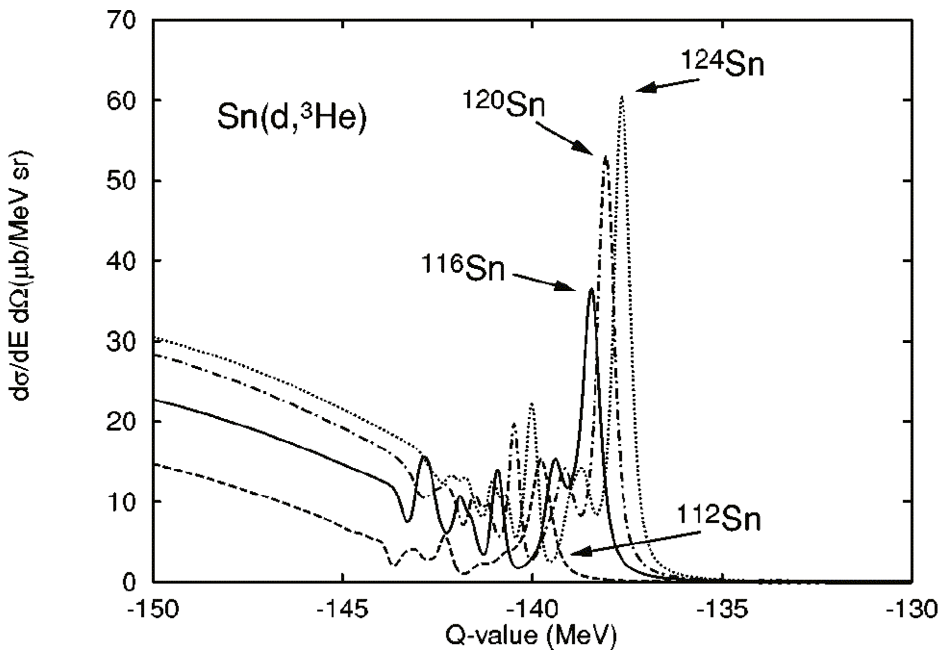
2nd part (F2-F4)
Particle Identification
Time of Flight F2-F4 (36m)
Energy Loss (at F2, F4)

1st part (TA-F2)
Dispersive focus (6.9 cm/%)
→ He momentum analysis
position resolution
0.3 mm (FWHM)

Experimental challenges

resolution, SIS absolute beam energy, energy calibration, long-term stability, etc.

- Beam energy 500 MeV
- Q-value -140 MeV
- Binding energy ~ 3.8 MeV
- Isotope shift B(^{123}Sn)-B(^{119}Sn) ~ 390 keV
- 1s width ~ 350 keV
- Resolution ~ 380 keV

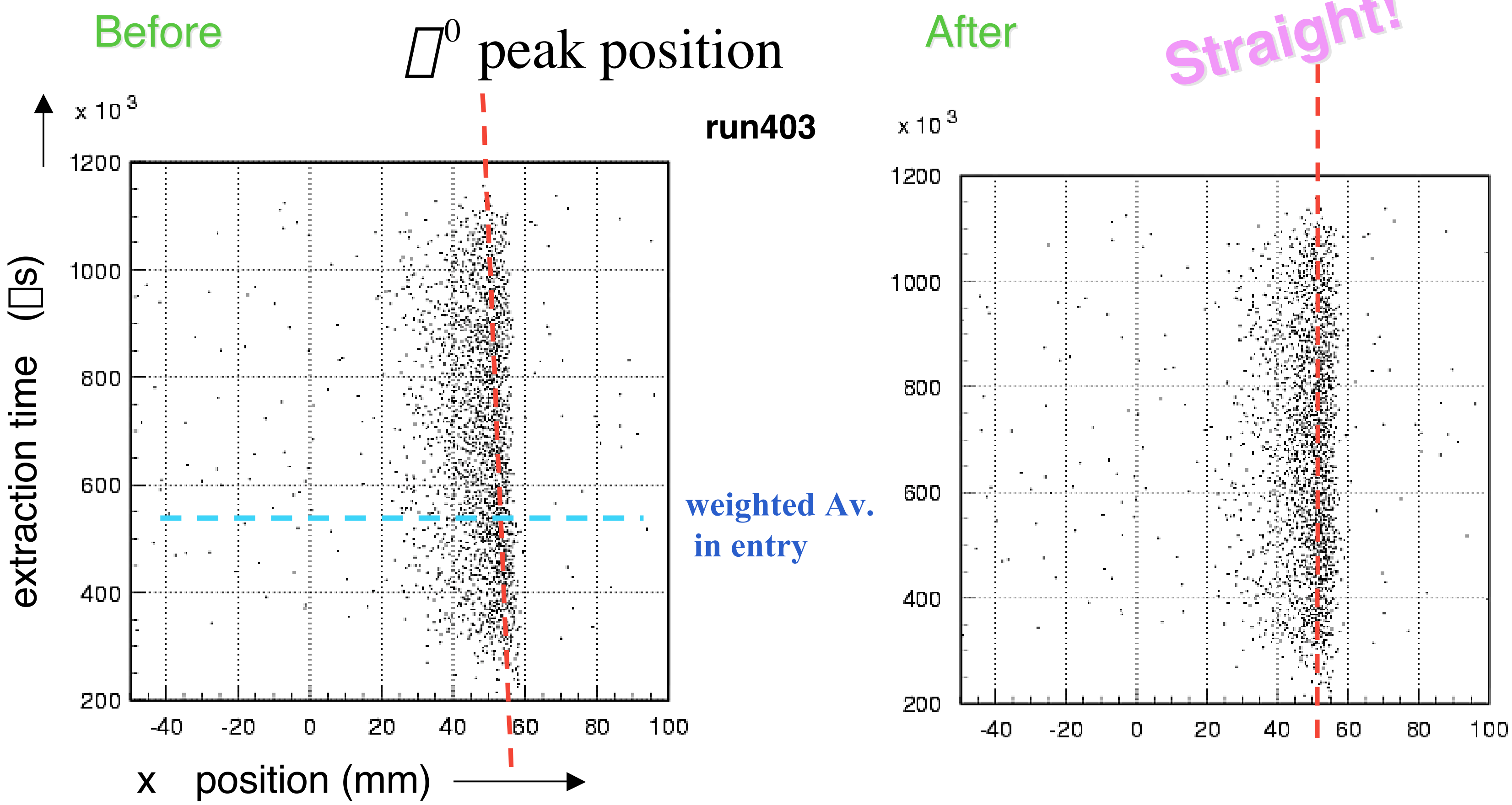


Theoretical prediction
Umemoto et al.

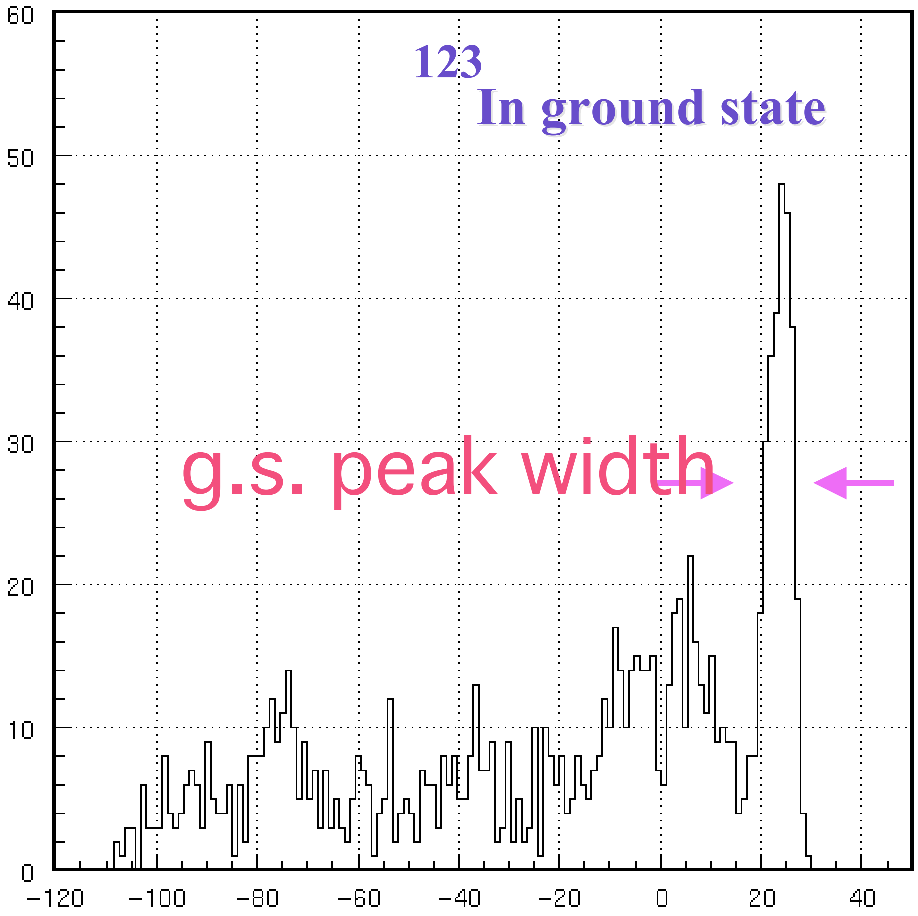
An example of one of many corrections to achieve high resolution

Beam energy changes within each beam spill

p(d,^{3}He)η^0 focal-plane position vs extraction time



Sn(d,^{3}He)In reaction used for calibration



x-position mm

Dispersion & absolute energy calibration

~20 keV achieved

Measurement of experimental resolution

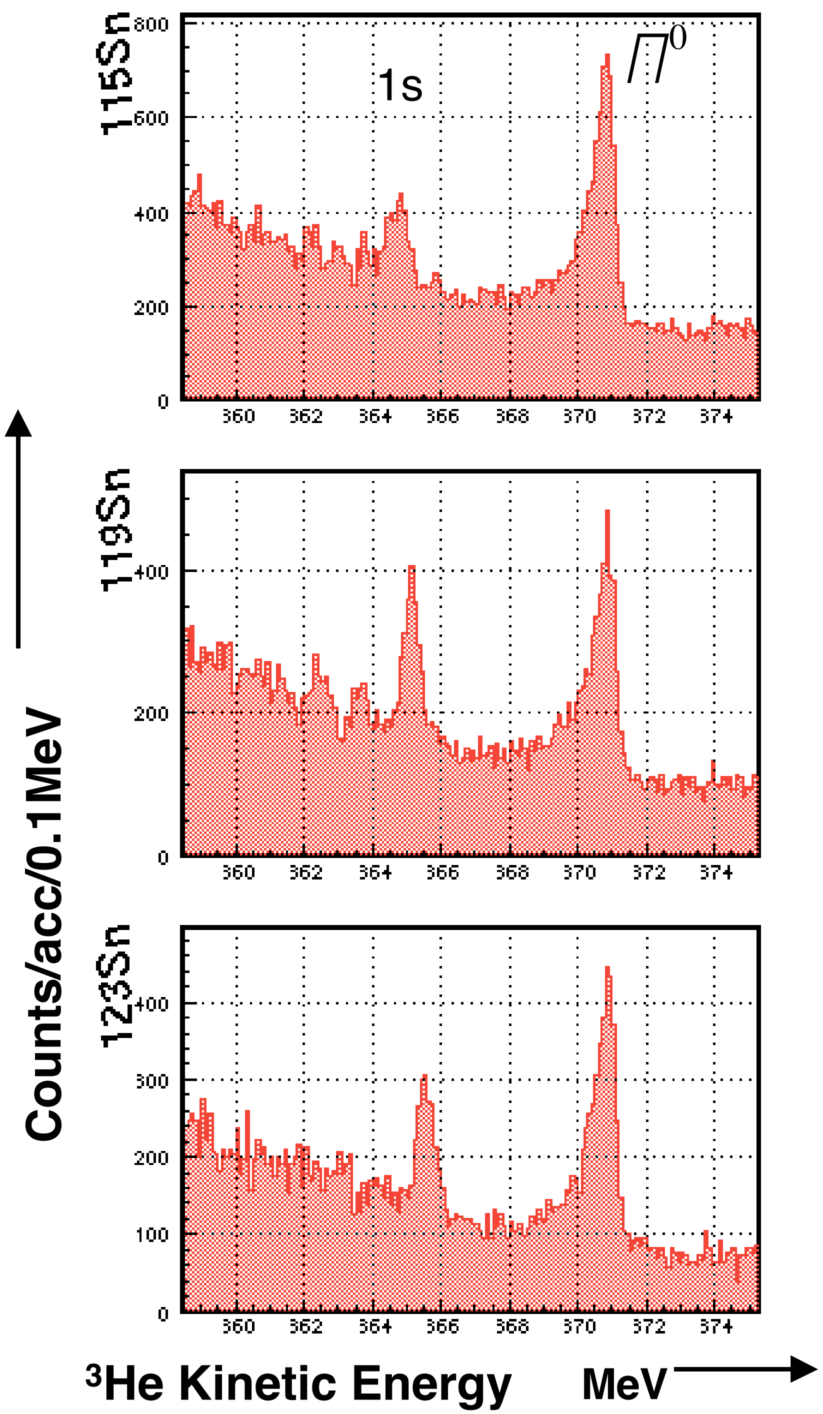
380 keV FWHM

~final Spectra

^{115}Sn
^{119}Sn
^{123}Sn

isotope shift
b_1 parameter
$f_{}$ modification, analyses in progress

Mylar film on the target: ^{0} peak used for energy calibration



S236 Summary

<u>High quality data on three Sn isotopes</u>

→ 1s pionic-atom peak

Absolute energy measurement is the key issue

~ 20 keV achieved

Indication of in-medium f_{π} modification obtained (figures & numbers not shown today)

Precise determination requires better knowledge of the neutron radii parameters

Our next goal is eta (η) and omega (ω) nuclei

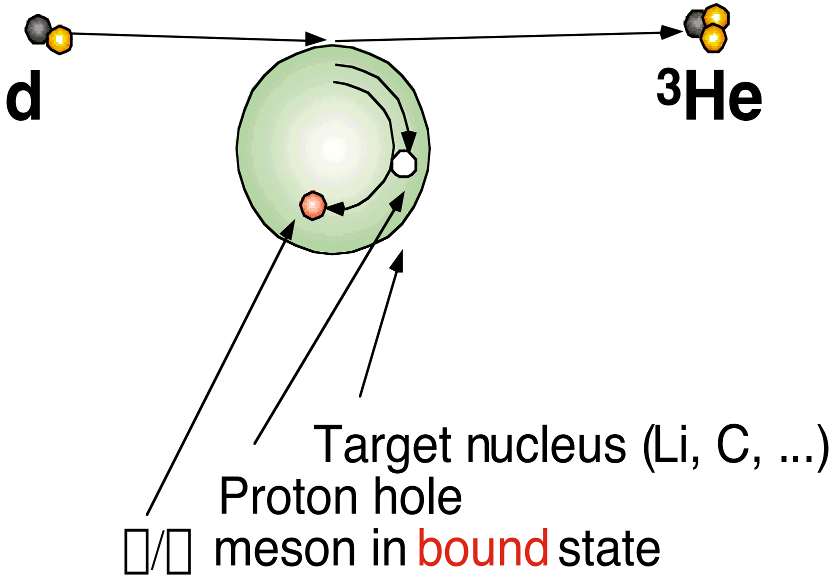
□ & □ mesons in nuclei (S214)

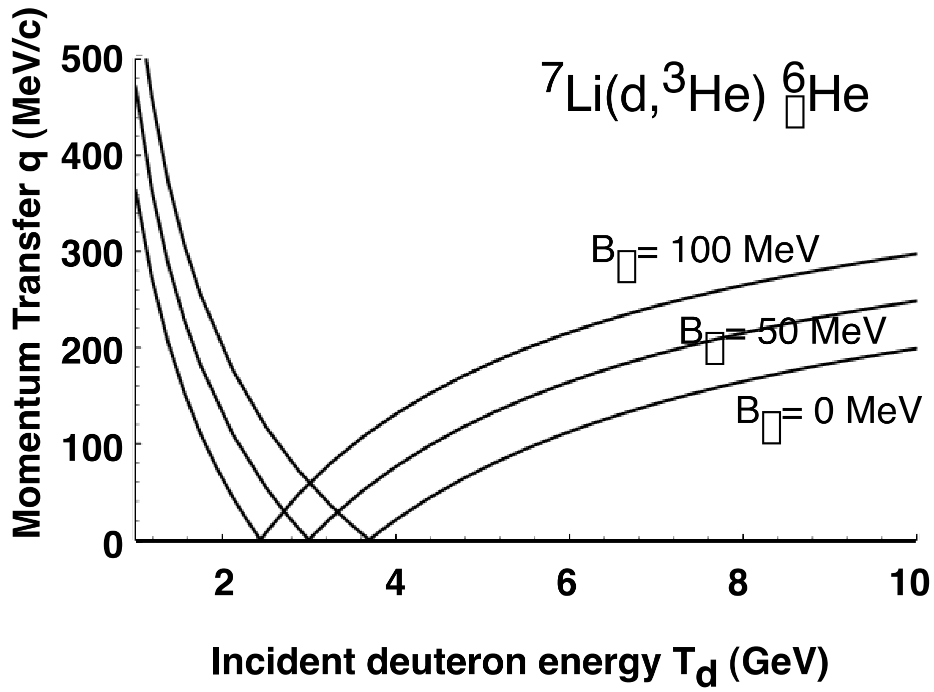
Apply the same method to study the behaviors of other mesons in nuclei

However, no Coulomb attraction

with S.Hirenzaki & A.Gillitzer
EPJA 6, 99 (1999)

Production of □ and □ bound state





- Recoilless □ production possible at GSI
- □ production also possible with small q
- Bound state peak position □ potential depth □ “mass”

Are there bound states?

- □-N scattering length

  0.717 + 0.263 i fm

  0.751 + 0.274 i fm

  0.52 + 0.25 i fm

  0.20 + 0.26 i fm

- □-nucleus optical potential (naive guess) - strongly attractive

  $V(r) = -(86+32i)\ □(r)/□_0$ MeV

- Binding energies

A	B.E(1s)	□(1s)	B.E(2p)	□(2p)
6	17.4	33.5		
11	35.3	48.8		
15	44.4	55.5	9.6	35.9

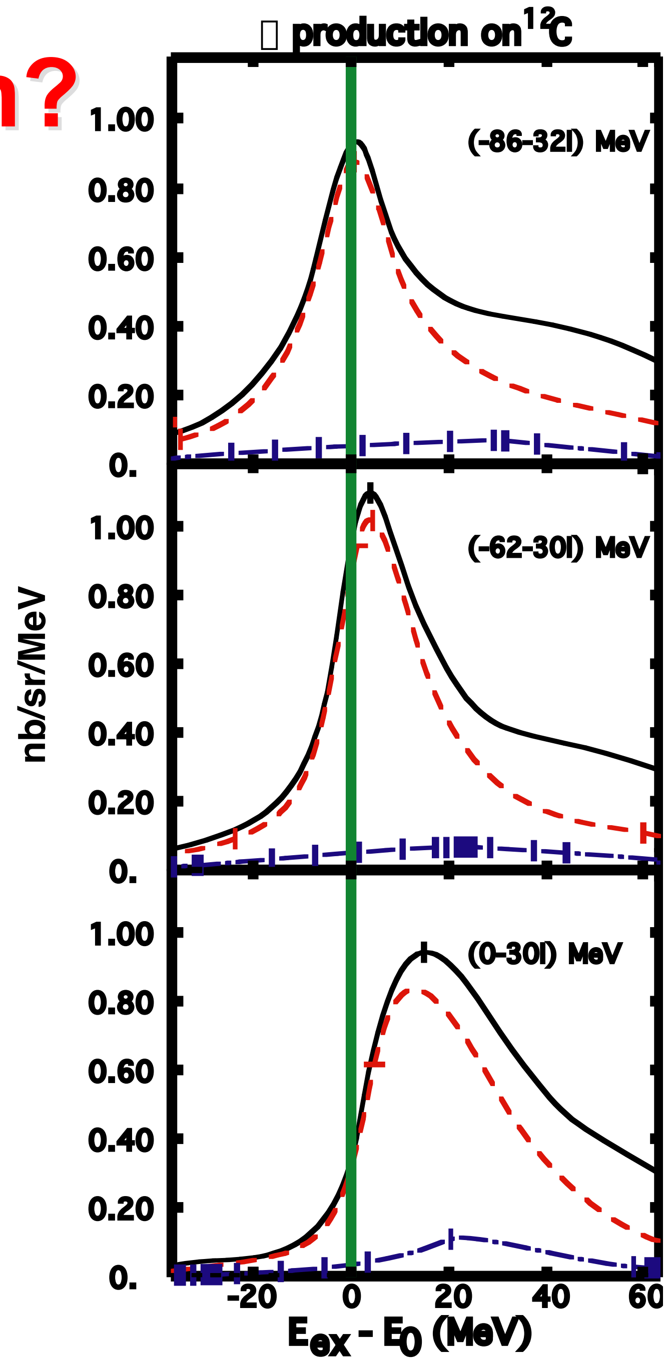
How about cross section?

$$\left.\frac{d^2\sigma}{d\Omega dE}\right|_{A(d,^3He)_\eta(A-1)} = \left.\frac{d\sigma}{d\Omega}\right|^{lab}_{p(d,^3He)\eta} \times \sum_{l_\eta, j_n, J} S(E)$$

Elementray cross section taken from SATURNE expts.

Response calculated by Green function, with eikonal distortion.

- Example: ^{7}Li target - peak position reflects potential depth
  blue: $(0s_{1/2})^{-1}_p$ s
  Red: $(0p_{3/2})^{-1}_p$ p



Technical Issues

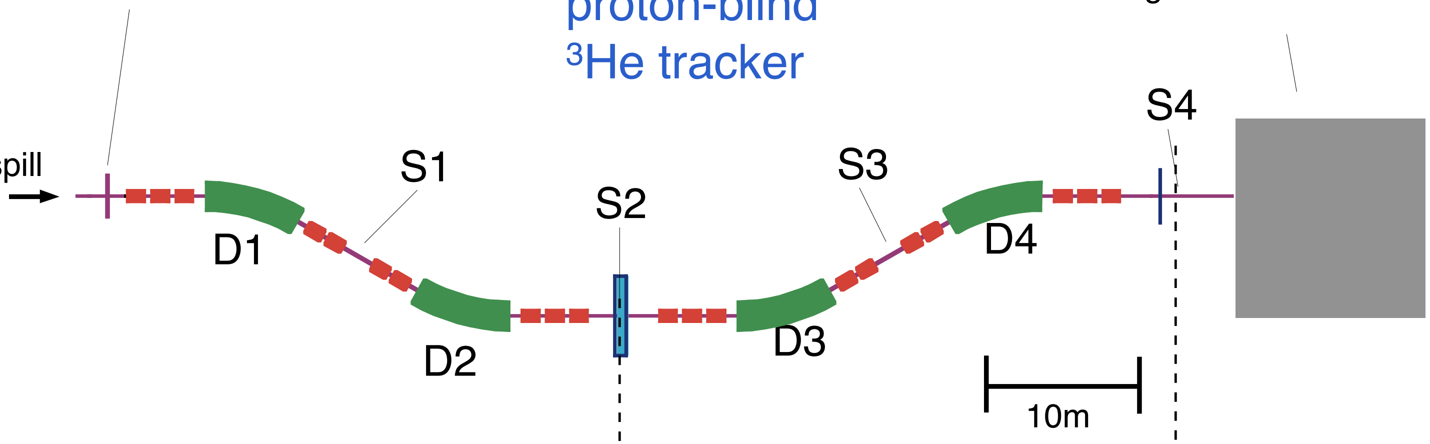
Large number of breakup protons must be dumped safely

Beam dump
All the ~10^8 protons transported to S4 and captured in the dump
Activation of FRS magnets and focus regions minimized

2mm strip, 1 g/cm^2 Li(C) target

Requires proton-blind ^{3}He tracker

Beam:
N(beam) ~ 7 x 10^{10}/spill
T(d)=3 GeV



3 GeV
d beam

TA-S2: dispersive
Proton-blind segmented Cherenkov
1.5 x 10^6 protons/ spill / slat

S2-S4: achromatic
use a coarse-segmentation proton-blind Cherenkov to detect ^{3}He, do S2-S4 TOF

S214 - approved (in December 1997!) & waiting for beam

- Expected spectra for 100 hours of running at GSI □
  - known continuum background taken into account
  - a new type of proton-blind Cerenkov tracker used to suppress d-breakup background (already beam-tested at KEK)
- <u>**Need test beam in 2002**</u>
- <u>**Data taking in early 2003**</u>