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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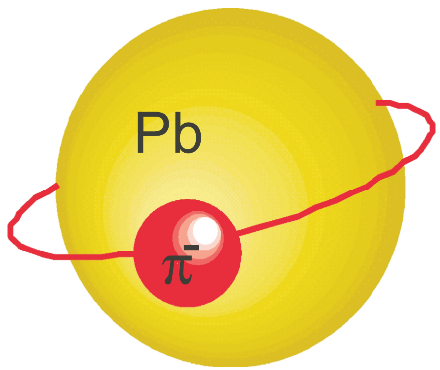
Introduction and Motivation

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

$U_{opt}(r) \begin{cases} \text{p-wave part} \\ \text{s-wave (local) part} \end{cases}$

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

Large Ambiguity

Deeply bound pionic states
are very sensitive

Treating medium effect in local potential.

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

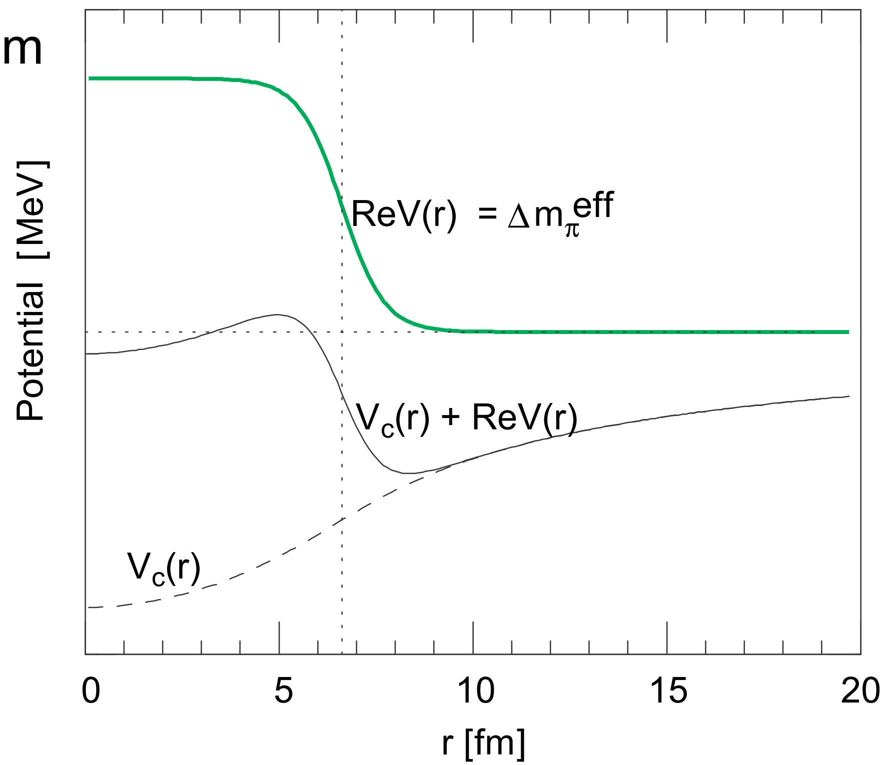
$$[m_{eff}(r)]^2 \equiv [m_\pi^2 + \mathbf{q}^2 + \mathrm{Re}\Pi]_{q\to 0}$$

Waas et al. PLB405 (97) 215

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

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

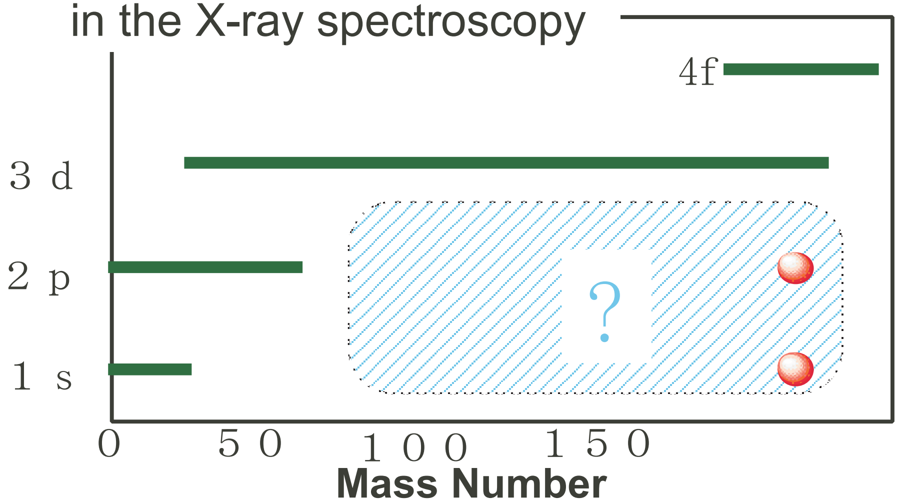
Medium effect is treated as local potential.

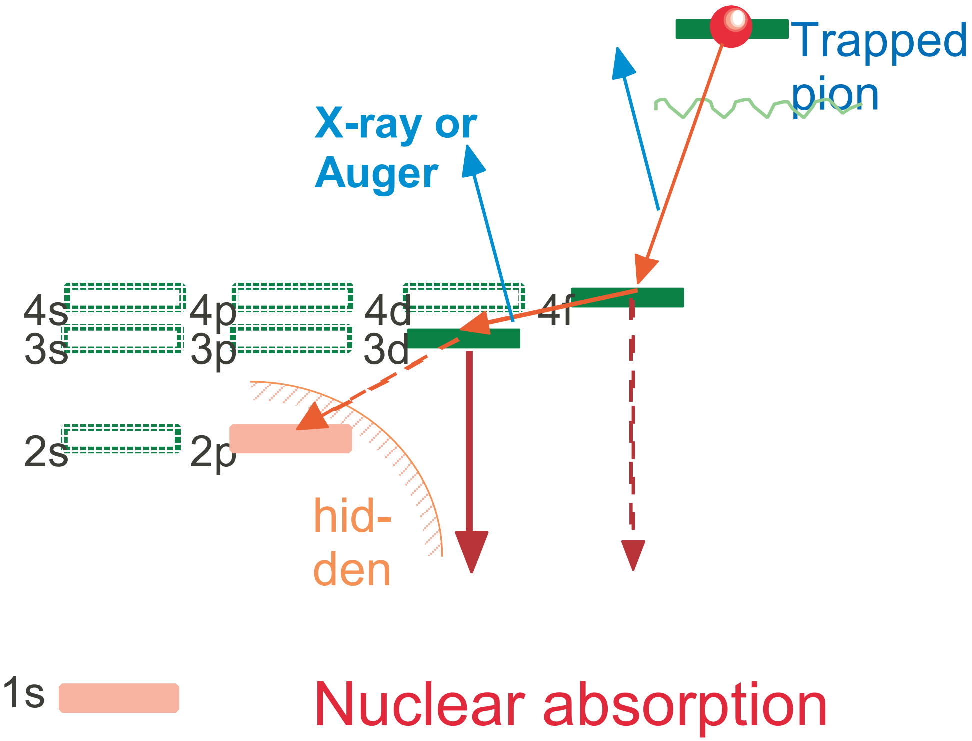


History

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



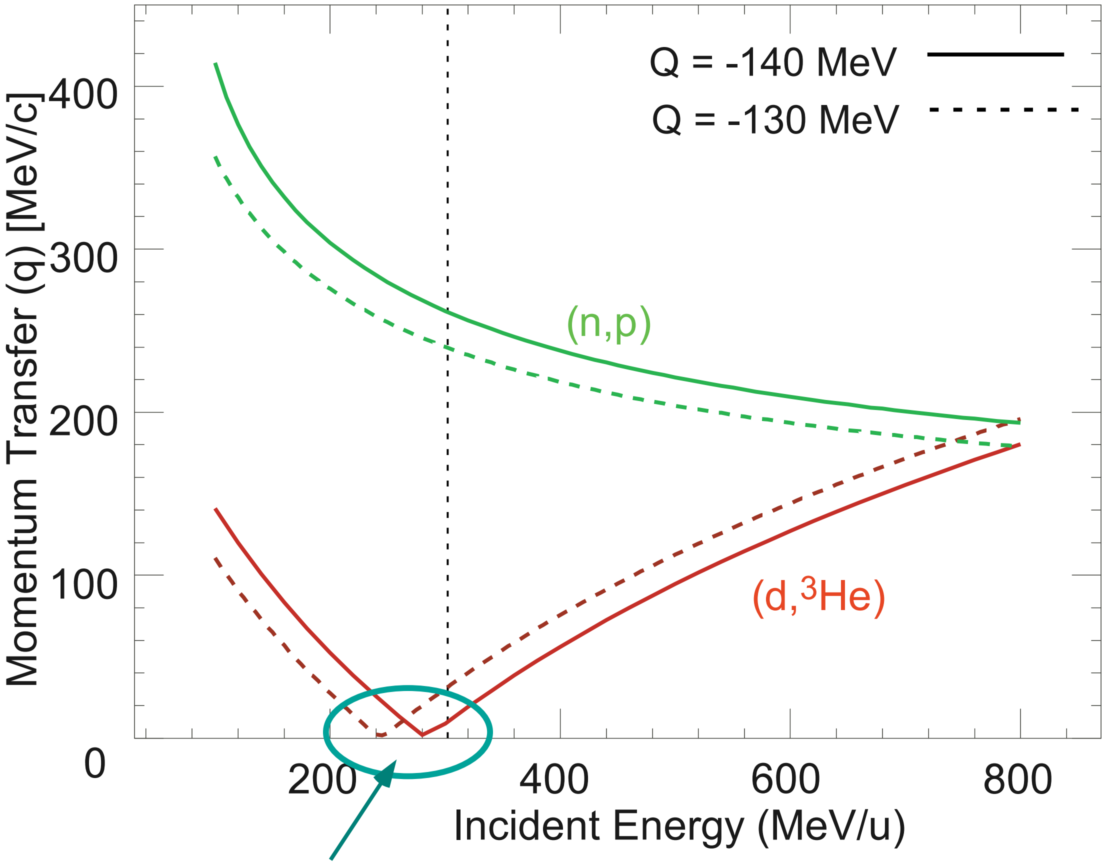


- π^- in nuclear medium Γ_{abs} ~ 20 MeV
- π^- radius ~ nuclear radius

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

A key of experimental condition

Recoilless kinematics



Quasi-substitutional ($\Delta l \sim 0$) reaction

Small momentum transfer(q)

Experimental trials and break-through

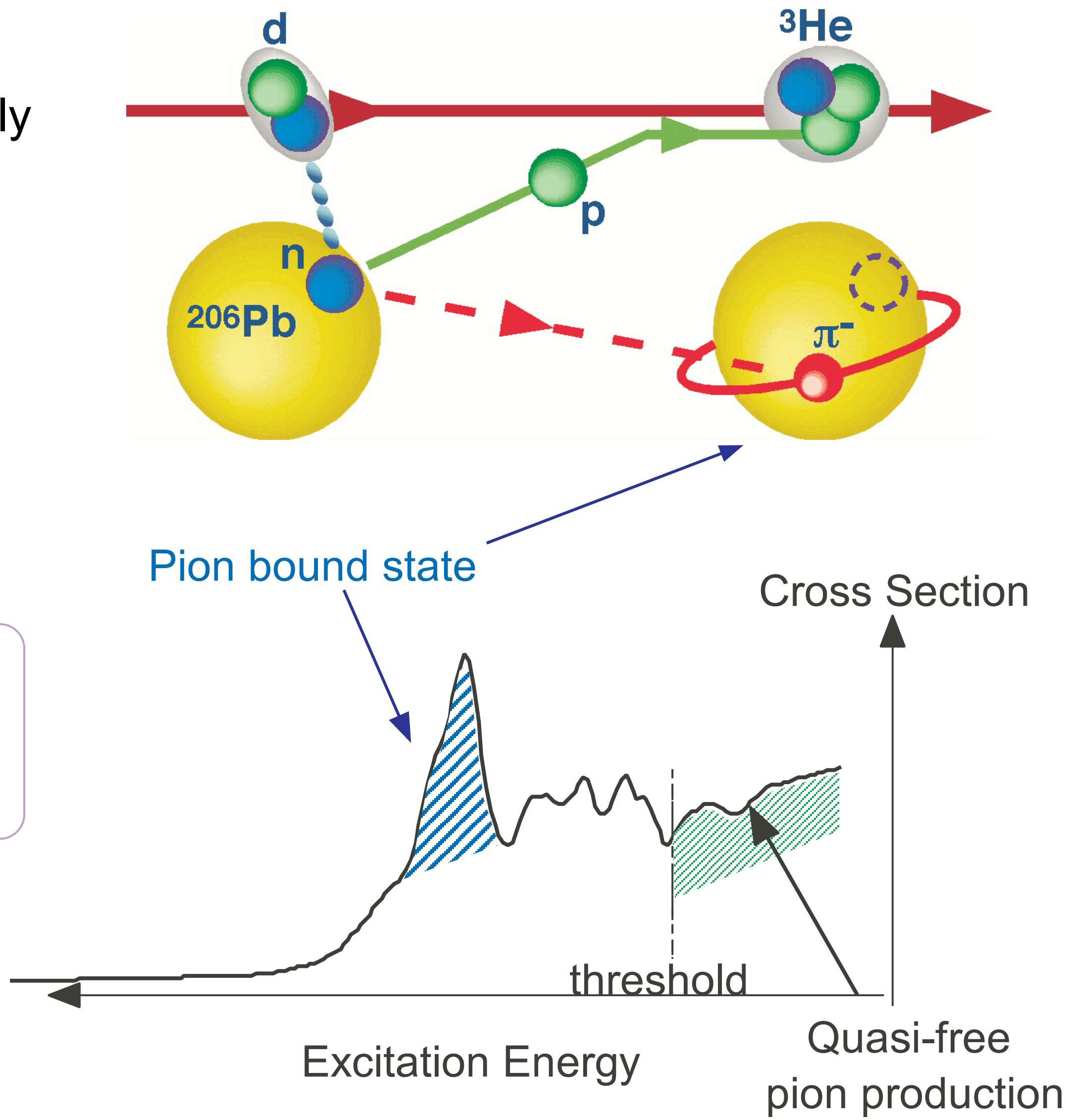
Nuclear reaction

Direct population of deeply bound states

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

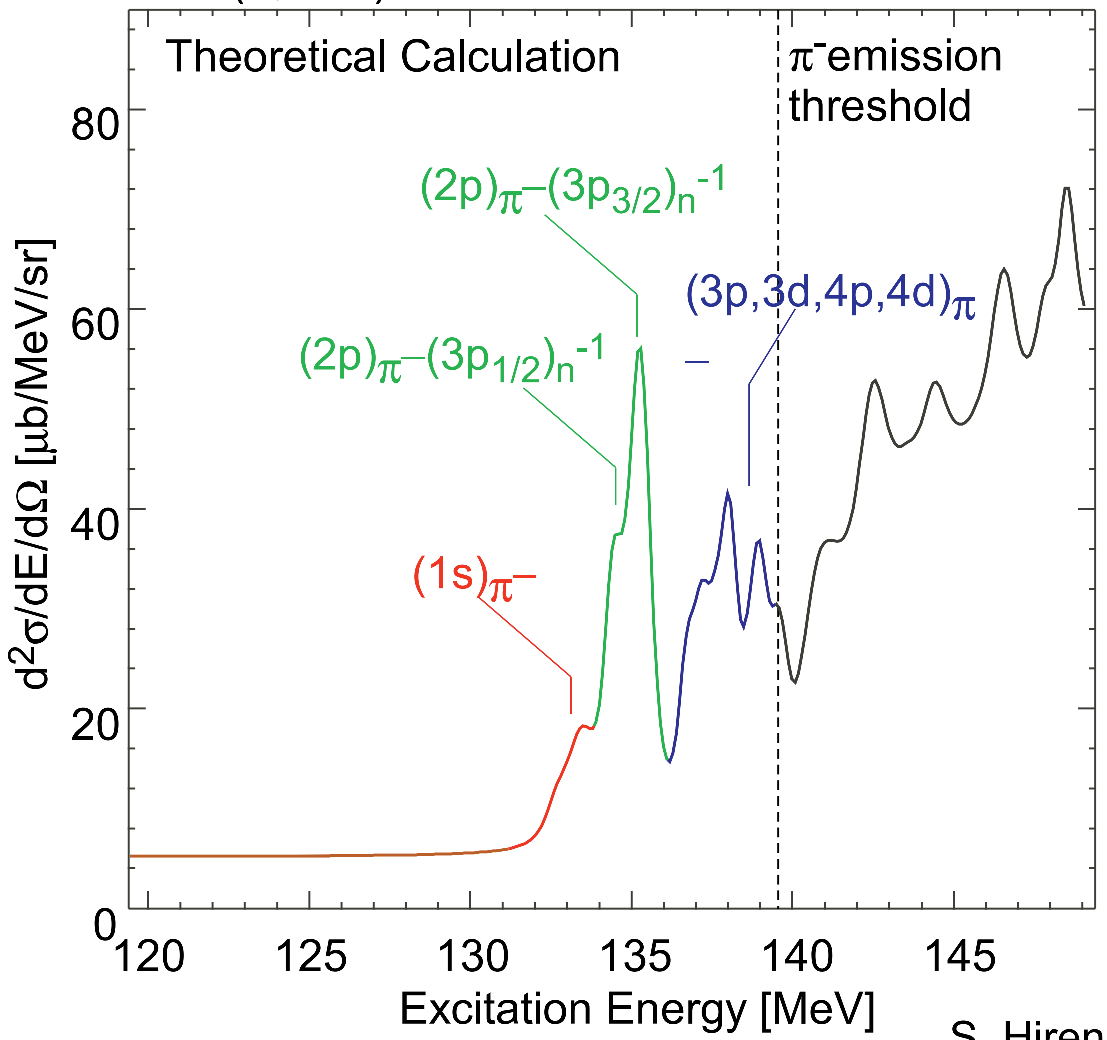
(*d*,^{3}He) at small momentum transfer

Produced state is coupling with a neutron hole



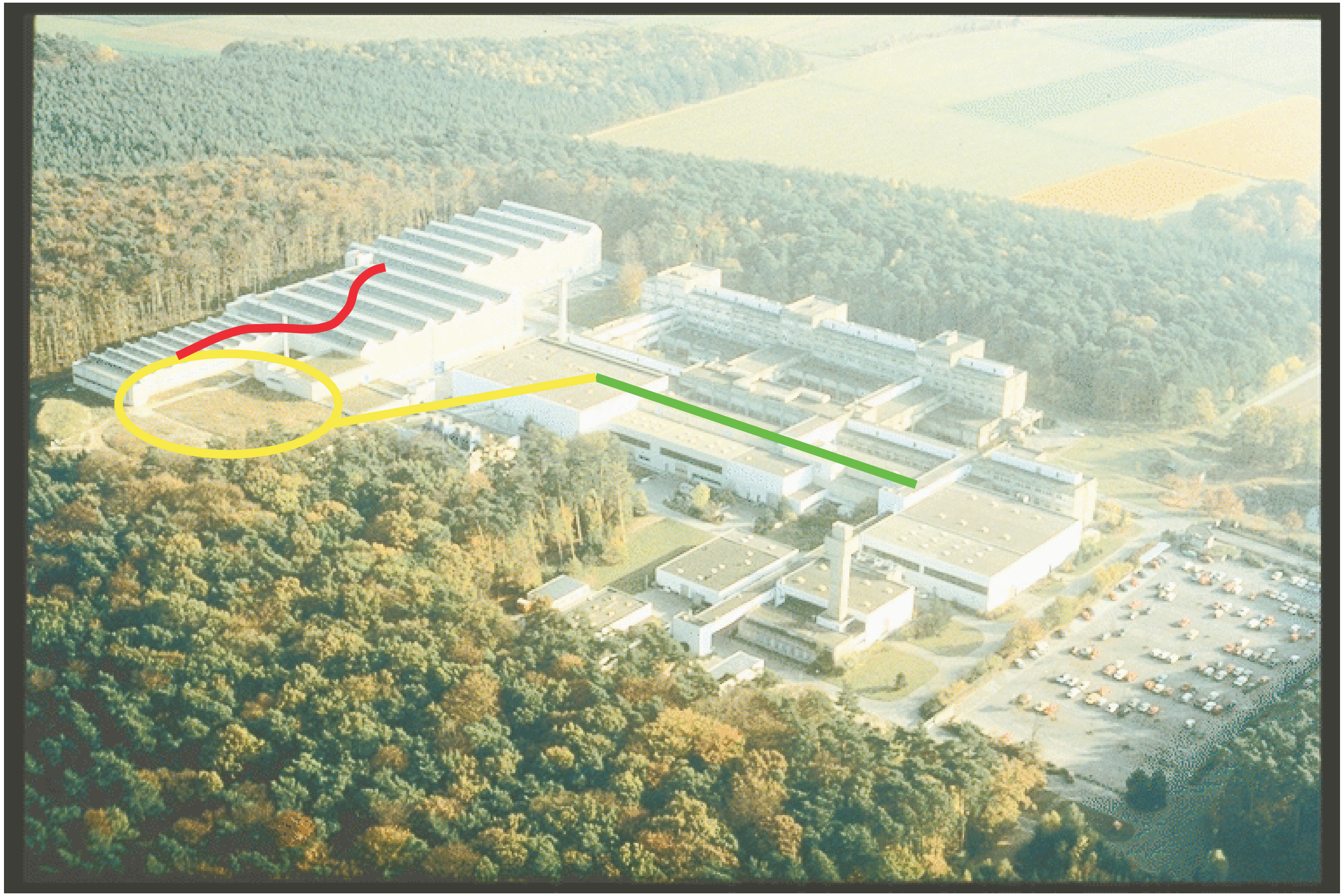
Theoretical Prediction

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

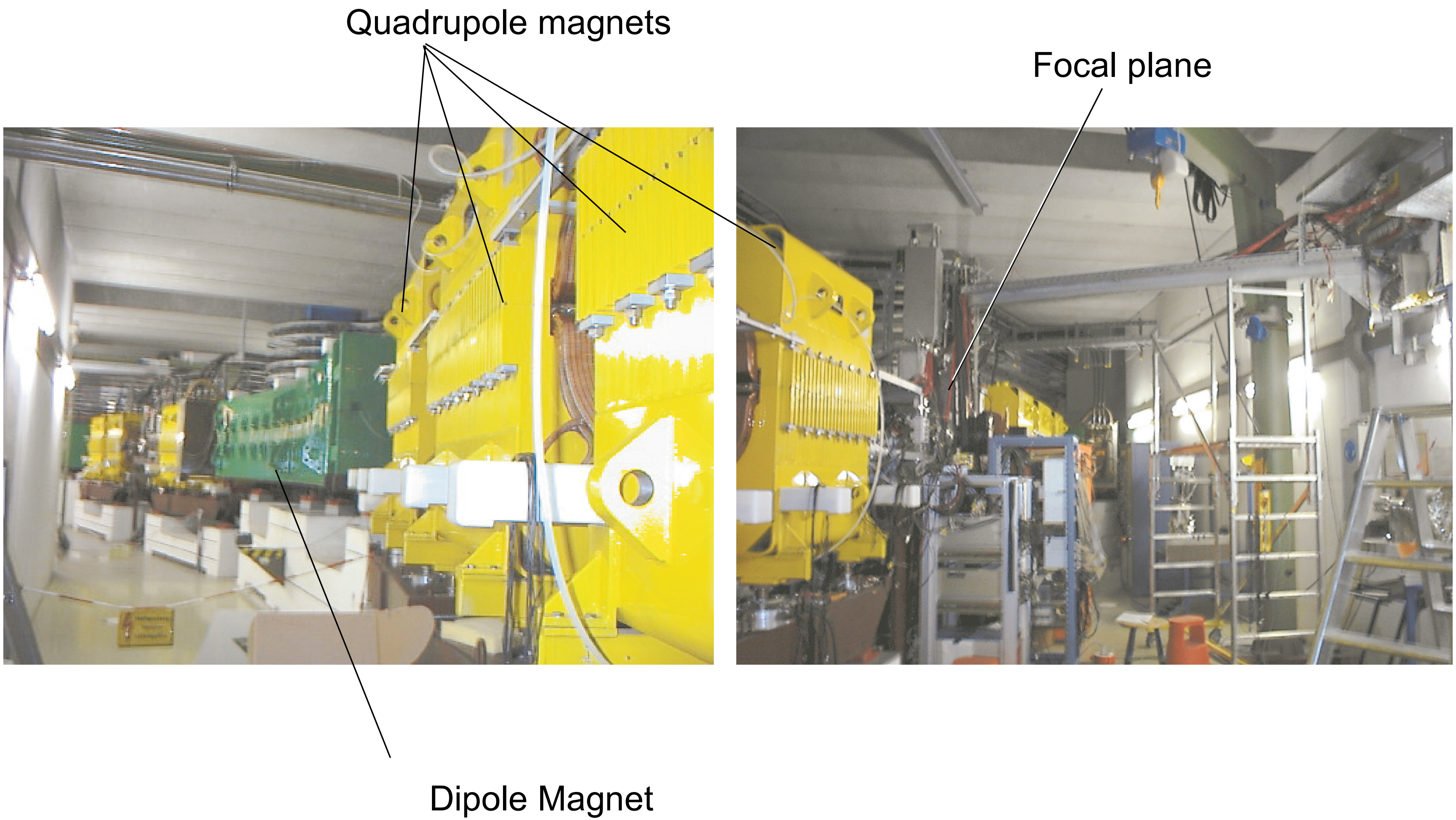


S. Hirenzaki et al.

Gesellschaft fuer Schwerionenforschung mbH, Darmstadt



Experimental Area

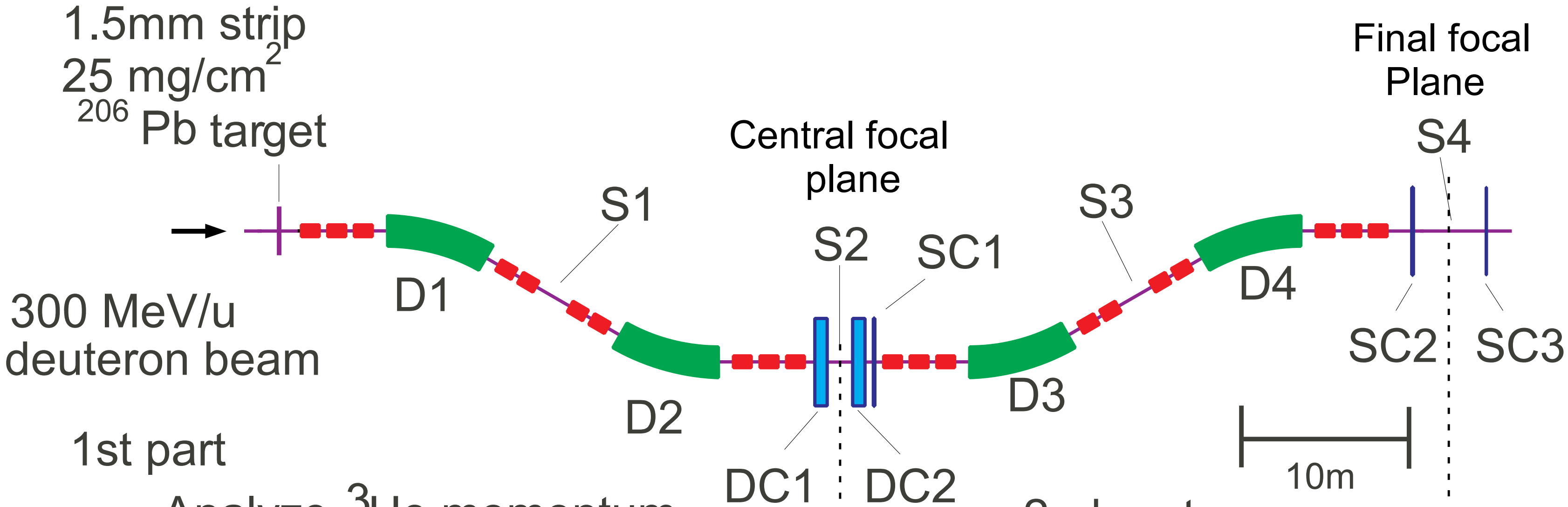


FRS Spectrometer

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

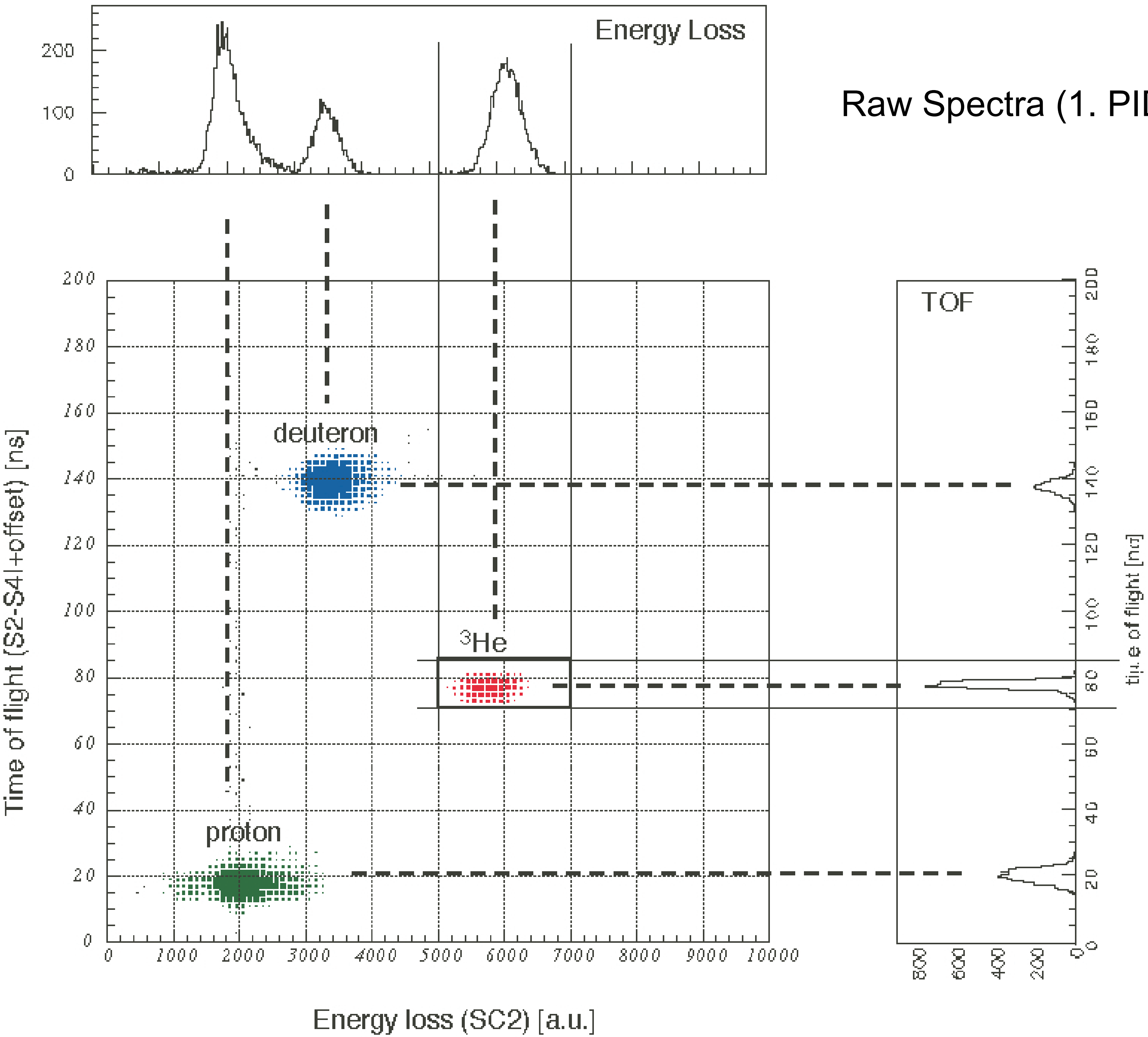
Detector:
DC1,DC2 : drift chamber
SC1-SC3 : scintillation counter



1st part
Analyze ^{3}He momentum
Dispersive mode
6.9 cm/%
Resolution 0.3 MeV FWHM

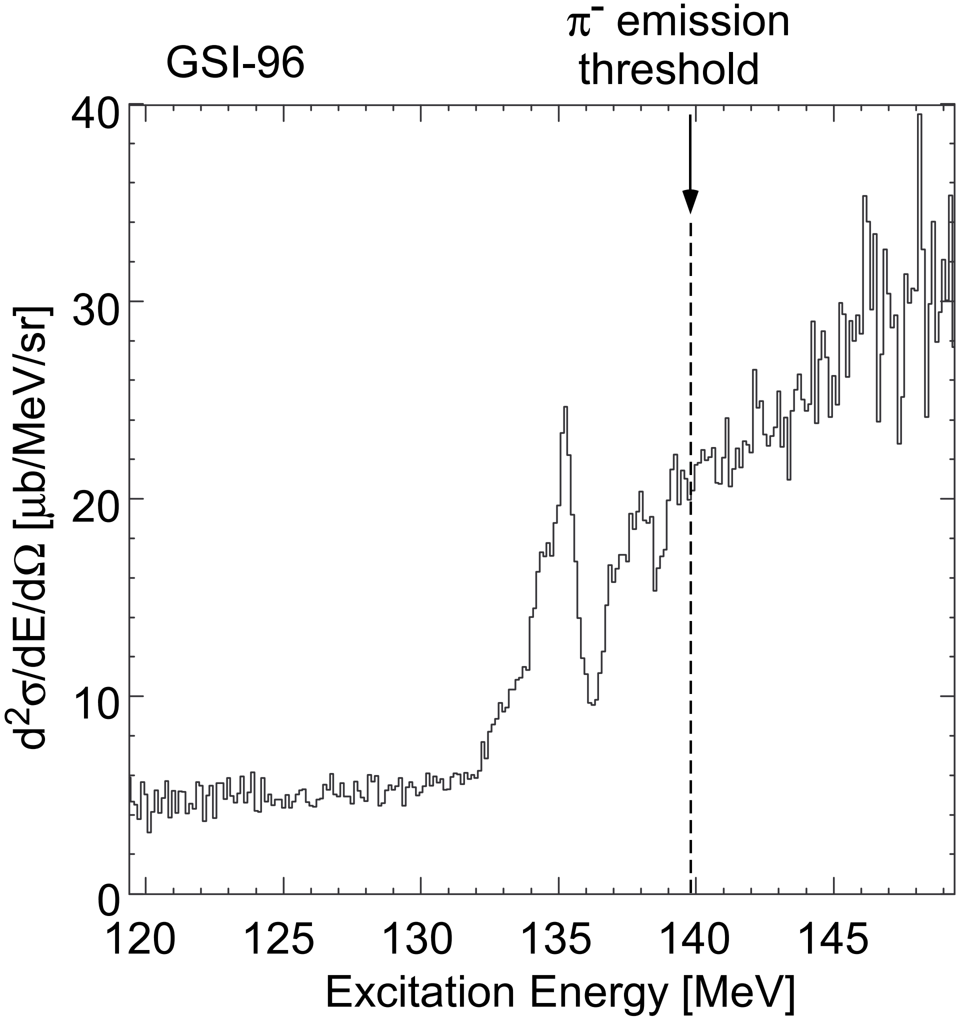
2nd part
Particle Identification
Time of flight S2-S4 (36 m)
Energy loss SC1, SC2 ,SC3

Raw Spectra (1. PID)



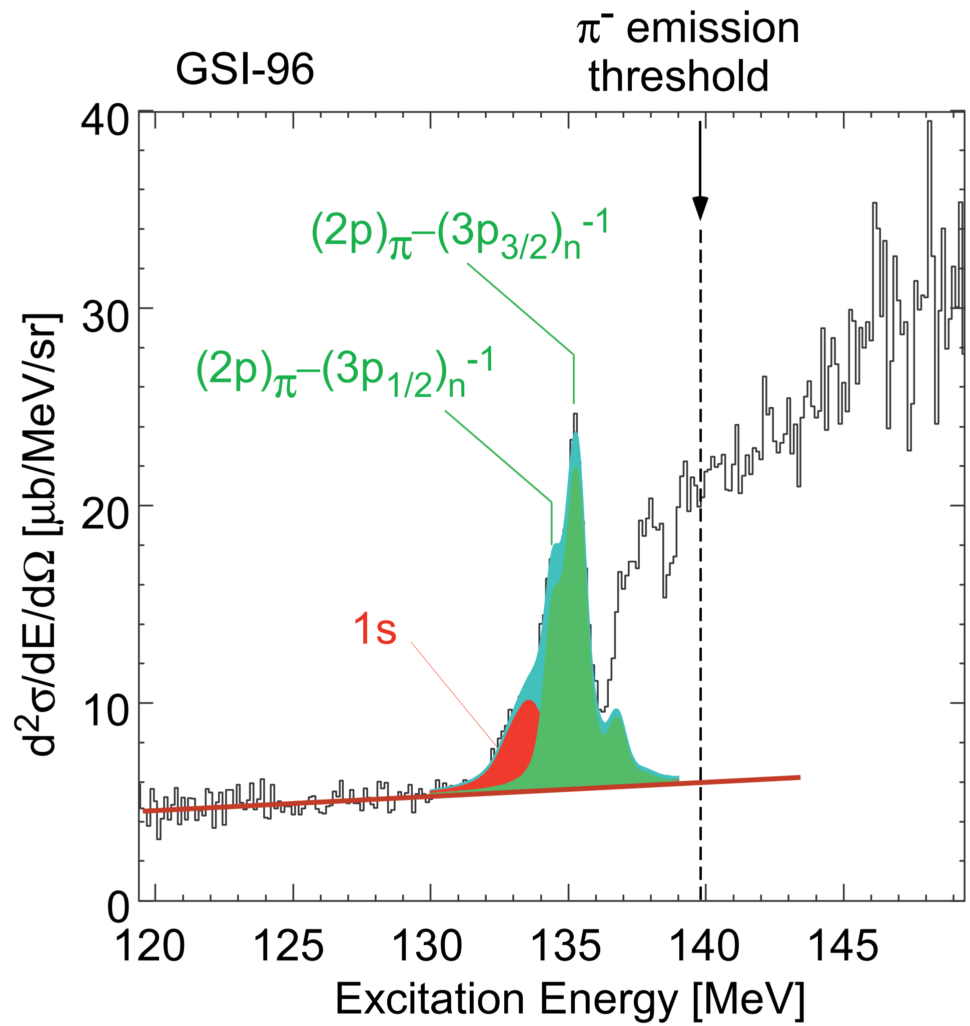
Bound pionic states in ^{207}Pb

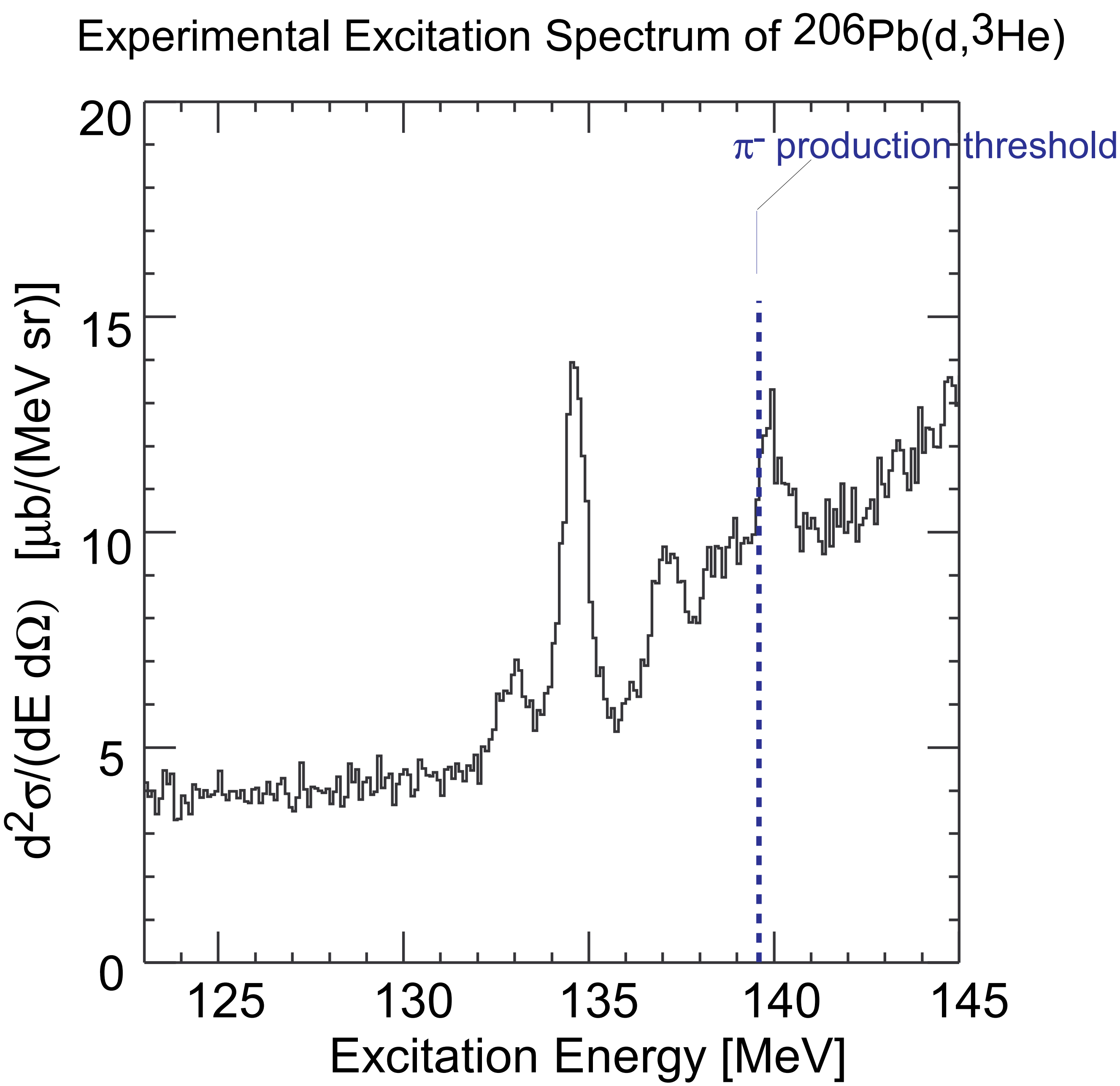
Experimentalexcitation spectrum of $^{208}Pb(d,^{3}He)$



Bound pionic states in ^{207}Pb

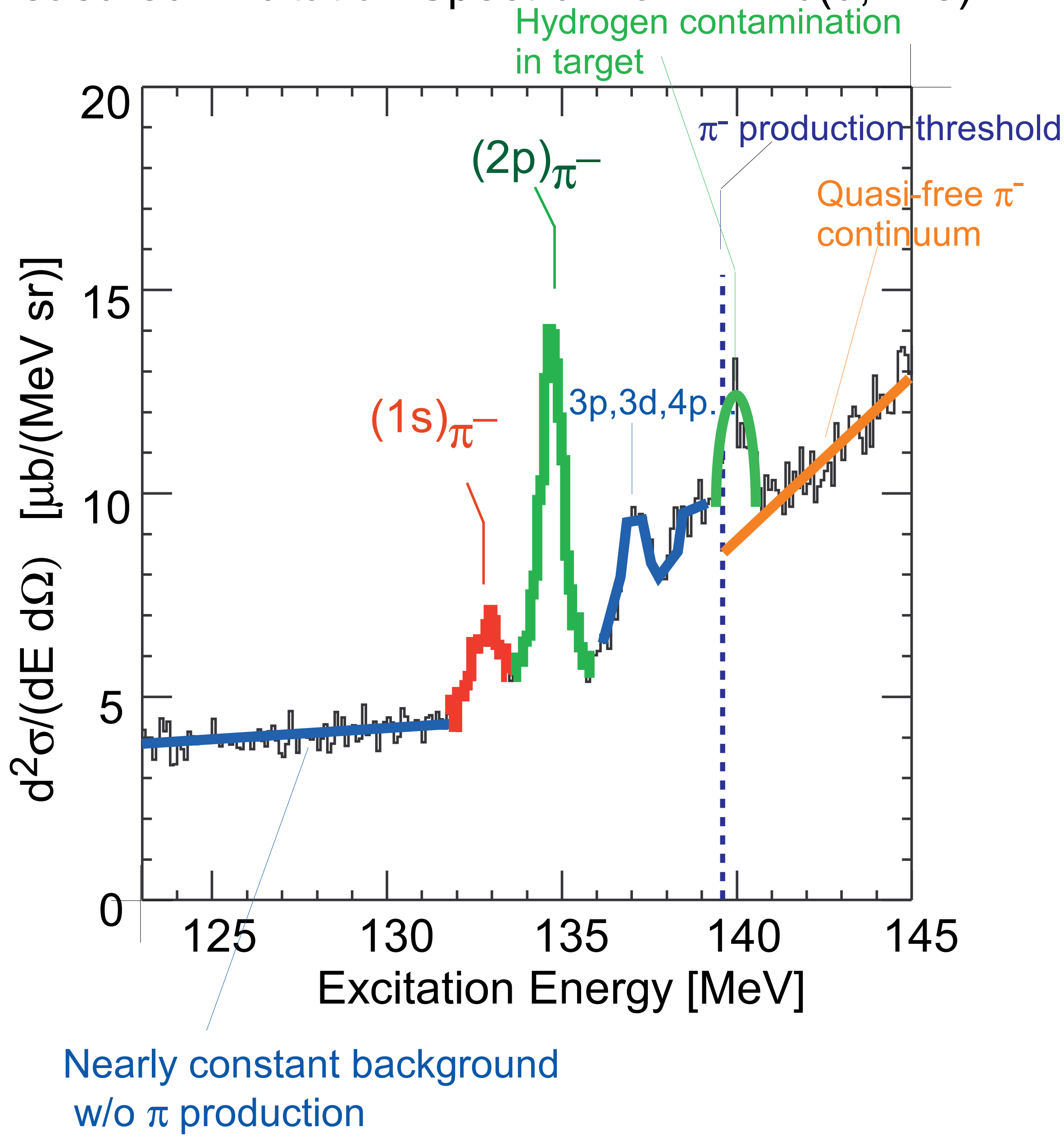
Experimentalexcitation spectrum of ^{208}Pb(d,^{3}He)



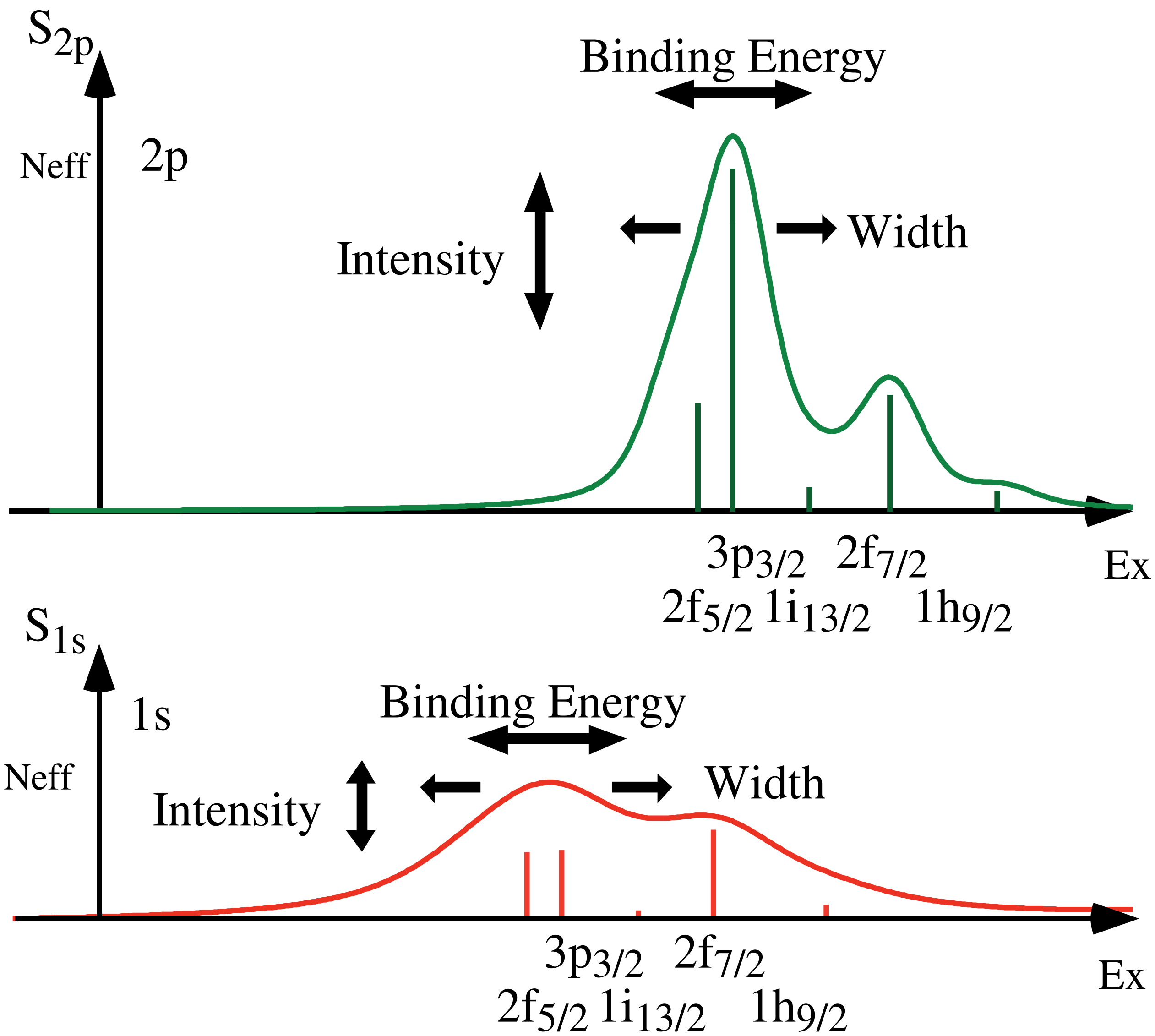


Experimental Excitation Spectrum of $^{206}Pb(d,^{3}He)$
π^{-} production threshold
$d^2\sigma/(dE\, d\Omega)$ [μb/(MeV sr)]
Excitation Energy [MeV]
0
5
10
15
20
125
130
135
140
145

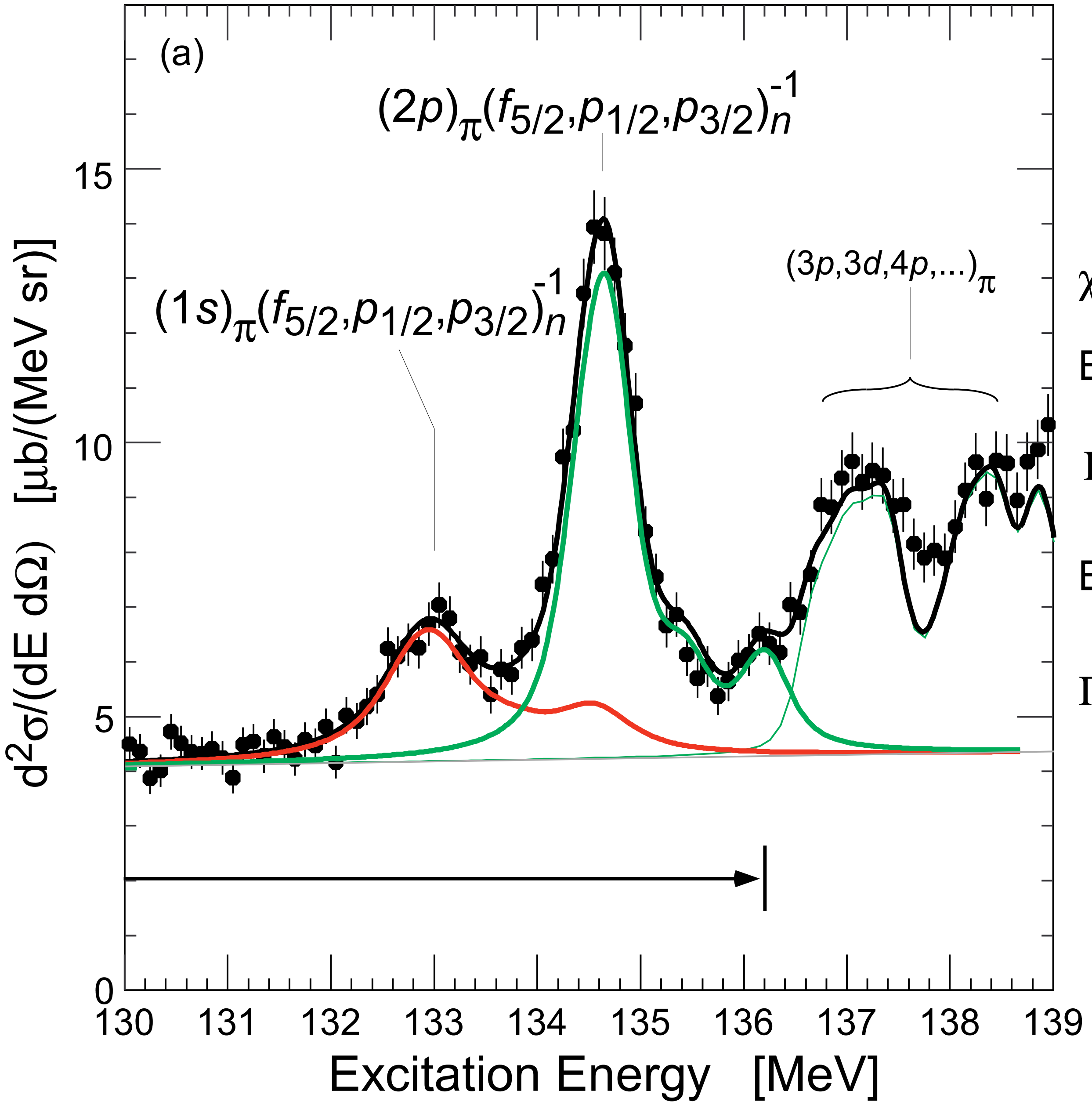
Measured Excitation Spectrum of $^{206}Pb(d,^{3}He)$



Fitting procedure



Fitting result



$\chi^2/N_{DF} = 0.75$ ($N_{DF}=125$)

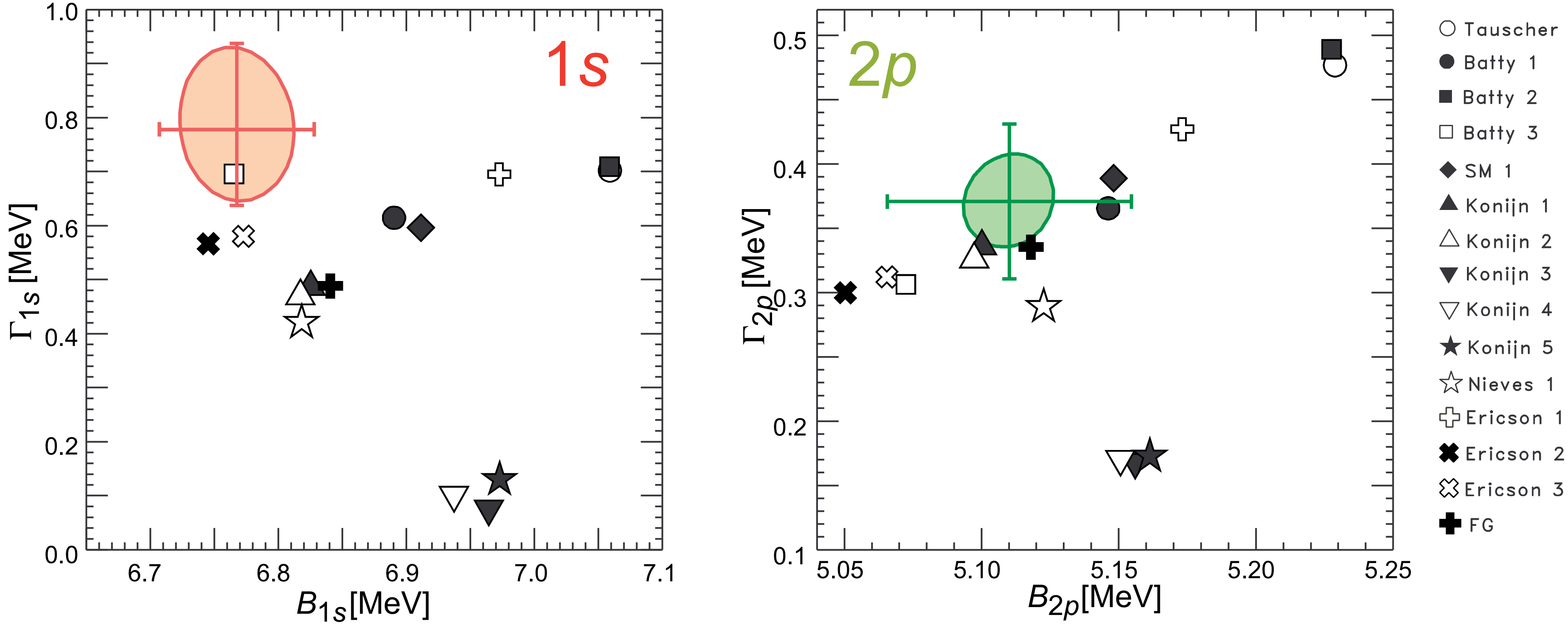
$B_{1s} = 6.768 \pm 0.044 \pm 0.041$ MeV

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

$B_{2p} = 5.110 \pm 0.015 \pm 0.042$ MeV

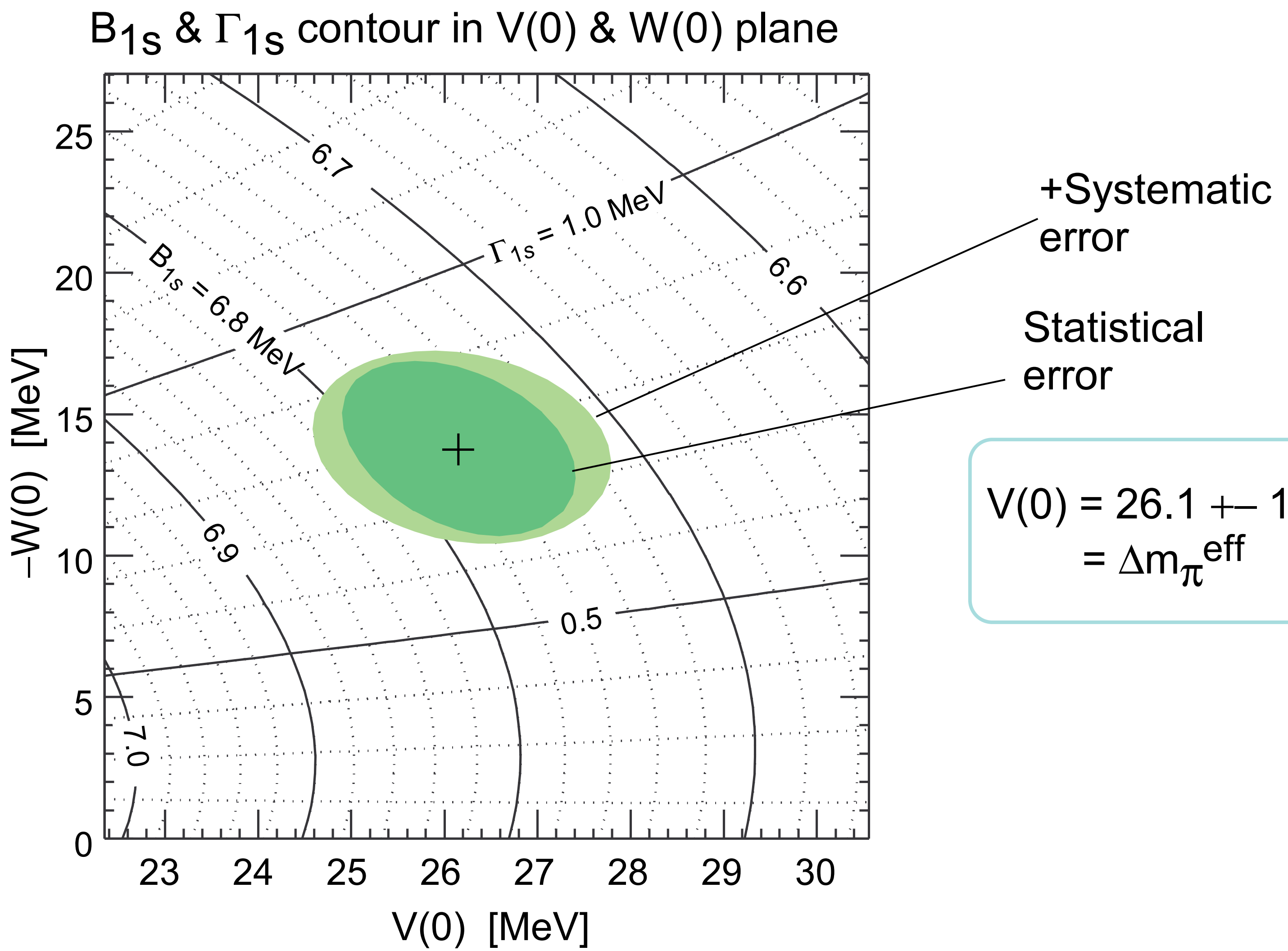
$\Gamma_{1s} = 0.371 \pm 0.037 \pm 0.048$ MeV

Comparison between theoretical prediction and experimental result



Fairly good agreement and very high precision.

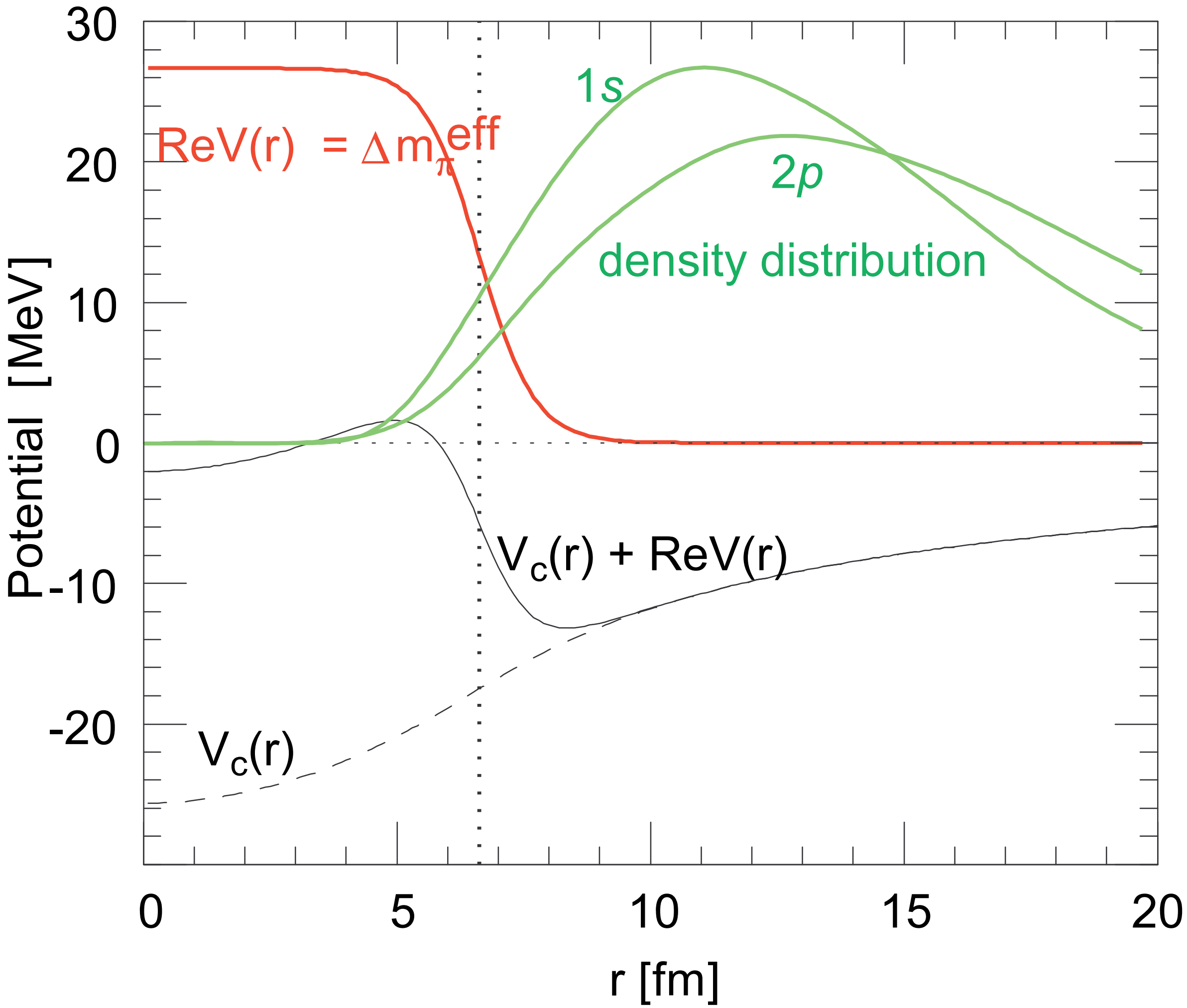
Deduction of Potential Depths



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.

Δm_π^{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 Γ_{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?

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