European Graduate School
Complex Systems of Hadrons and Nuclei
Copenhagen, Giessen, Helsinki, Jyväskylä

Workshop on "In-Medium Hadron Physics"
Gießen, Nov. 11-13, 2004

Chiral restoration probed by pionic atoms

-as an alternative way to experimentally pursuit the medium modification "Meson-Nucleus bound system"

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S160/S236 collaboration
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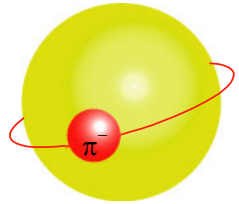
Exp. Methods aiming for M.M.

- Heavy-Ion Collision
  - CERES, HADES, E325/KEK
- Meson-Meson Correlation (σ/f_0)
  - Chaos/TRIUMF, DIRAC/CERN-PS
- Sub-Threshold Production
  - KaoS
- Meson-Nucleus bound state spec.
  - (Deeply Bound) Pionic Atom
    - $R_\pi \fallingdotseq r_{\text{heavy nucleus}}$
  - Photo pruduction

(deeply bound) pionic atom



Levels of bound pionic state in ^{207}Pb

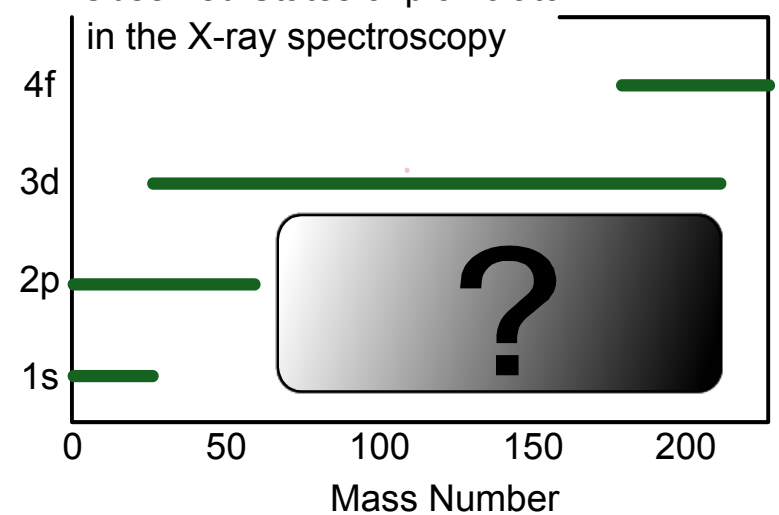
Stopped pion

Stopped pion

X-ray spectroscopy

5s
4s
3s
2s
5p
4p
3p
5d
4d
3d
4f
2p
1s
repulsive
repulsive
Deeply Bound States
Finite Size Coulomb Only
Optical Potential in addition
Absorption Width
0 1 2 3 4 5 6 7 8 9 10 11 12 13
B.E. [MeV]

Observed States of pionic atom in the X-ray spectroscopy



Nuclear reactoin

(d,^{3}He) reaction

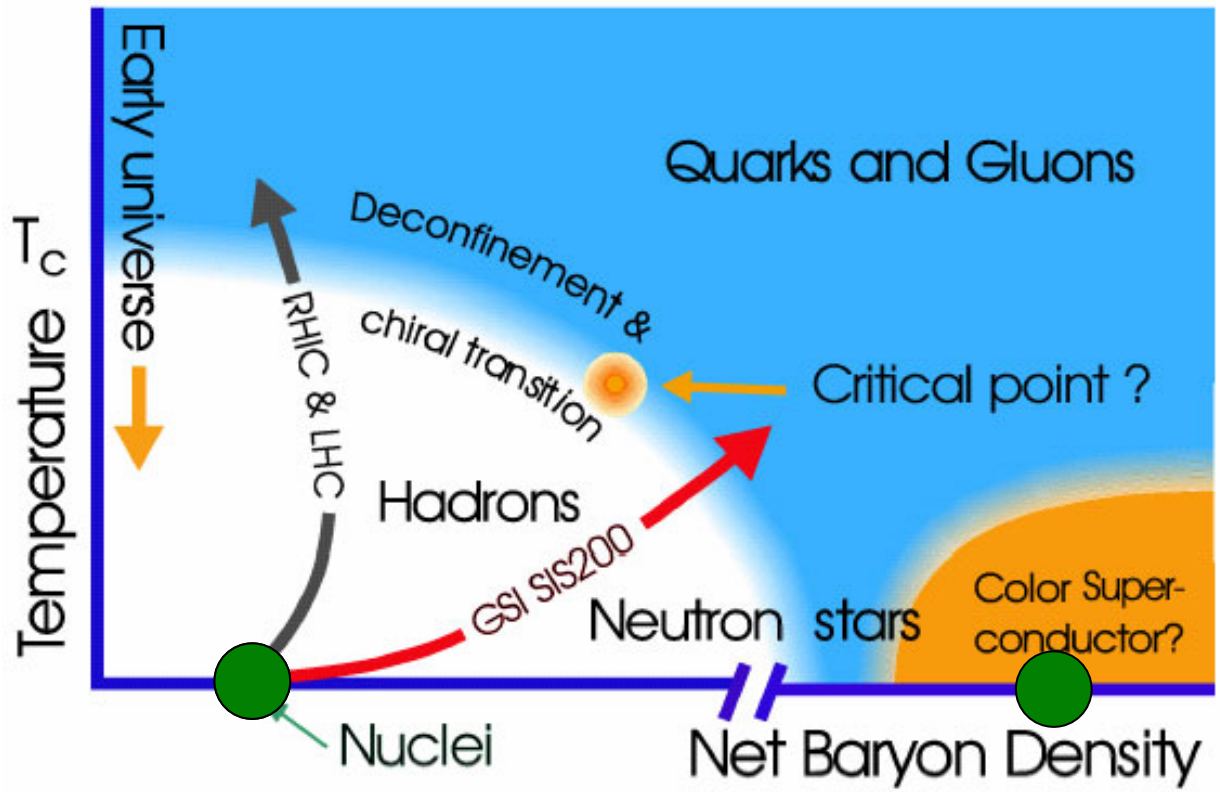
Nuclear Absorption

vs. HIC

	HIC	Meson−Nucleus Bound System
What to measure?	M_{inv} from l^+l^-	B.E.(Energy Shift), Γ
What Changes	Meson Mass	Interaction
Which Meson?	ρ, ω, ϕ,,	π, η, ω,,
Which State?	Continuum (relativistic)	Well−Defined State
Which T, ρ?	+"Controllable" −Certain Ambiguity (T(t),ρ(t))	+Uncontrollable (T=0, $\rho=\rho_0$) −No Ambiguity
e.x.	CERES, HADES, E325/KEK,,,	Pionic Atom
T=ρ=0 Calib.	p+A, p+p	Pionic Hydrogen
Maj. Error Src	T, ρ, t	neutron radius

Which T,ρ?

–In case of MHCNBS



π−nucleus int. to <qq>

π−nucleus interaction *

Tomozawa−Weinberg Relation

$$-4\pi(1+m_\pi/M)b_1 = m_\pi/2f_\pi^2$$

$$\frac{f_\pi^*(\rho)^2}{f_\pi^{\,2}} = \frac{b_1^{\text{free}}}{b_1(\rho)}$$

Thorsson et al. NPA589 (1995)633

Weise et al. Acta PPB31 (2000)2715

Kolomeitsev, Kaiser, Weise PRL90 (2003) 92501

pion decay constant: fπ *

time component

Gell=Mann−Oakes−Renner Relation

$$m_\pi^{*2} f_\pi^{*2} = -\frac{m_u + m_d}{2}\langle \bar{q}q\rangle_\rho$$

$$\left(\frac{m_\pi}{m_\pi^*}\right)^2 \cdot \frac{\langle \bar{q}q\rangle_\rho}{\langle \bar{q}q\rangle_0} \approx \frac{f_\pi^*(\rho)^2}{f_\pi^{\,2}}$$

<qq>$_\rho$

Pion–Nucleus potential

$$\left[-\nabla^2 + \mu^2 + 2\mu U_{\text{opt}}(r)\right]\phi(r) = [E - V_{\text{coul}}(r)]^2 \phi(r)$$

$$2\mu U_{\text{opt}}(r) = -q(r) + \nabla \cdot \alpha(r) \nabla$$

S–wave + P–wave

$$q\left(r; b_0, b_1, \mathbf{B}_0, \rho_p(r), \rho_n(r)\right) \quad \alpha\left(r; c_0, c_1, \mathbf{C}_0, \xi, \rho_p(r), \rho_n(r)\right)$$

$$q(r) = -4\pi\left[\varepsilon_1\{b_0[\rho_n(r) + \rho_p(r)] + b_1[\rho_n(r) - \rho_p(r)]\}\right]$$

$$= -4\pi\left[\varepsilon_2 B_0[\rho_n(r) + \rho_p(r)]^2\right]$$

$$\alpha(r) = 4\pi\left[\varepsilon_1^{-1}\{c_0[\rho_n(r) + \rho_p(r)] + c_1[\rho_n(r) - \rho_p(r)]\}\right]$$

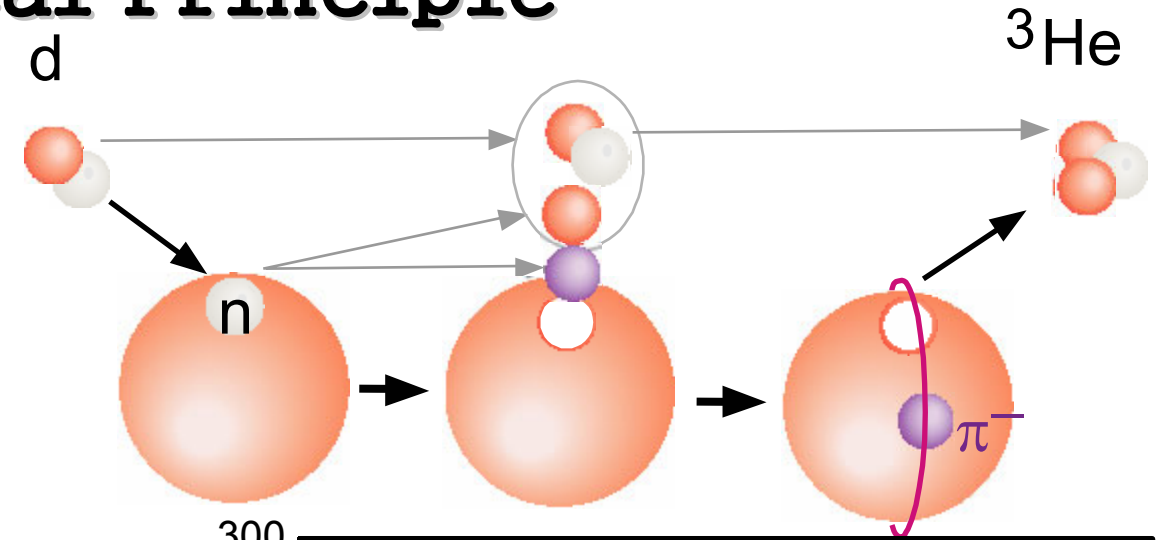
$$= 4\pi\left[\varepsilon_2^{-1} C_0[\rho_n(r) + \rho_p(r)]^2\right]$$

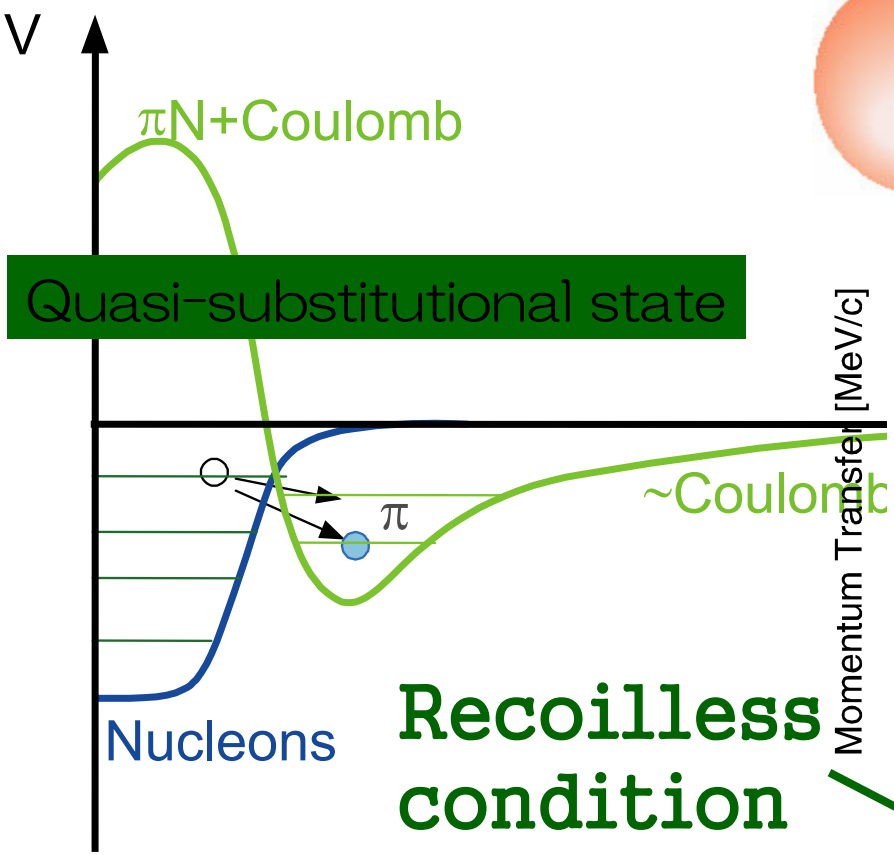
$$\varepsilon_1 = 1 + m_\pi / M$$

$$\varepsilon_2 = 1 + m_\pi / 2M$$

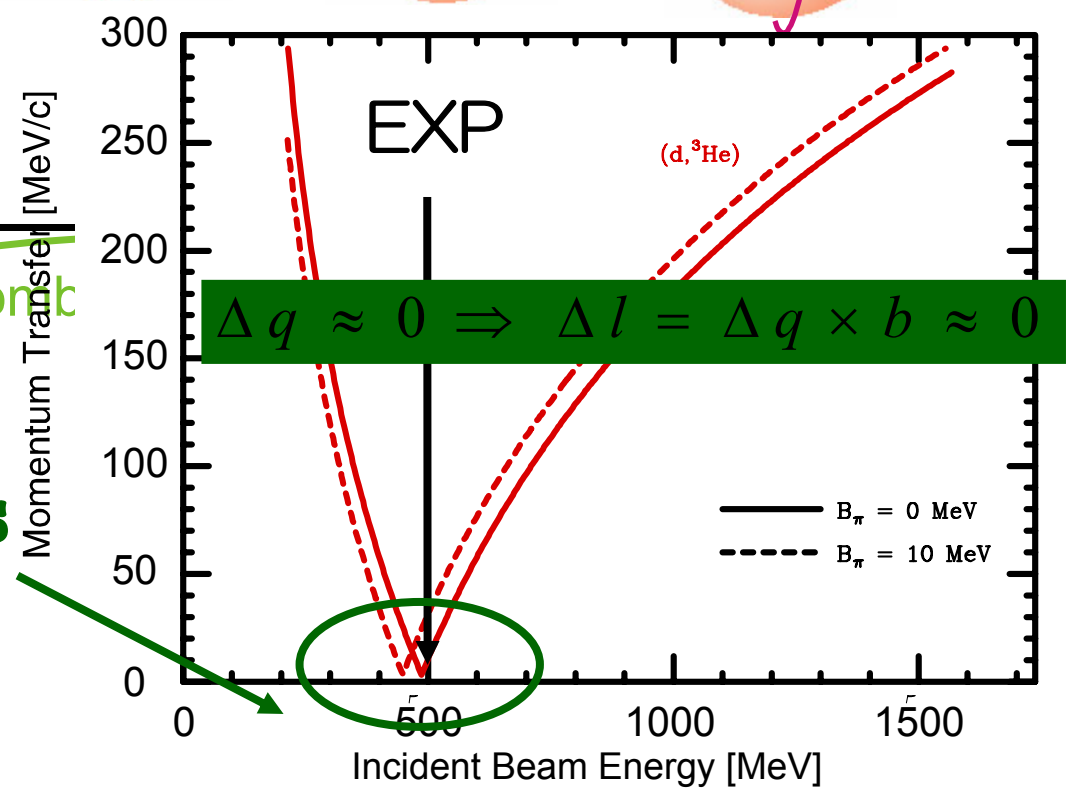
Conventional units : b_0 and b_1 in m_π^{-1}, and B_0 in m_π^{-4}

Experimental Principle

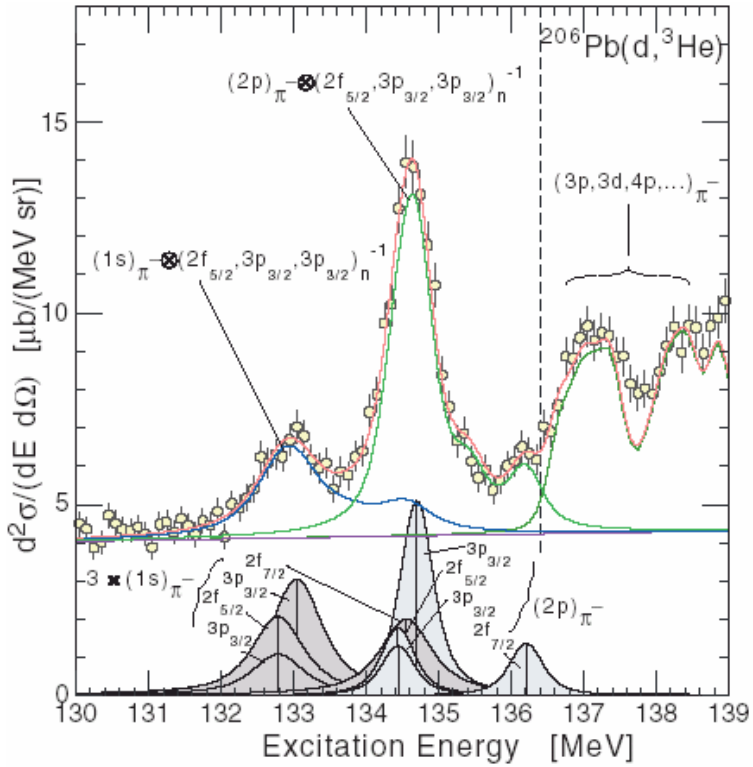


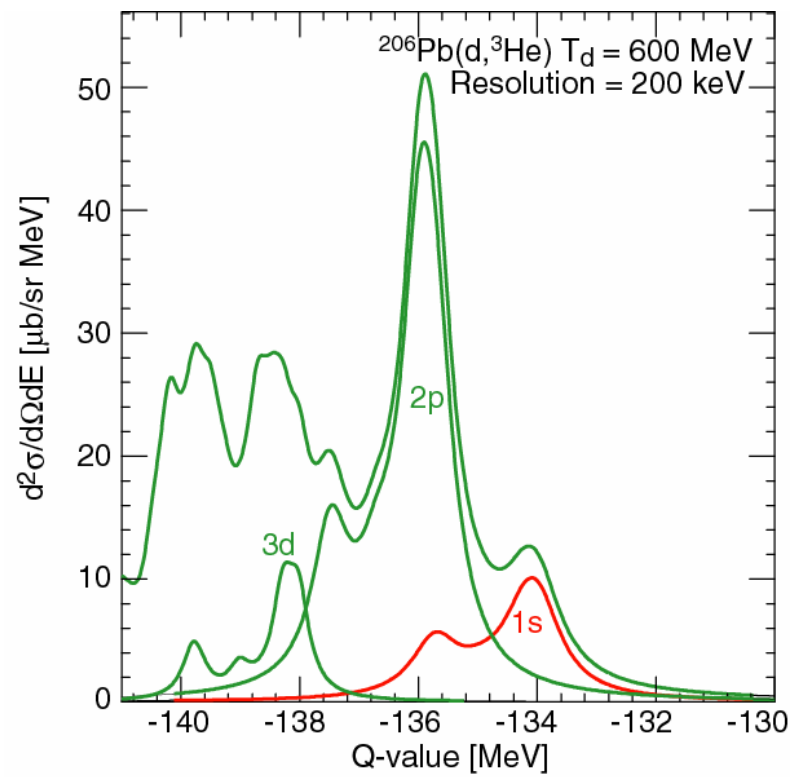


Recoilless condition



^{206}Pb(d,^{3}He) at T_d=600MeV

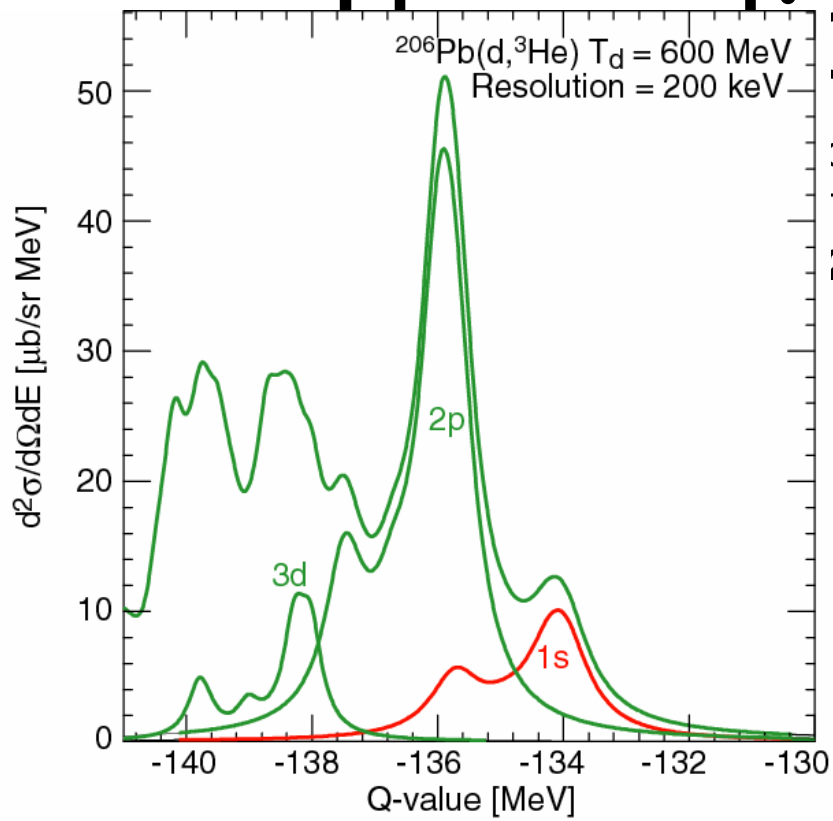




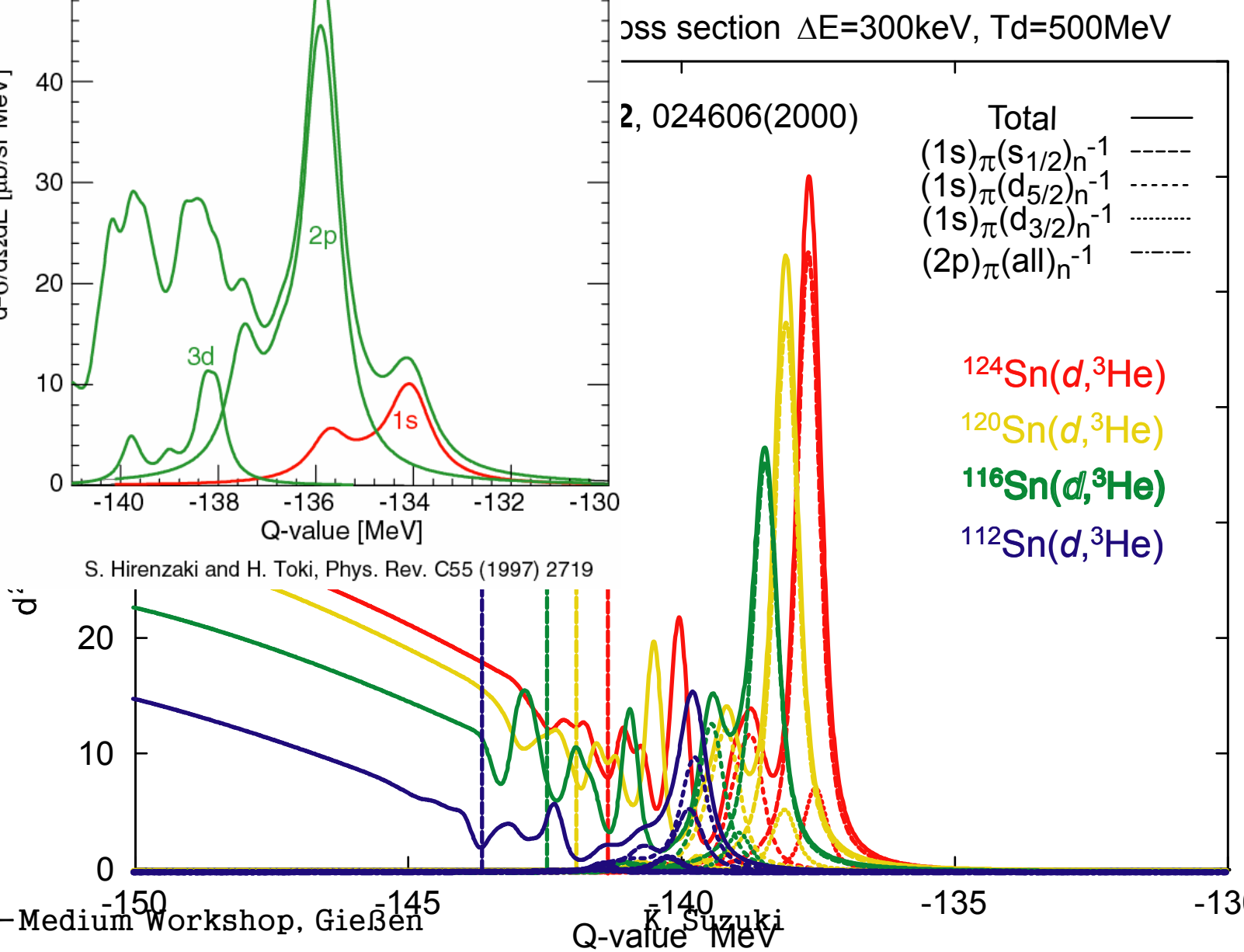
S. Hirenzaki and H. Toki, Phys. Rev. C55 (1997) 2719

H. Geissel et al. PRL 88 (2002) 122301

Theoretical Spectra



S. Hirenzaki and H. Toki, Phys. Rev. C55 (1997) 2719



Spectrometer –FRS–

Target
$^{116,120,124}Sn$
20mg/cm^2

Central focal plane to final focal plane

deuteron beam

Particle Identification
- Time of Flight Measurement
- Energy Loss

Second Half

First Half

Target to Central focal plane

10 m

Background reduction
Momentum analysis
- Dispersion 6.7cm/%
- Drift Chamber

Central Focal Plane

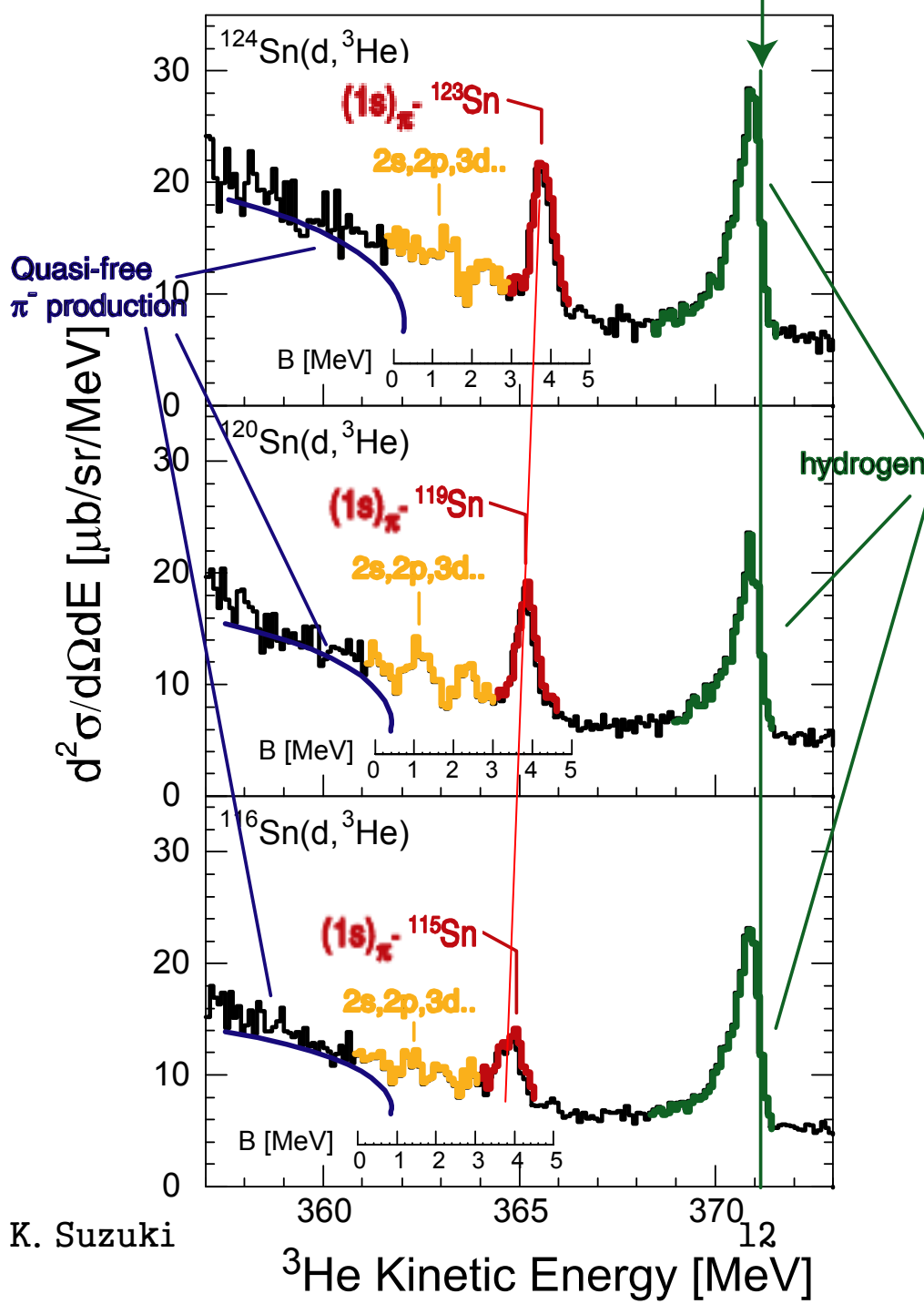
Drift Chamber
Segmented Scintillator

Final Focal Plane

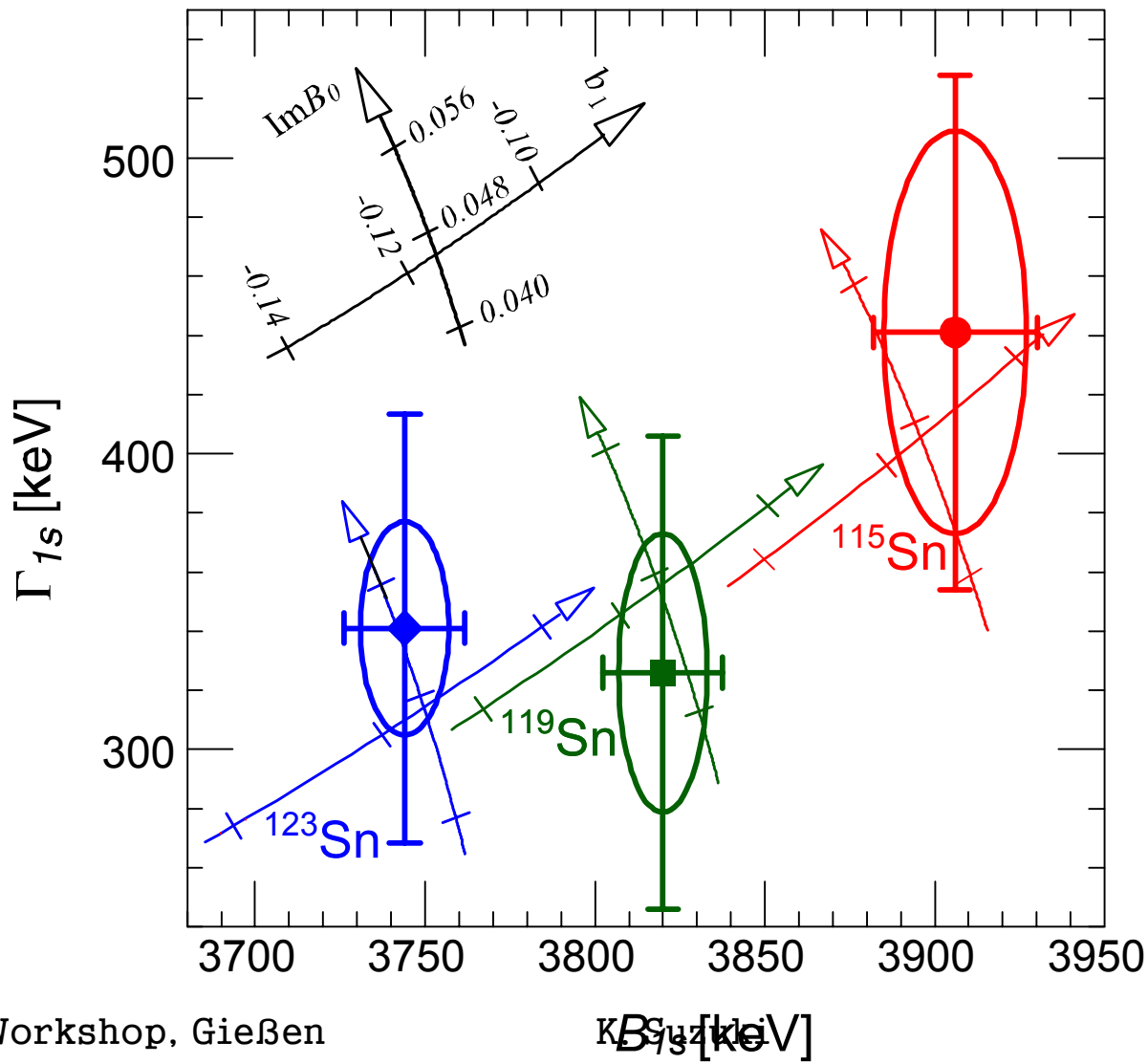
Scintillator

Energy Spectra

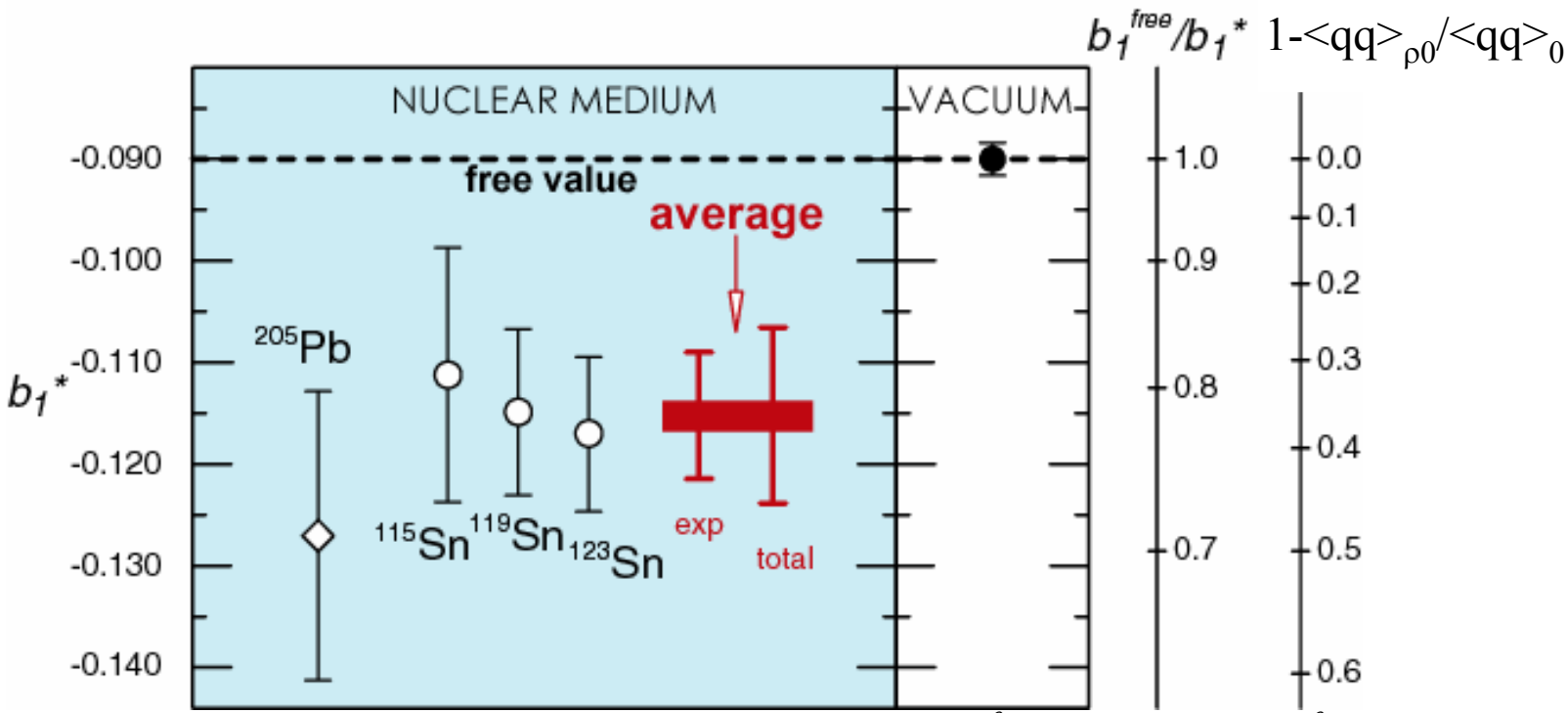
- Deeply bound pionic *1s* states in ^{123,119,115}Sn clearly observed
- Monotonic shift due to isotope effect
- Built-in indicator of Absolute energy calibration from Mylar backing targets



Experimental Result



Determination of in-medium b_1



K. Suzuki et al., PRL92 (2004) 72302

$$\frac{b_1^{free}}{1-\alpha\rho(r)} \Rightarrow \frac{b_1^{free}}{1-\alpha\rho_{eff}} \equiv b_1^*$$

- s-wave Isovector parameter b_1 determined to be:

$$b_1^* = -0.115 \pm 0.007 m_\pi^{-1}$$

- <qq> value largely modified in nuclear medium