Hadron 2001, Protvino

Deeply bound 1*s* and 2*p* pionic states in ^{205}Pb and effective pion mass in nuclear matter

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S160 collaboration
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Introduction and Motivation

Pionic Atom

Coulomb potential

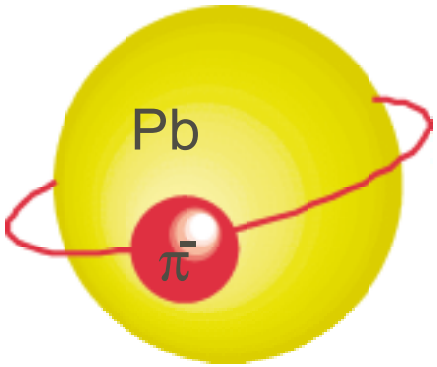
+Strong Interaction

Pionic atom we observe:

deeply bound π^- states

Large overlap

π^- w.f. & nucleus



Spectroscopy to determine

1*s* and 2*p* binding energies and widths

Information on the local part of strong interaction between pion and nucleus

π-nucleus Optical Potential

$U_{opt}(r)$ { p-wave part
s-wave (local) part

Deeply bound pionic states are very sensitive

$V(r) \propto b_0\rho(r) + b_1\Delta\rho(r) + \varepsilon_2 B_0\rho^2(r)$

Large Ambiguity

Treating medium effect in local potential.

$[m_{eff}(r)]^2 \equiv [m_\pi^2 + \mathbf{q}^2 + \mathrm{Re}\Pi]_{q->0}$ Waas et al. PLB405 (97) 215

Self Energy $\Pi = 2m_\pi U_{opt}$

$\Delta m_{eff}(r) = \mathrm{Re}V(r)$ Mass shift of π meson in nuclear medium

Effective mass of pion in nuclear medium

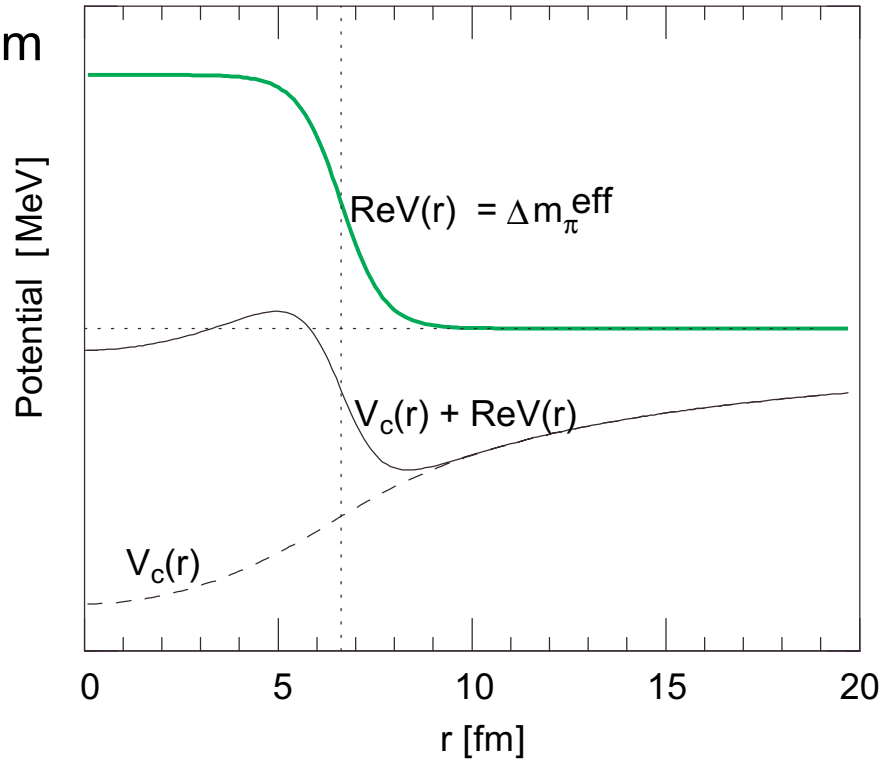
$$[m_{eff}(r)]^2 \equiv [m_\pi^2 + \mathbf{q}^2 + Re\Pi]_{q->0}$$

Waas et al. PLB405 (97) 215

Self Energy $\Pi = 2m_\pi U_{opt}$

$$\Delta m_{eff}(r) = ReV(r)$$

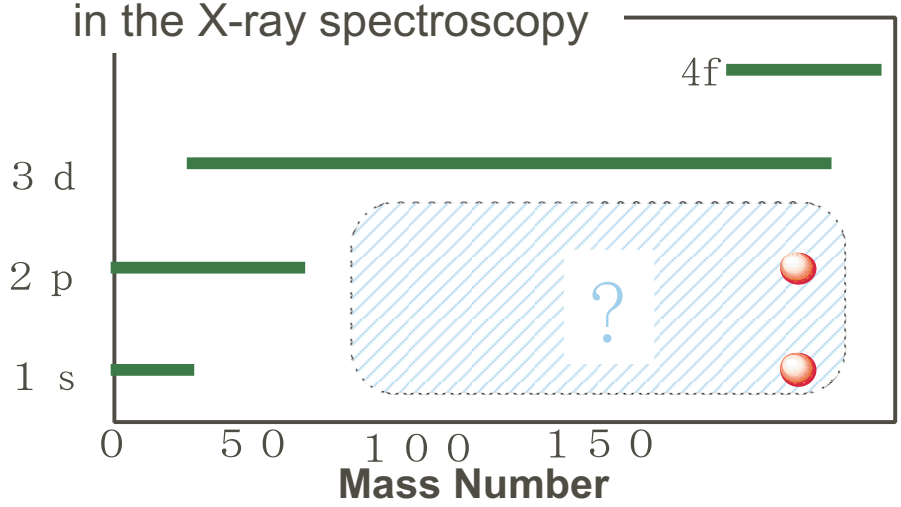
Medium effect is treated as local potential.

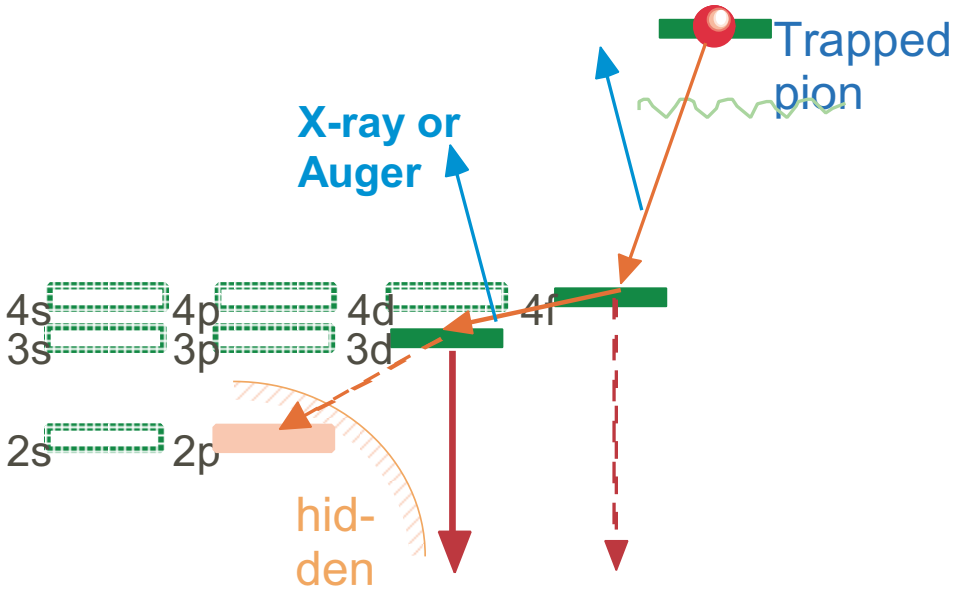


History

Pionic Atom X-ray spectroscopy
(Stopped pion method) (Backenstoss Ann. Rev. of Nucl. Sci. 20 (1970) 467)

- Observed States of pionic atom in the X-ray spectroscopy





- π^- in nuclear medium Γ_{abs} ~ 20 MeV
- π^- radius ~ nuclear radius

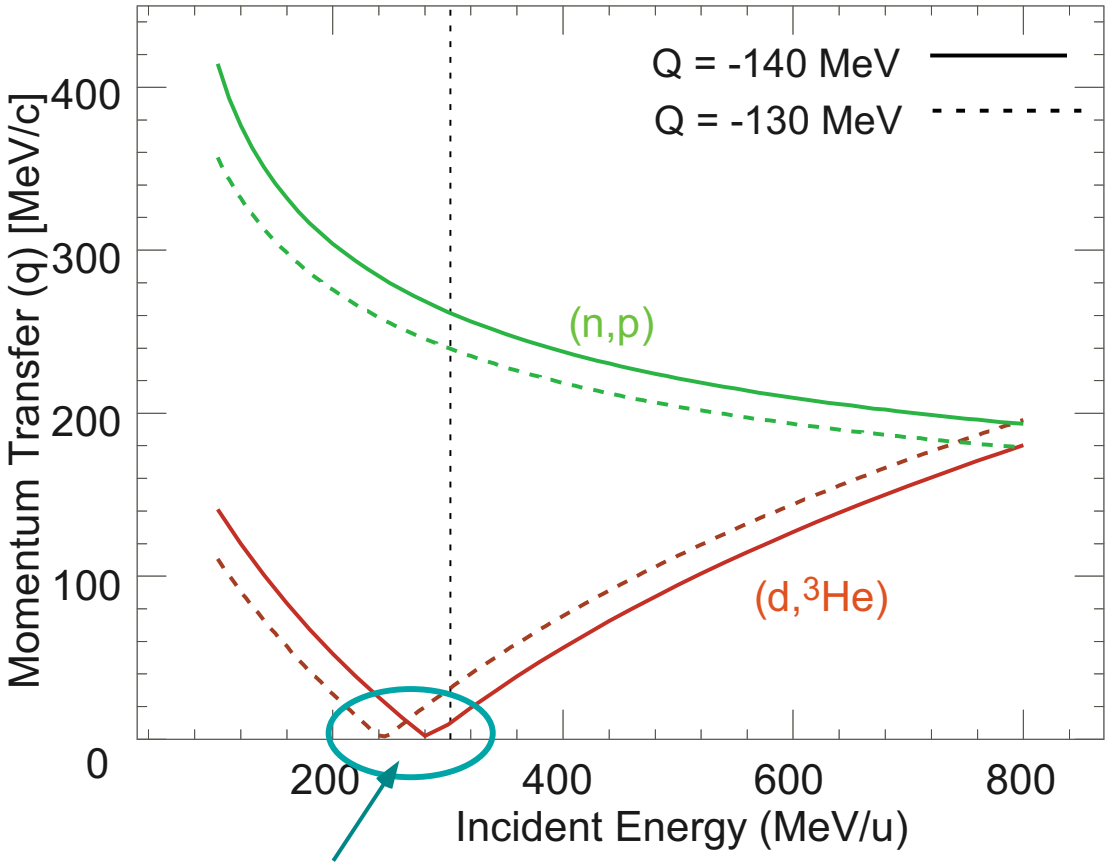
→ Deeply bound states are not stable and do not exist (?)

1s

Nuclear absorption

A key of experimental condition

Recoilless kinematics



Quasi-substitutional (Δl~0) reaction

Small momentum transfer(q)

Experimental trials and break-through

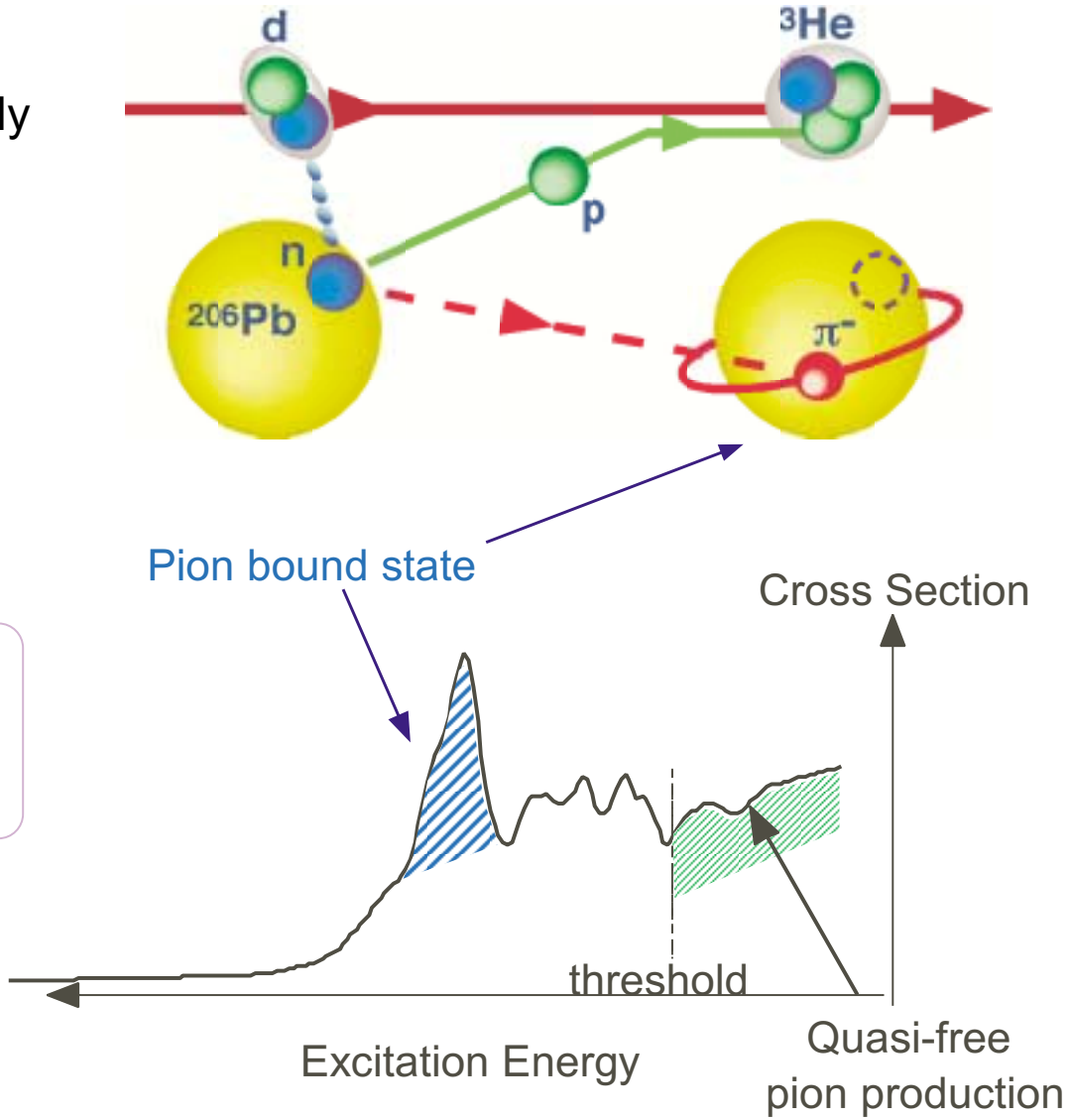
Nuclear reaction

Direct population of deeply bound states

(n,p), (p,d),($p,2p$)...

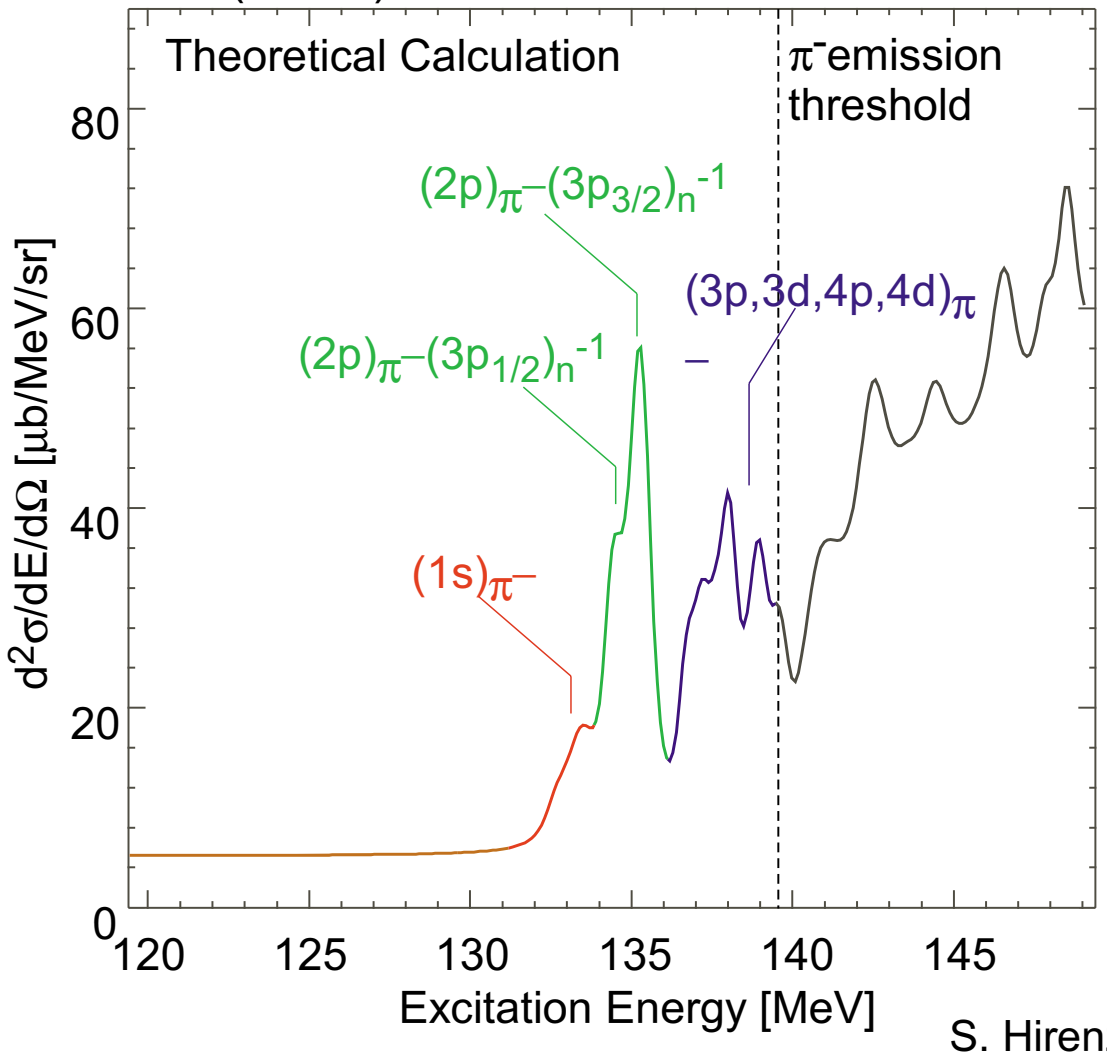
(d,^{3}He) at small momentum transfer

Produced state is coupling with a neutron hole



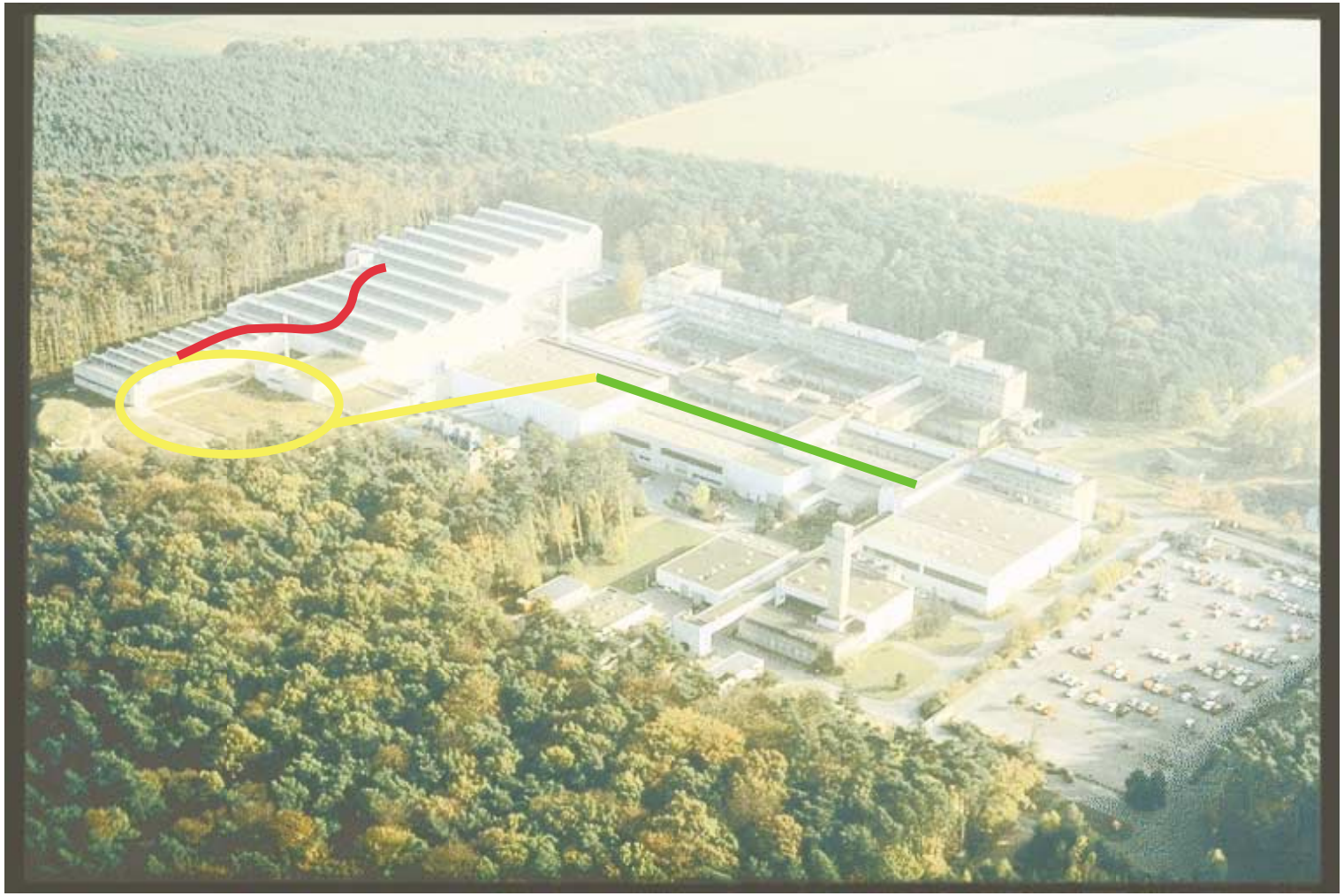
Theoretical Prediction

Theoretically calculated excitation spectrum of $^{208}Pb(d,^{3}He)$

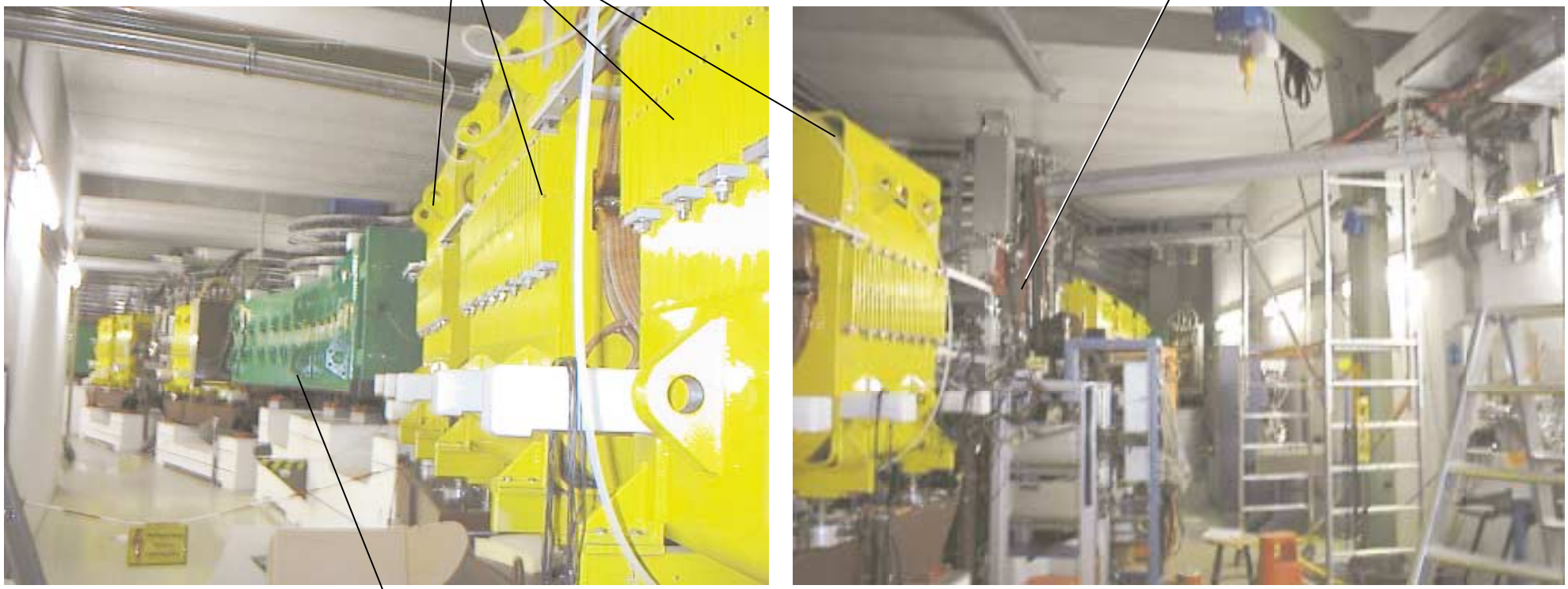


S. Hirenzaki et al.

Gesellschaft fuer Schwerionenforschung mbH, Darmstadt



Experimental Area



FRS Spectrometer

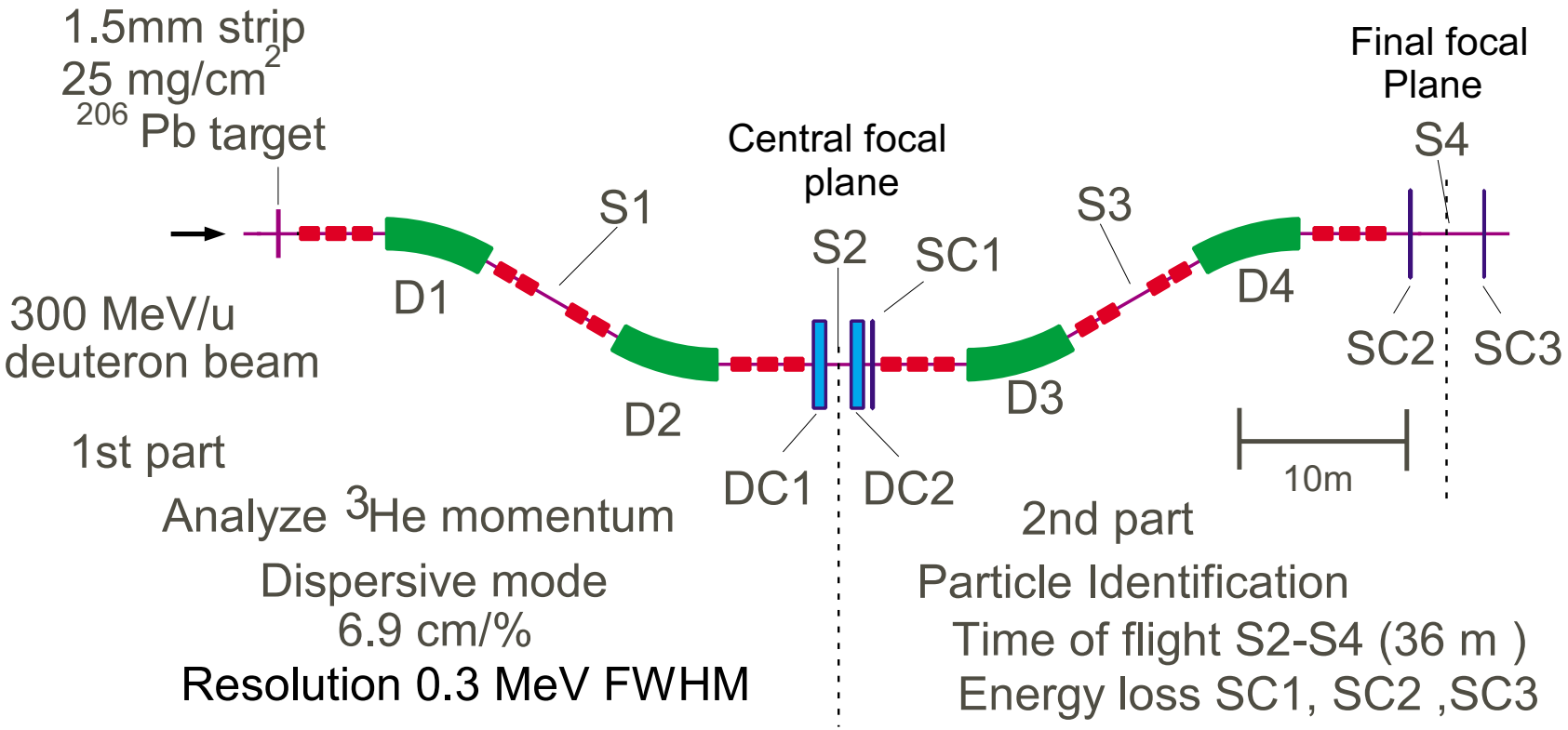
Acceptance at 0 degree
Background Suppression { Primary beam / Break-up proton

Deuteron beam

momentum spread $\Delta p/p < 3 \times 10^{-4}$

Ex ⟷ ^{3}He momentum

Detector:
DC1,DC2 : drift chamber
SC1-SC3 : scintillation counter



1st part

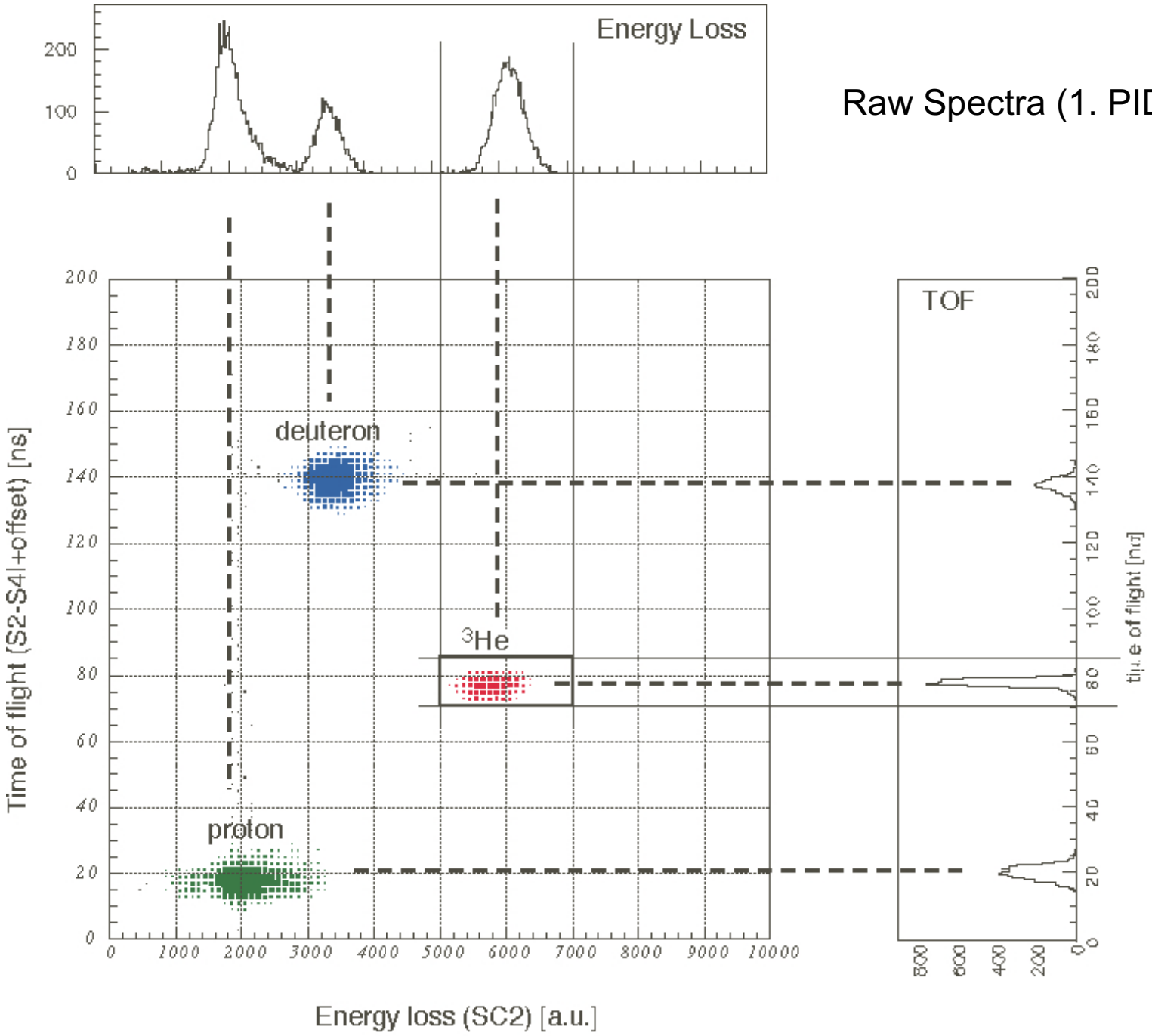
Analyze ^{3}He momentum

Dispersive mode
6.9 cm/%
Resolution 0.3 MeV FWHM

2nd part

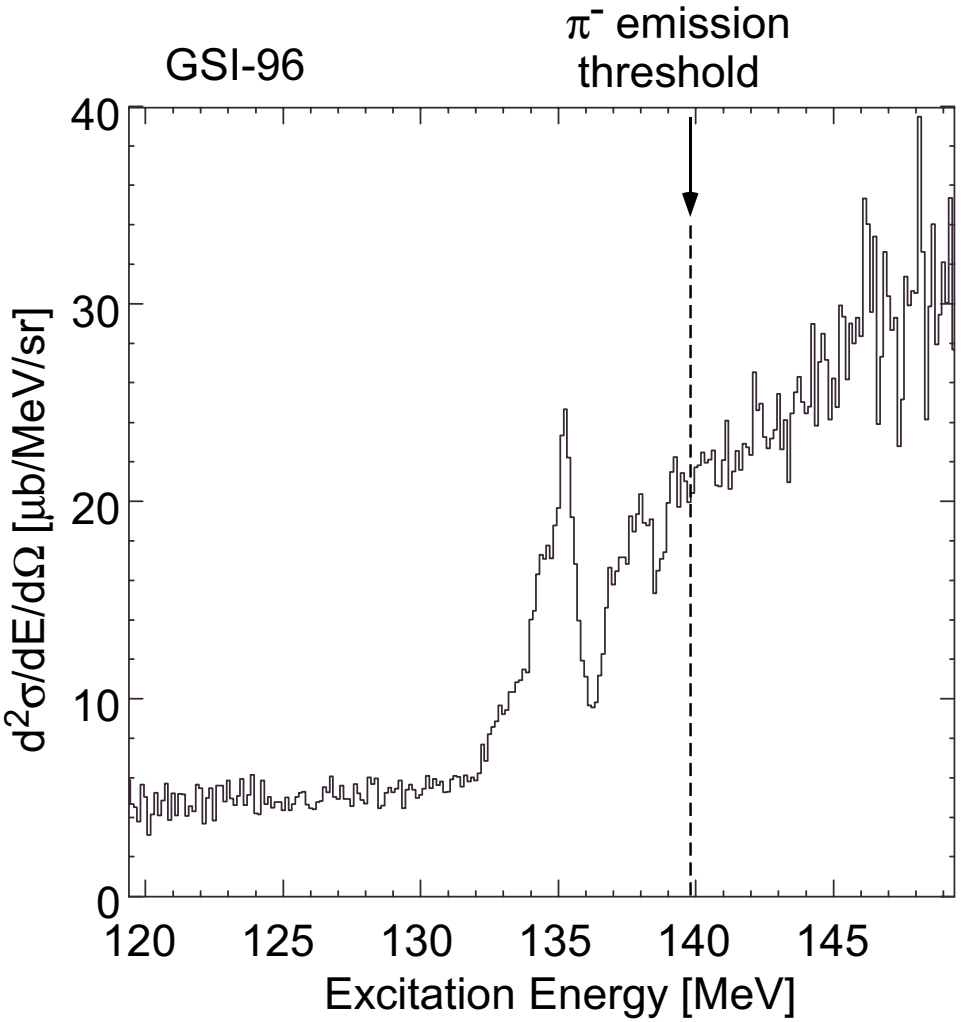
Particle Identification
Time of flight S2-S4 (36 m)
Energy loss SC1, SC2 ,SC3

Raw Spectra (1. PID)



Bound pionic states in ^{207}Pb

Experimentalexcitation spectrum of ^{208}Pb(d,^{3}He)



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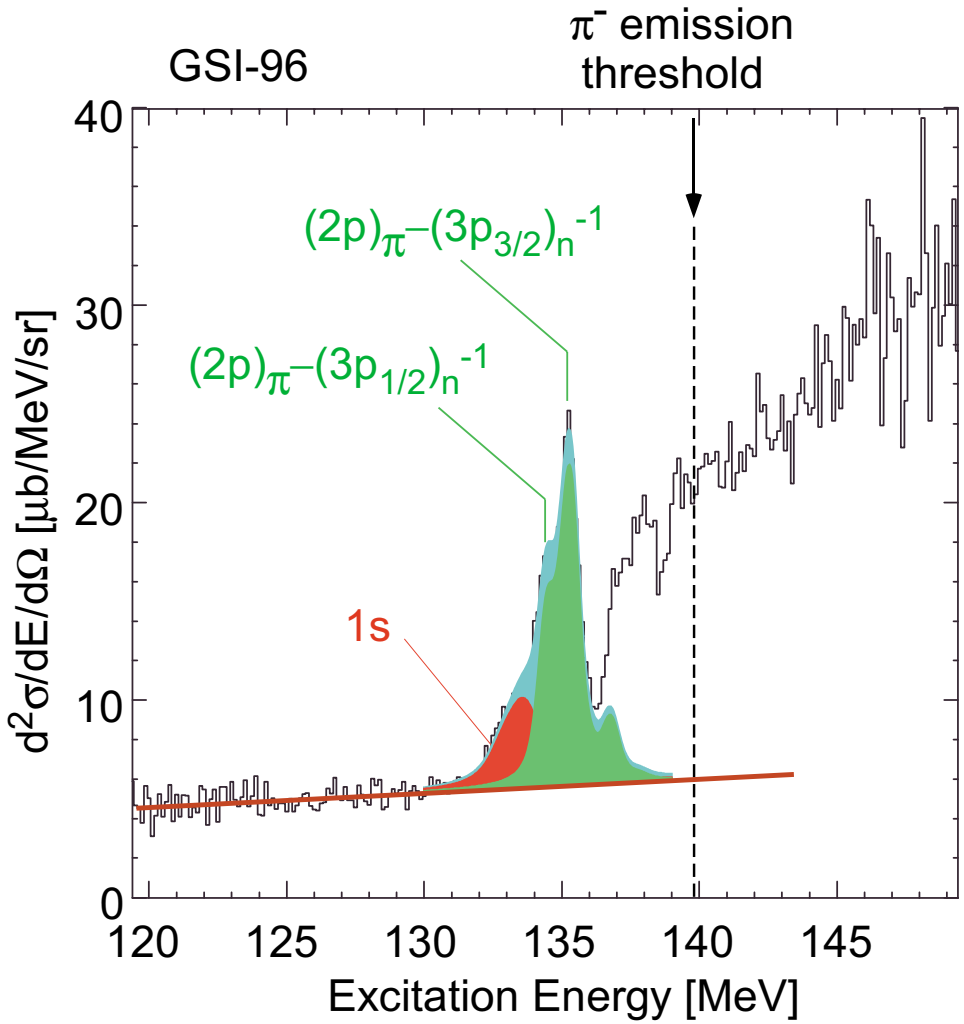
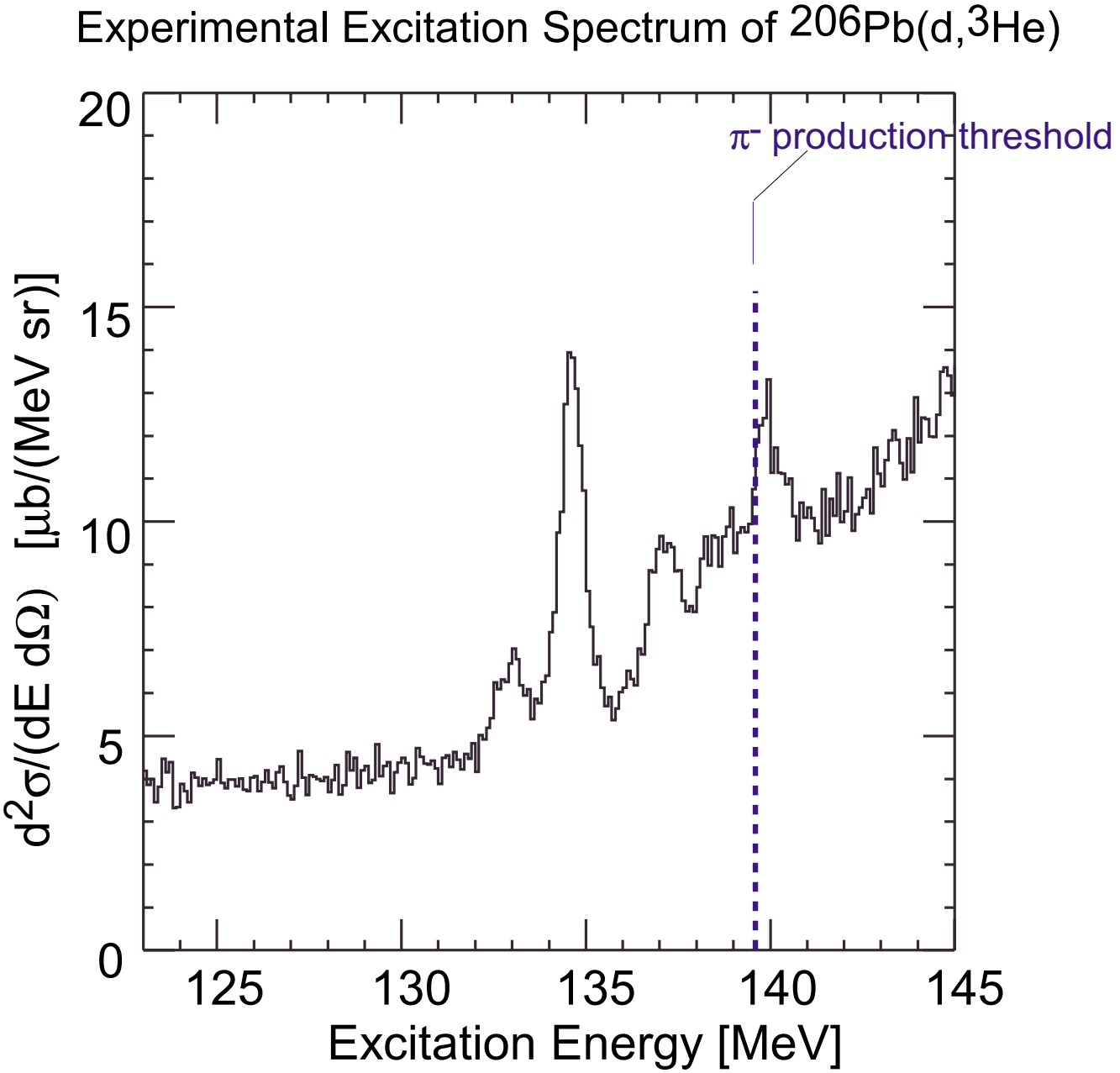
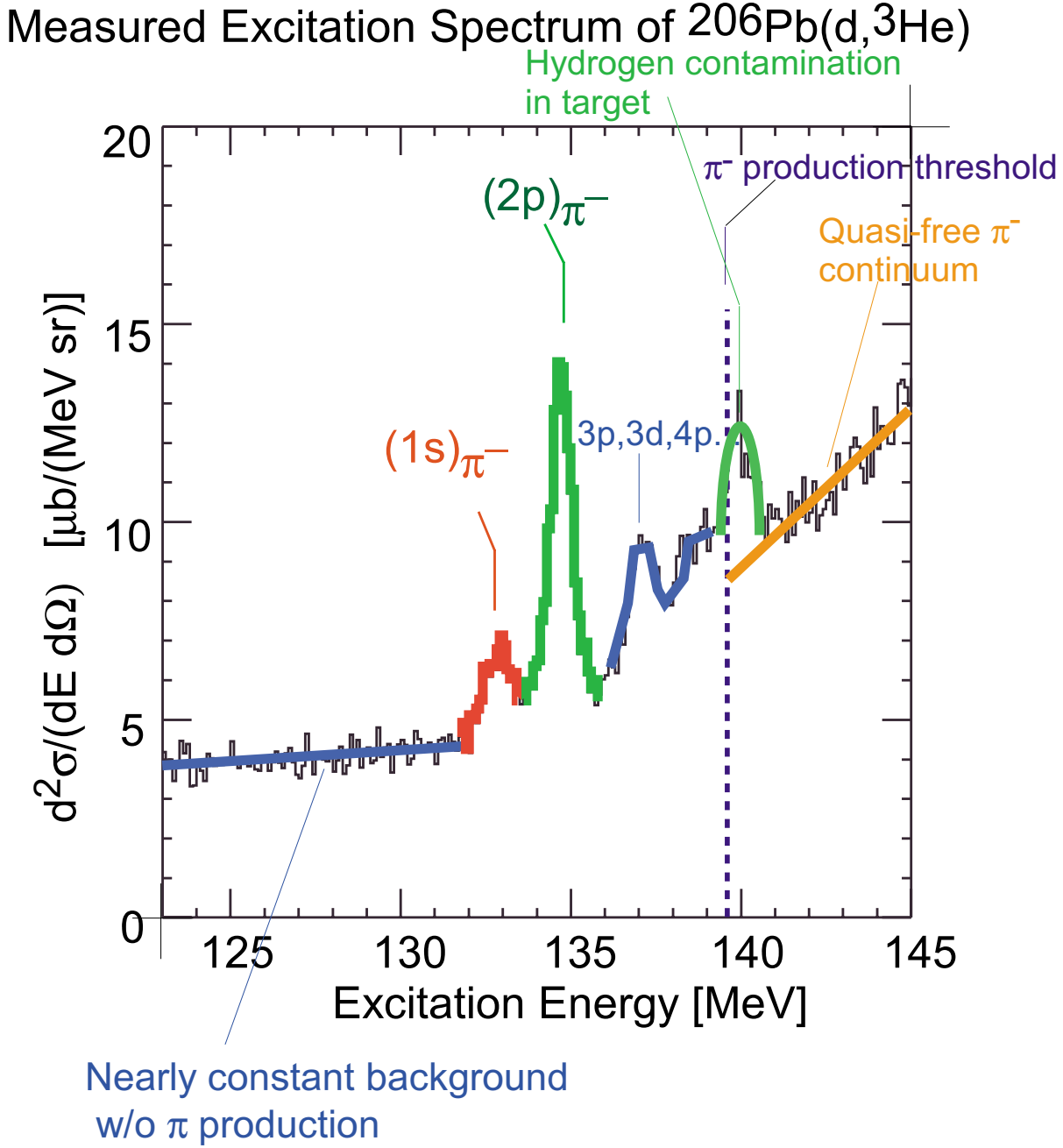
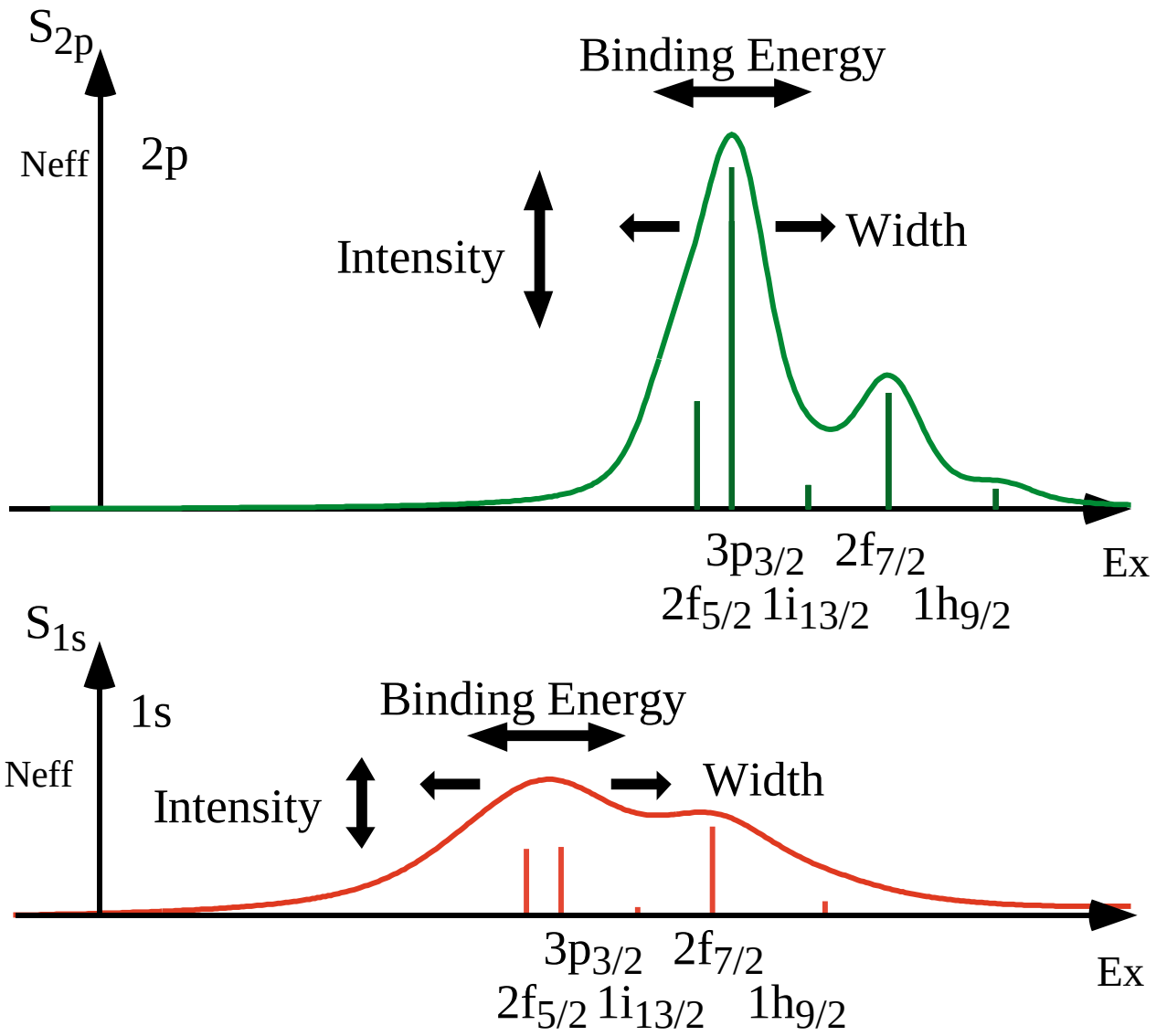


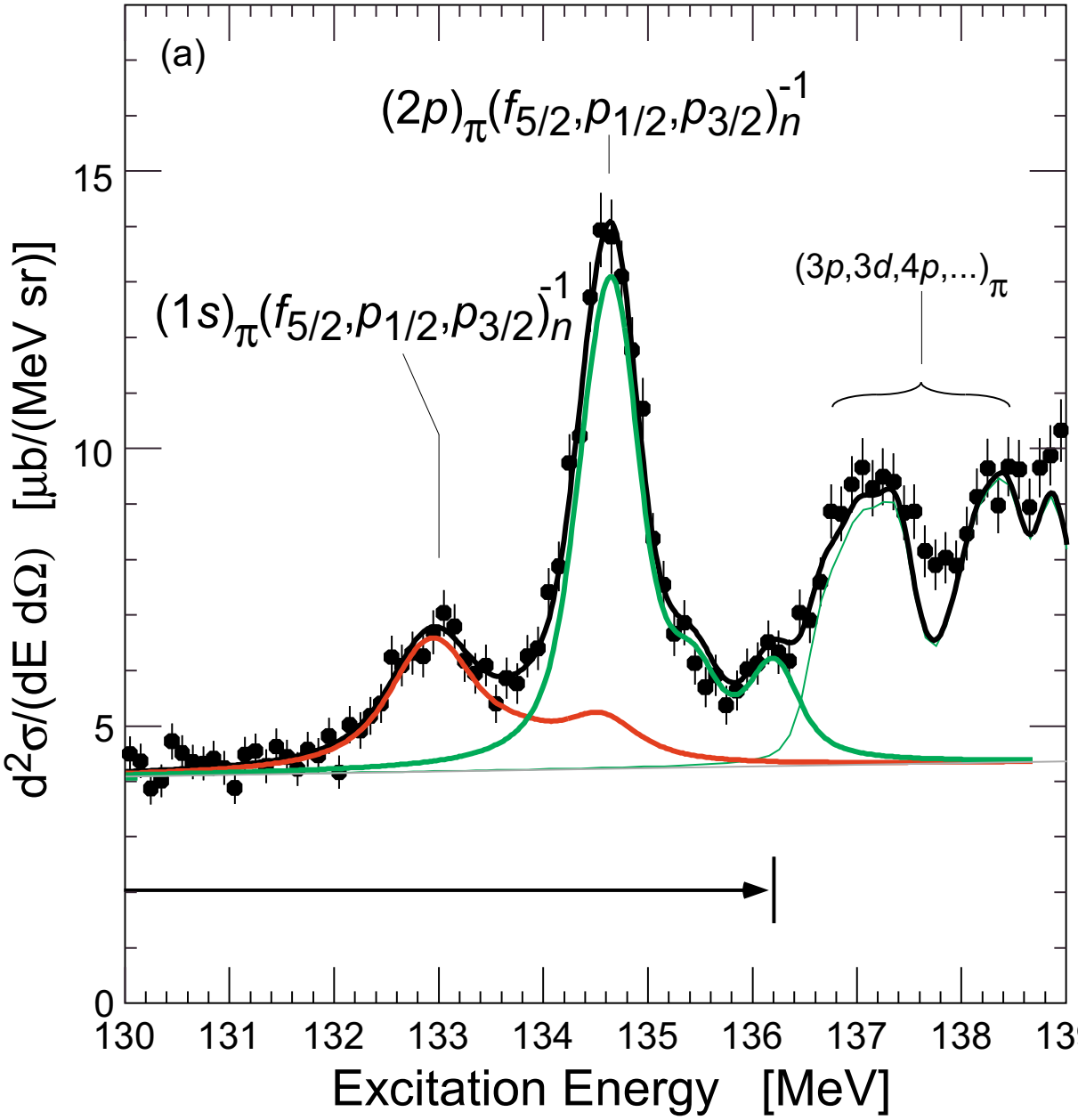

Experimental Excitation Spectrum of 206Pb(d,3He)
π⁻ production threshold
d²σ/(dE dΩ) [μb/(MeV sr)]
Excitation Energy [MeV]
0
5
10
15
20
125
130
135
140
145


Measured Excitation Spectrum of 206Pb(d,3He)
Hydrogen contamination in target
π⁻ production threshold
(2p)π⁻
Quasi-free π⁻ continuum
(1s)π⁻
3p,3d,4p..
d²σ/(dE dΩ) [μb/(MeV sr)]
0
5
10
15
20
125
130
135
140
145
Excitation Energy [MeV]
Nearly constant background w/o π production

Fitting procedure



Fitting result



χ^2 /N_{DF} = 0.75 (N_{DF}=125)

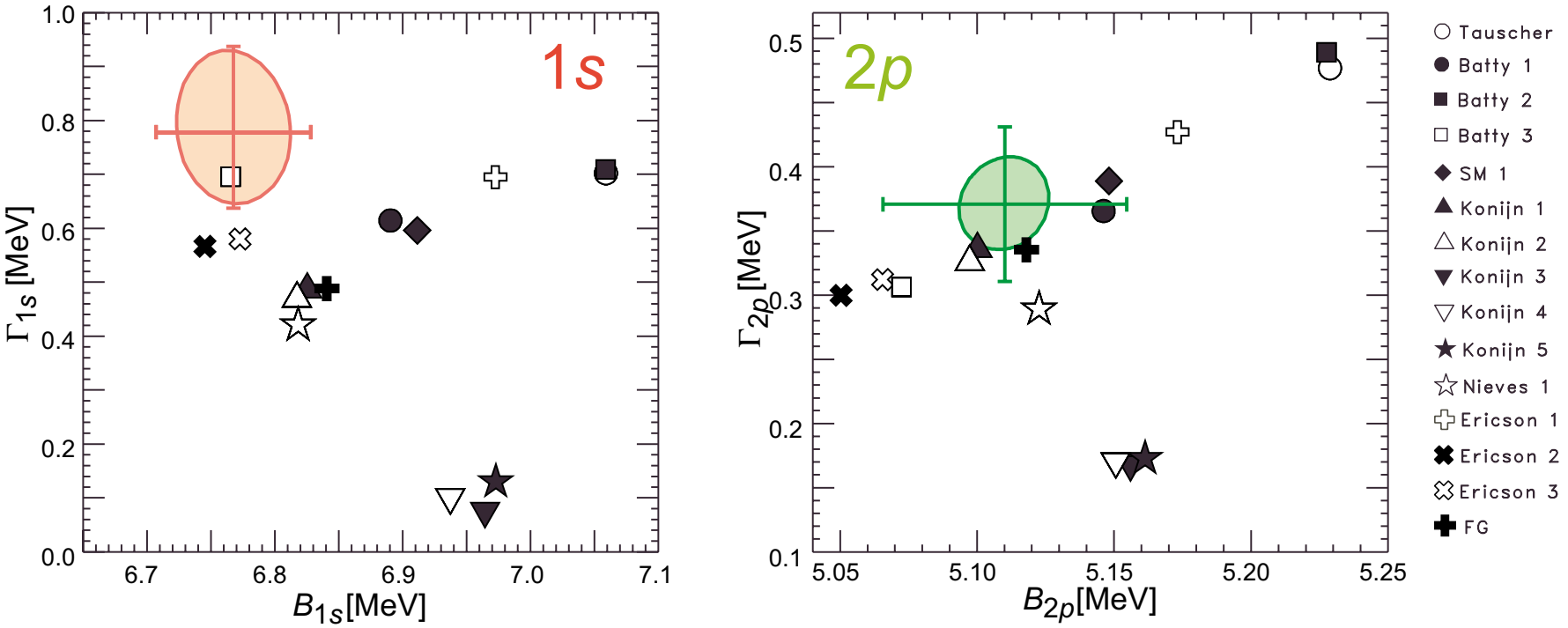
B_{1s} = 6.768+−0.044+−0.041 MeV

$\Gamma_{1s} = 0.778^{+0.150}_{-0.130}$ +−0.055 MeV

B_{2p} = 5.110+−0.015+−0.042 MeV

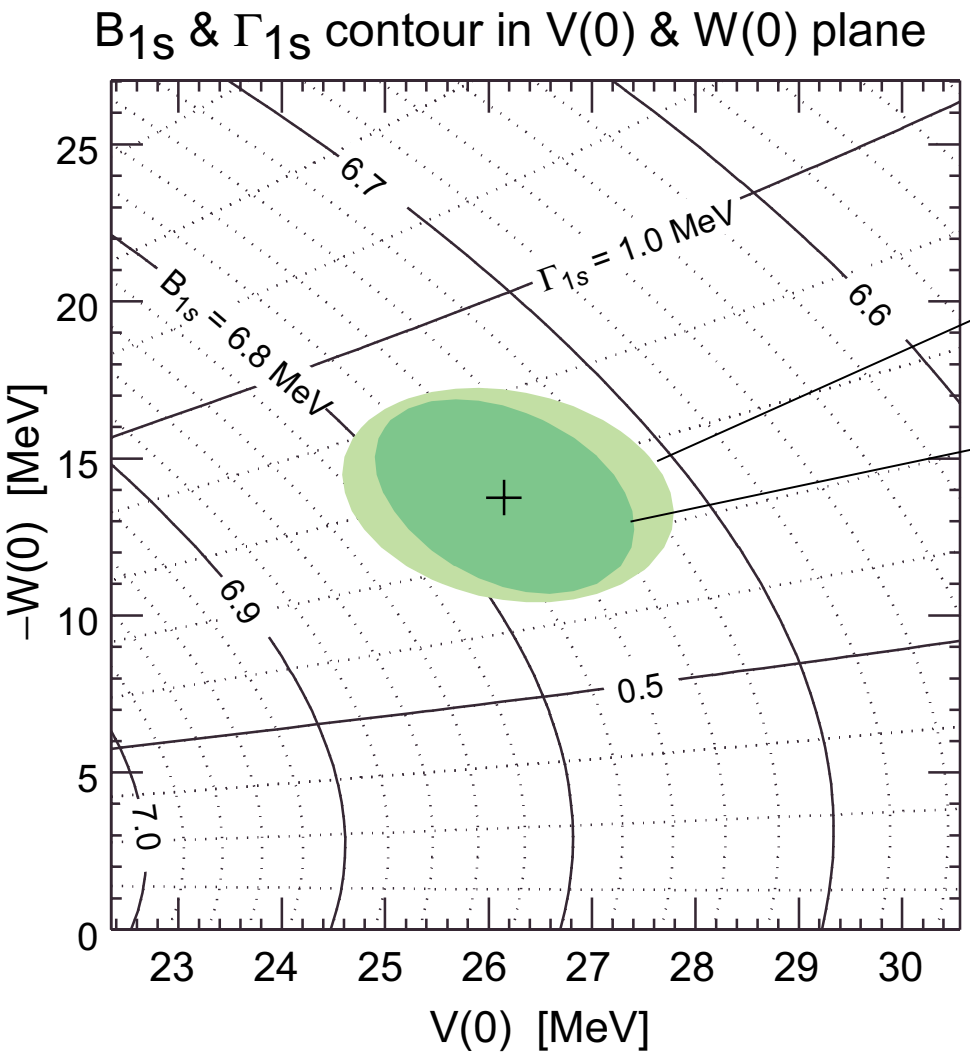
Γ_{1s} = 0.371+−0.037+−0.048 MeV

Comparison between theoretical prediction and experimental result



Fairly good agreement and very high precision.

Deduction of Potential Depths



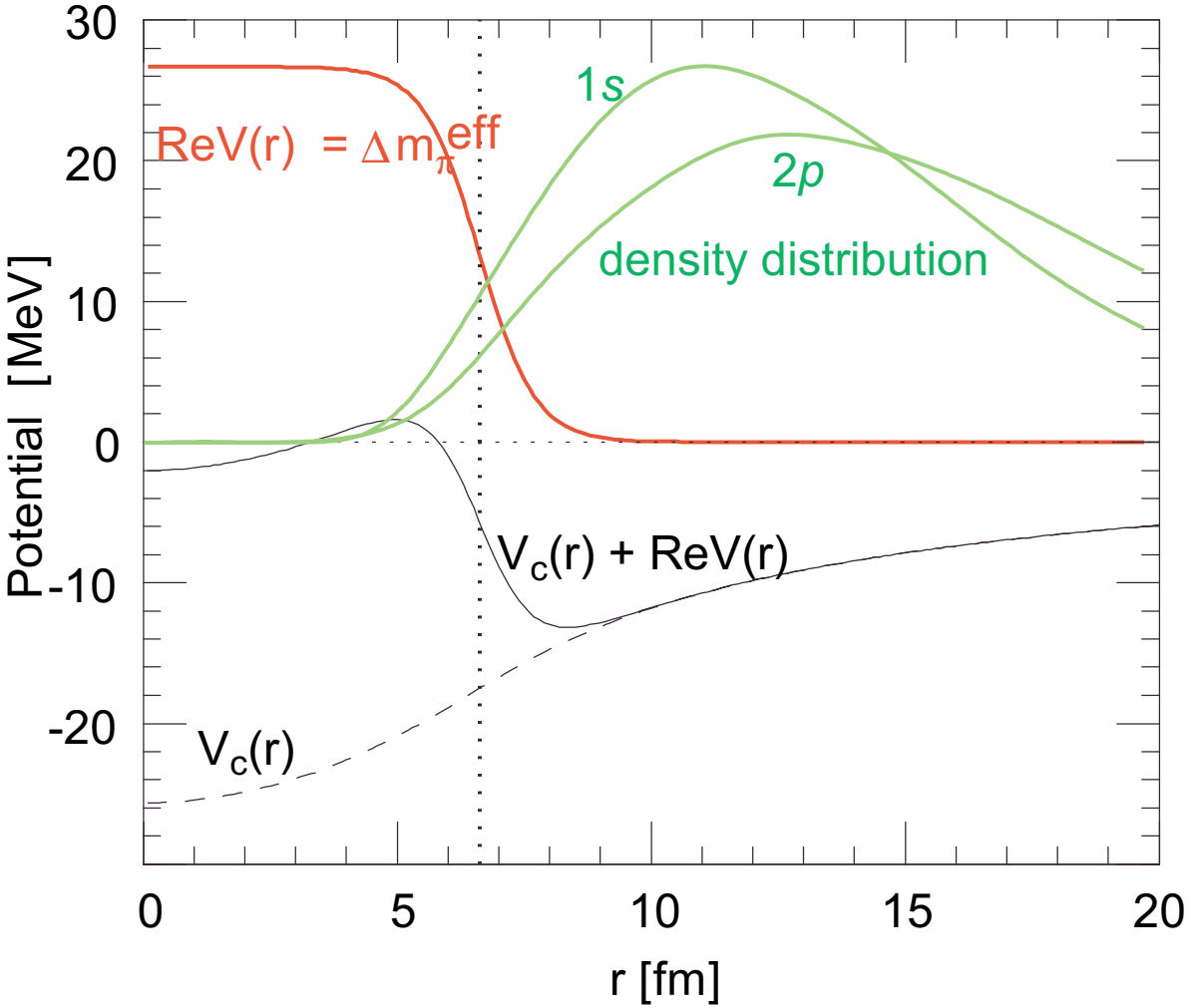
+Systematic error

Statistical error

V(0) = 26.1 +– 1.7 MeV
= Δm_{π}^{eff}

V(0) & W(0): Real & Imaginary part potential depths

Deduced optical potential



Binding energy and
width are sensitive to
the depth at half density.

$\Delta m_\pi^{eff} = V(0) = 26 - 30$ MeV

Summary

- Observation of 1*s* and 2*p* bound pionic states in ^{205}Pb as well separated peaks in the excitation spectrum

- Binding energies and widths are determined with very high precision

$B_{1s} = 6.768 \pm 0.044 \pm 0.041$ MeV $B_{2p} = 5.110 \pm 0.015 \pm 0.042$ MeV

$\Gamma_{1s} = 0.778^{+0.150}_{-0.130} \pm 0.055$ MeV $\Gamma_{1s} = 0.371 \pm 0.037 \pm 0.048$ MeV

- Obtained data set rigid constraints on existing theory and effective pion mass in center of lead is deduced to be 26 - 30 MeV larger than in vacuum

Future Plans

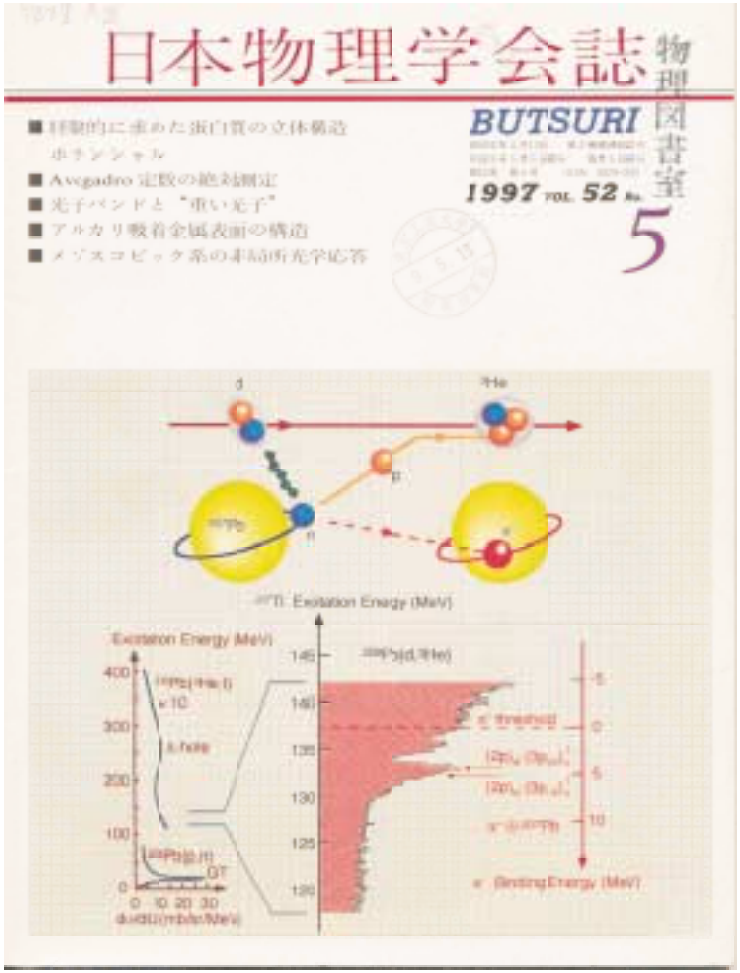
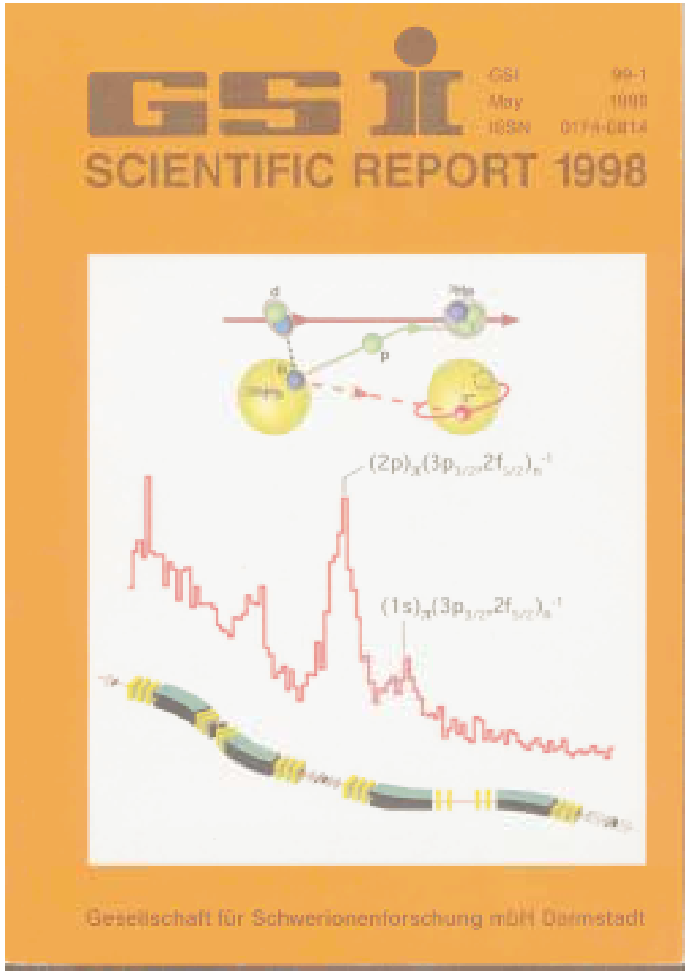
- η and ω -mesic nuclei spectroscopy in (d,^{3}He) reaction
- Kaonic nuclear bound states search in ^{4}He(K^-,n) reaction
- Inverse Kinematics for pionic atoms with unstable nuclei?
- Pionic atom with a long chain of Tin isotopes
  (Apr. & May/2001 in GSI and now in analysis)

→ Isovector part (b_1)

Tomozawa-Weinberg relation

$-4\pi(1+m_\pi/M)b_1=m_\pi/2f_\pi^2$ → Order parameter of chiral symmetry breaking?

PRL17(66)616,PR175(68)2195

M. Fujita, H. Geissel, H. Gilg, A. Gillitzer, R.S. Hayano, S. Hirenzaki
K. Itahashi, N. Iwasa, M. Iwasaki, P. Kienle, M.Knuelle, G. Muenzenberg,
T. Ohtsubo, K. Oyama, M. Sato, W. Schott, M. Shindo, K. Suzuki, T. Suzuki,
H.Toki, D. Tomono, Y. Umemoto, H. Weick, T. Yamazaki, T. Yoneyama

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