

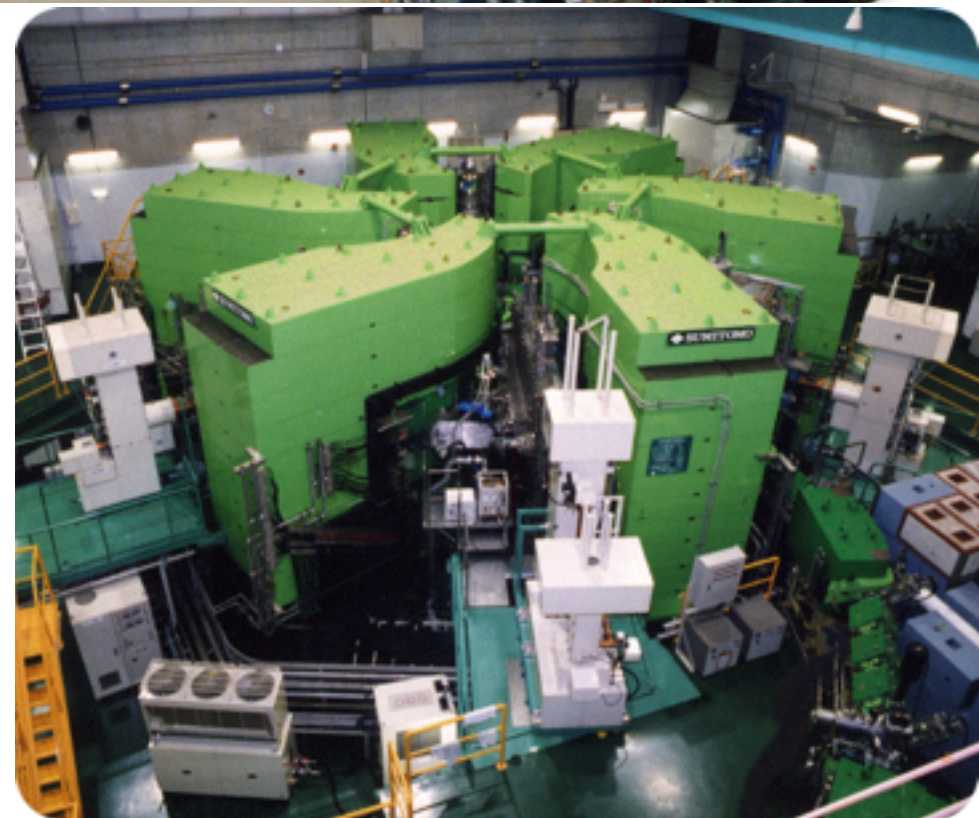
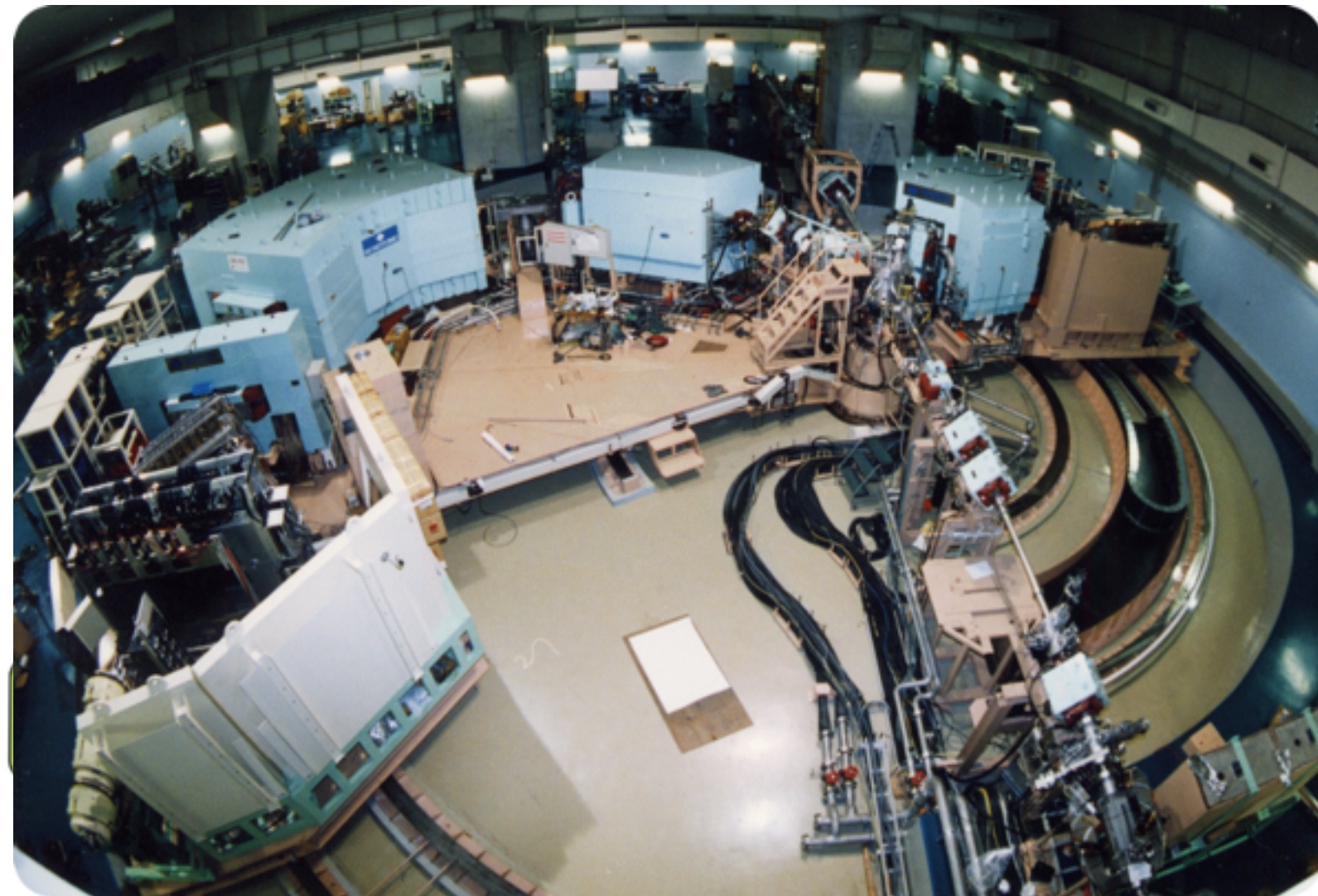
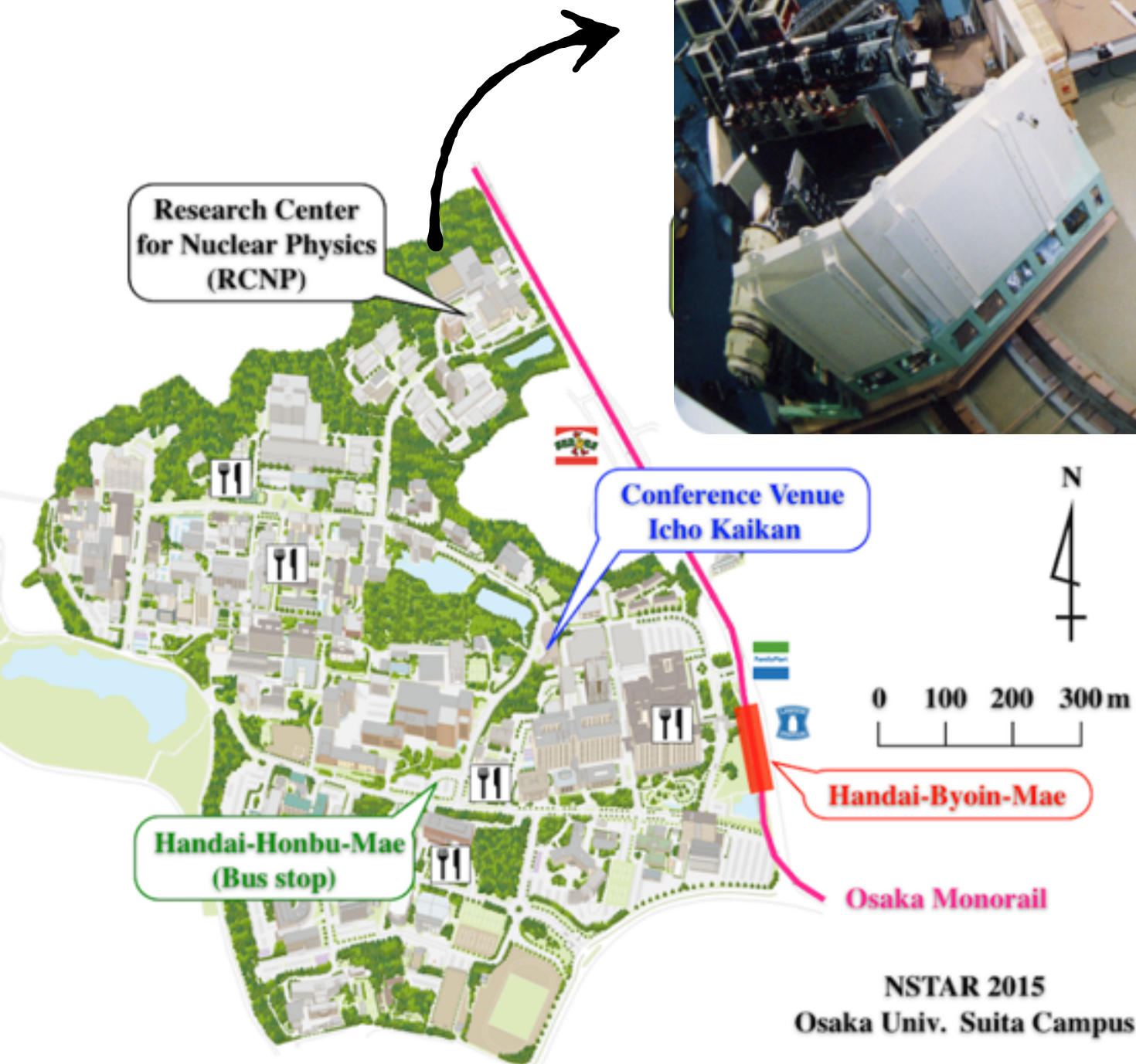
Spectroscopy of pionic atoms in the (p,²He) reaction at RCNP

H. Fujioka (Kyoto Univ.)
for the RCNP E451 collaboration

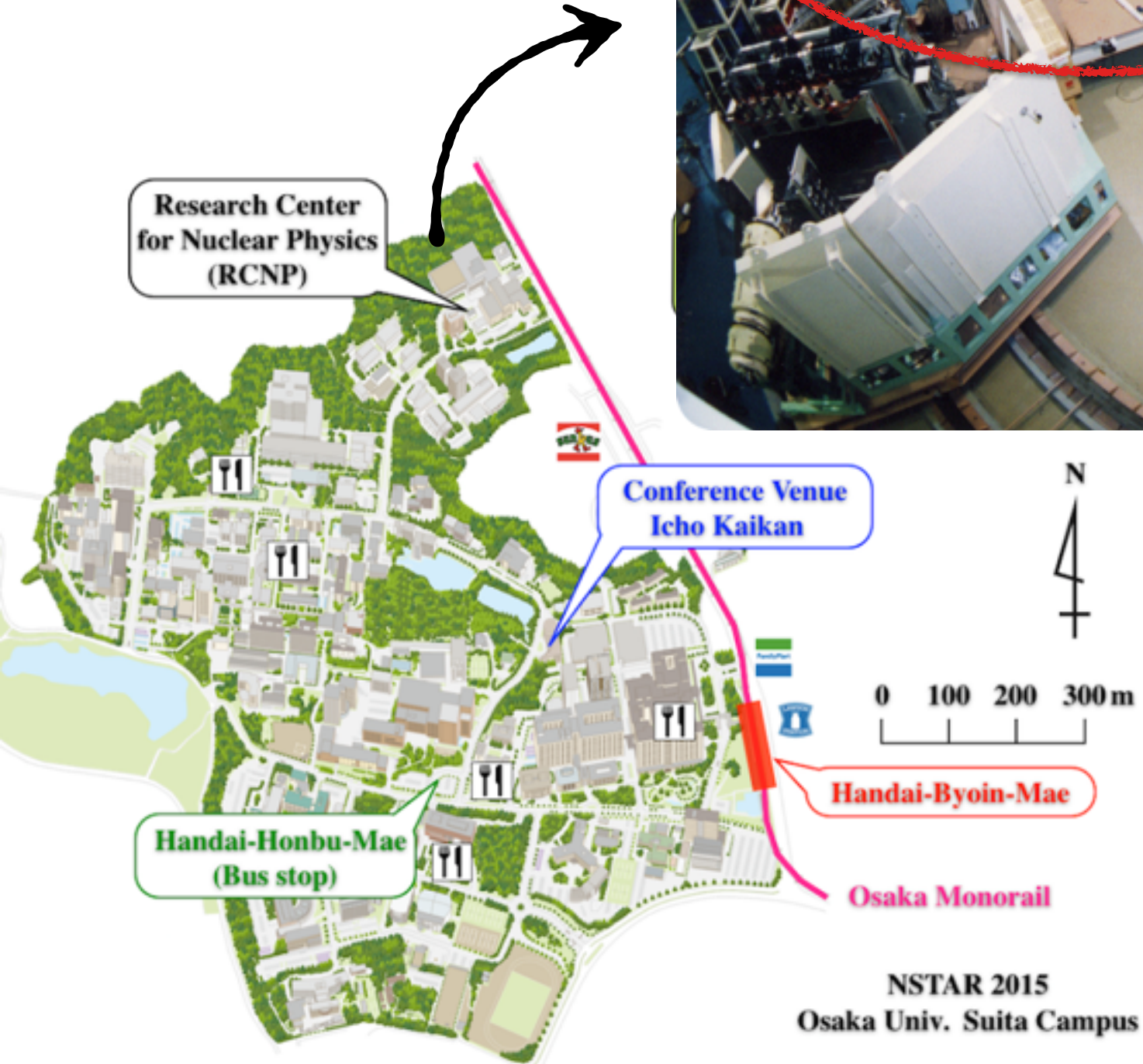
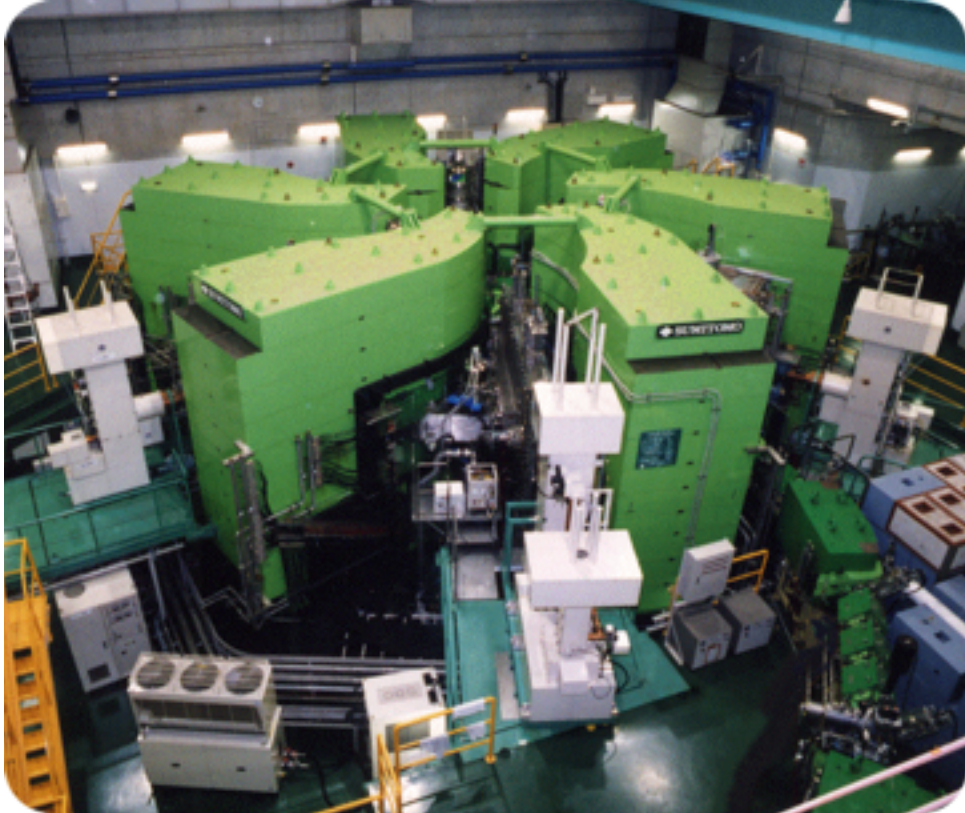
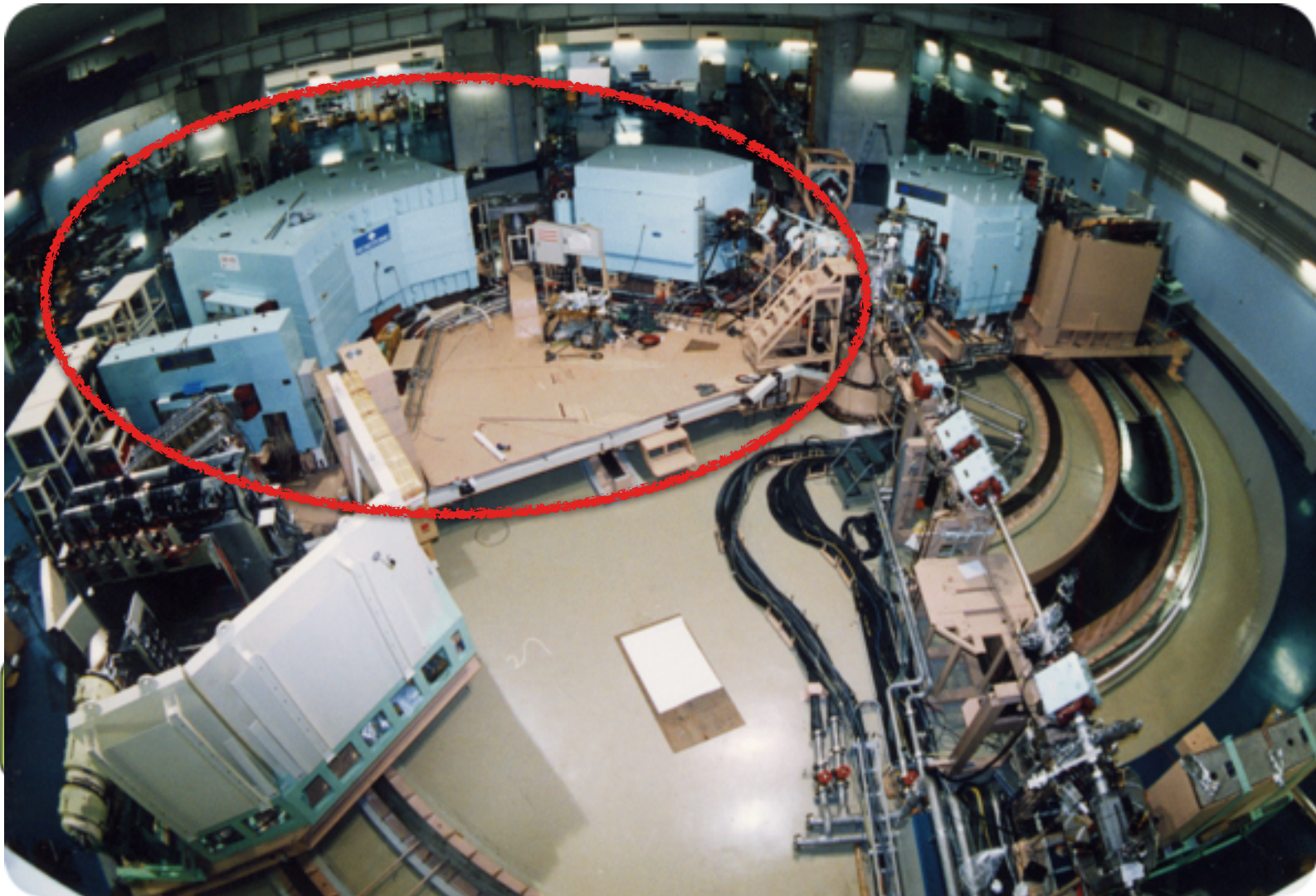
S. Adachi, N. Aoi, H. Fujioka*, T. Furuno, T. Hashimoto,
K. Hatanaka, R.S. Hayano, A. Inoue, K. Itahashi, C. Iwamoto,
T. Kawabata*, M. Murata, T. Nishi, S. Noji, A. Tamii, Y.K. Tanaka,
R. Tang, M. Tsumura, Y.N. Watanabe

* spokesperson

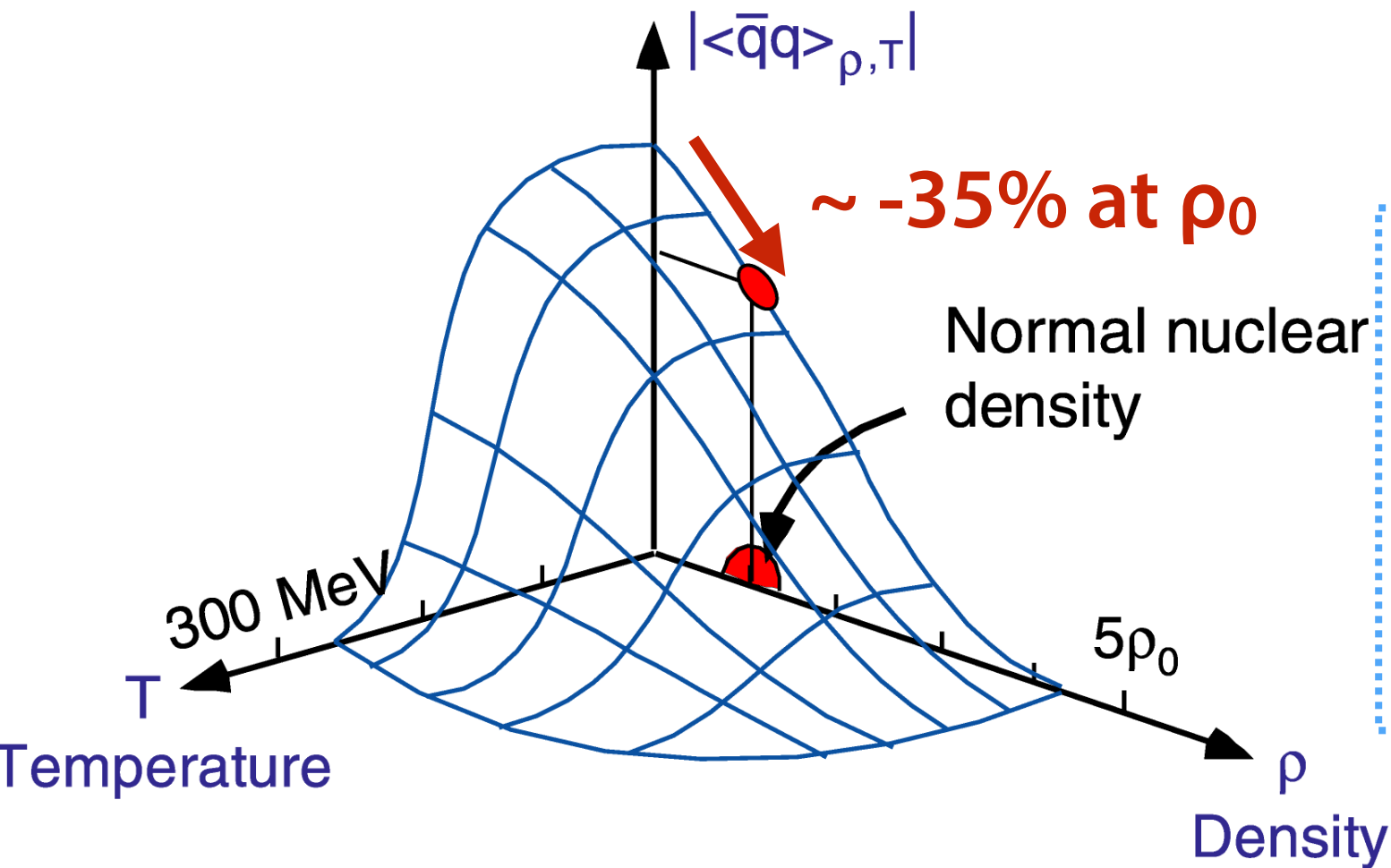
Kyoto U., Institute for Basic Science,
RCNP, RIKEN Nishina Center, U. Tokyo



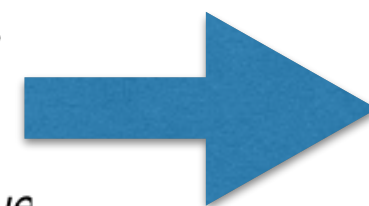
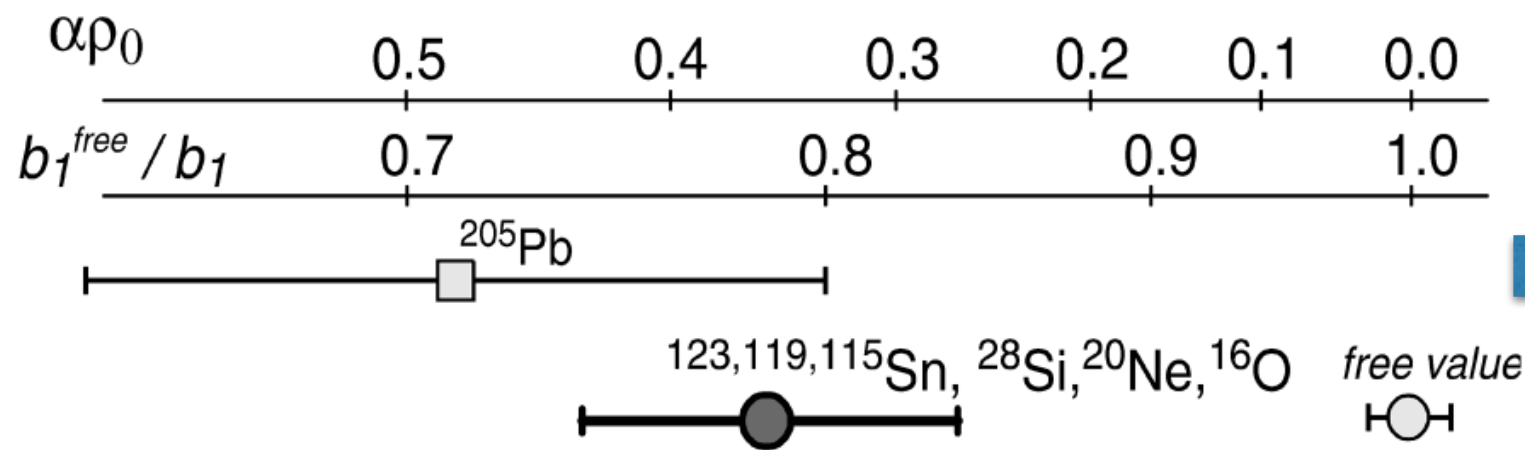
Hiroyuki Fujioka (Kyoto Univ.), NSTAR 2015 @ Osaka Univ.



Hiroyuki Fujioka (Kyoto Univ.), NSTAR 2015 @ Osaka Univ.



deeply-bound pionic atoms
 η mesic nuclei
 (= $N^*(1535)$ in nuclei)
 η' mesic nuclei
 ...



$$\frac{\langle \bar{q}q \rangle_{\rho=\rho_0}}{\langle \bar{q}q \rangle_0} \approx 0.64$$

b_1^{free} : isovector πN scattering length ↷

K. Suzuki et al., PRL 92 (2004) 072302

B and Γ of pionic 1s state

Ericson-Ericson type

$$V_s(r) = -\frac{2\pi}{\mu} [\epsilon_1 \{ b_0 \rho(r) + b_1 \delta\rho(r) \} + \epsilon_2 B_0 \rho(r)^2]$$

$$\delta\rho(r) = \rho_p(r) - \rho_p(n)$$

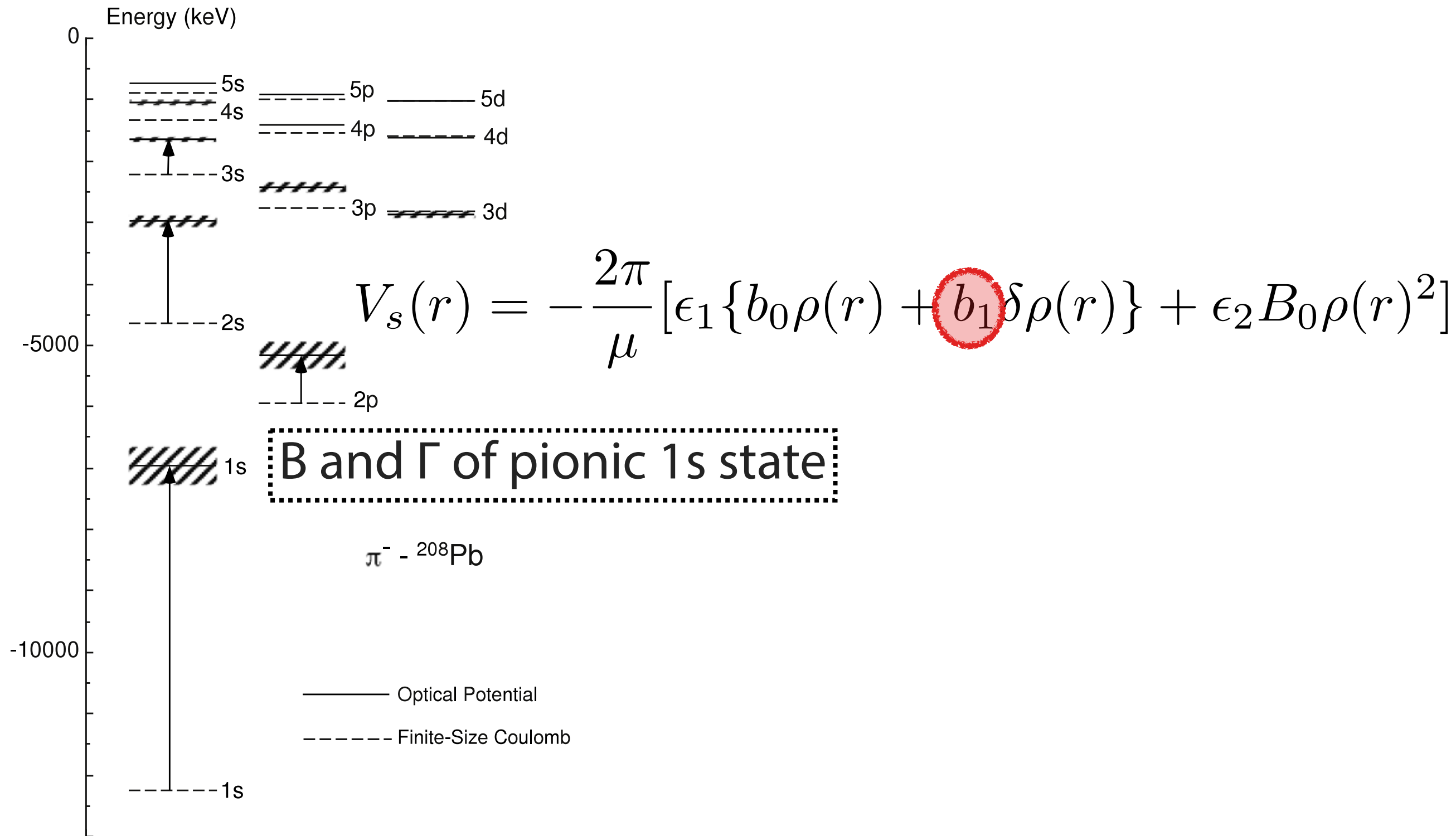
Gell-Mann-Oakes-Renner relation

Tomozawa-Weinberg relation

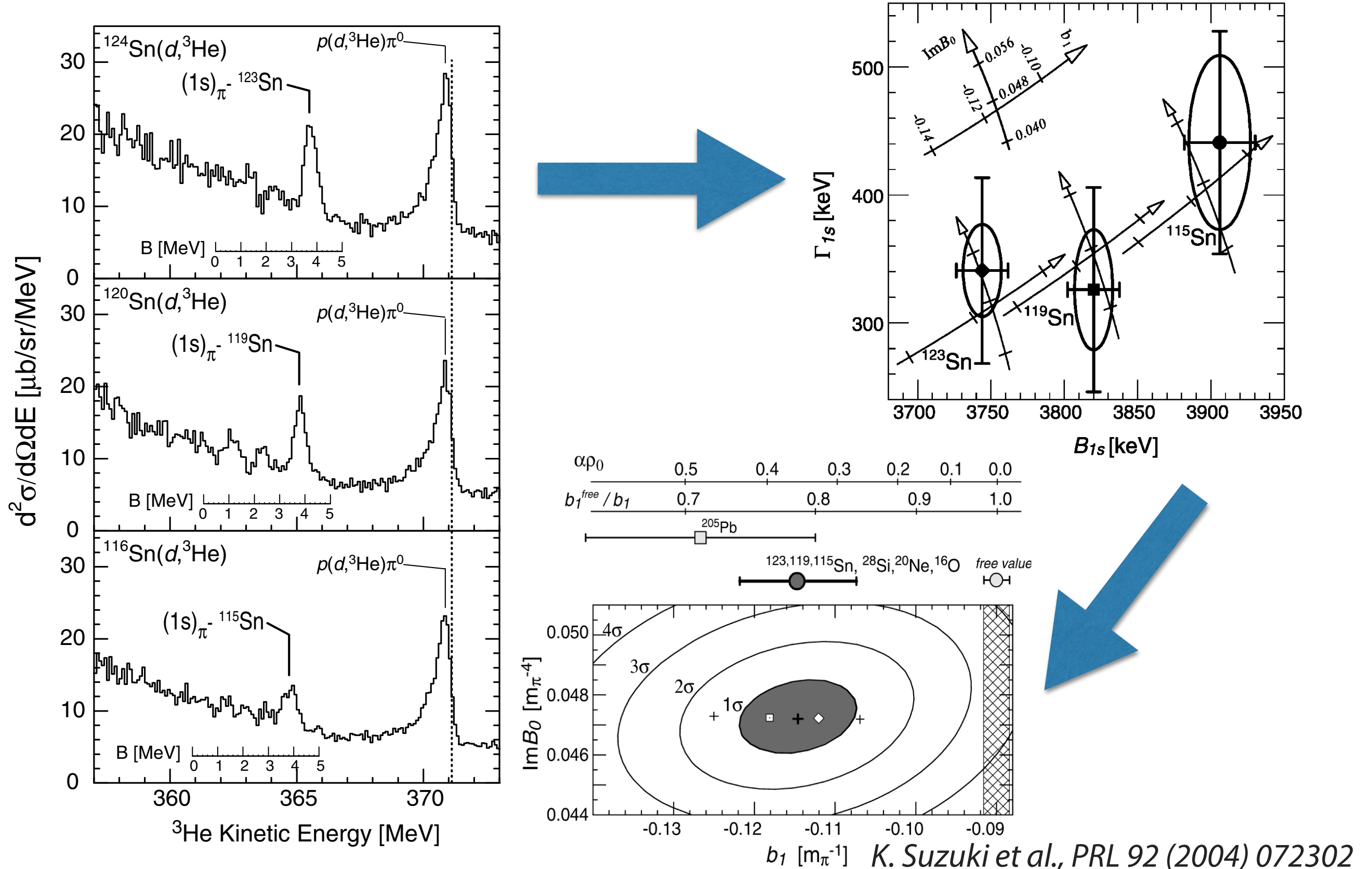
$$b_1 = -\frac{m_\pi}{8\pi f_\pi^2} \quad \text{---} \quad f_\pi^2 m_\pi^2 = -2m_q \langle \bar{q}q \rangle$$

$$\frac{\langle \bar{q}q \rangle_\rho}{\langle \bar{q}q \rangle_0} \approx \frac{b_1^{\text{free}}}{b_1(\rho)}$$

Review: T. Yamazaki et al., Phys. Rep. 514 (2012) 1



pionic 1s state in Sn isotopes

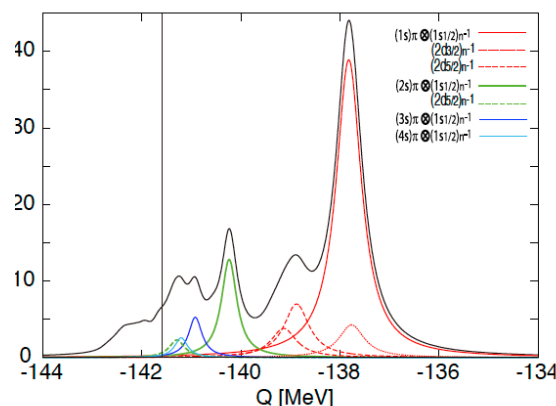


HHIQCD2015

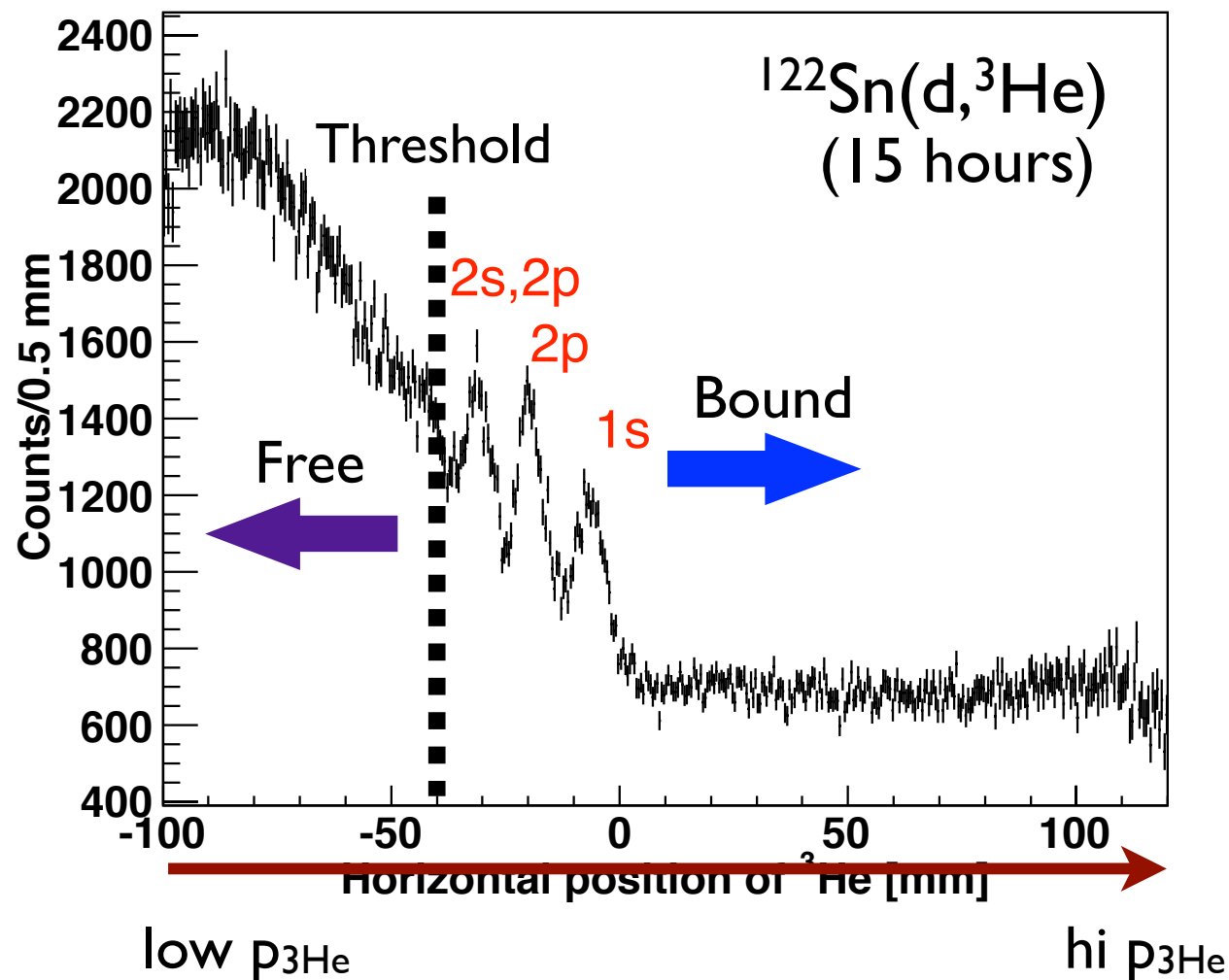
Focal Plane ³He Spectrum in 2010 (acceptance roughly corrected)

15 hours

data accumulatio
with 10¹²/s beam
for pilot exp.



N. Ikeno, Eur.Phys.J.A47 (2011) 161



2010: ¹²²Sn

2014: ¹²²Sn
¹¹⁷Sn, ¹¹⁶Cd



Kenta Itahashi, RIKEN

RIBF-54

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K. Itahashi, "Hadrons and Hadron Interactions in QCD 2015" at YITP

Hiroyuki Fujioka (Kyoto Univ.), NSTAR 2015 @ Osaka Univ.

(p,²He) reaction at RCNP

(p,²He) reaction at RCNP

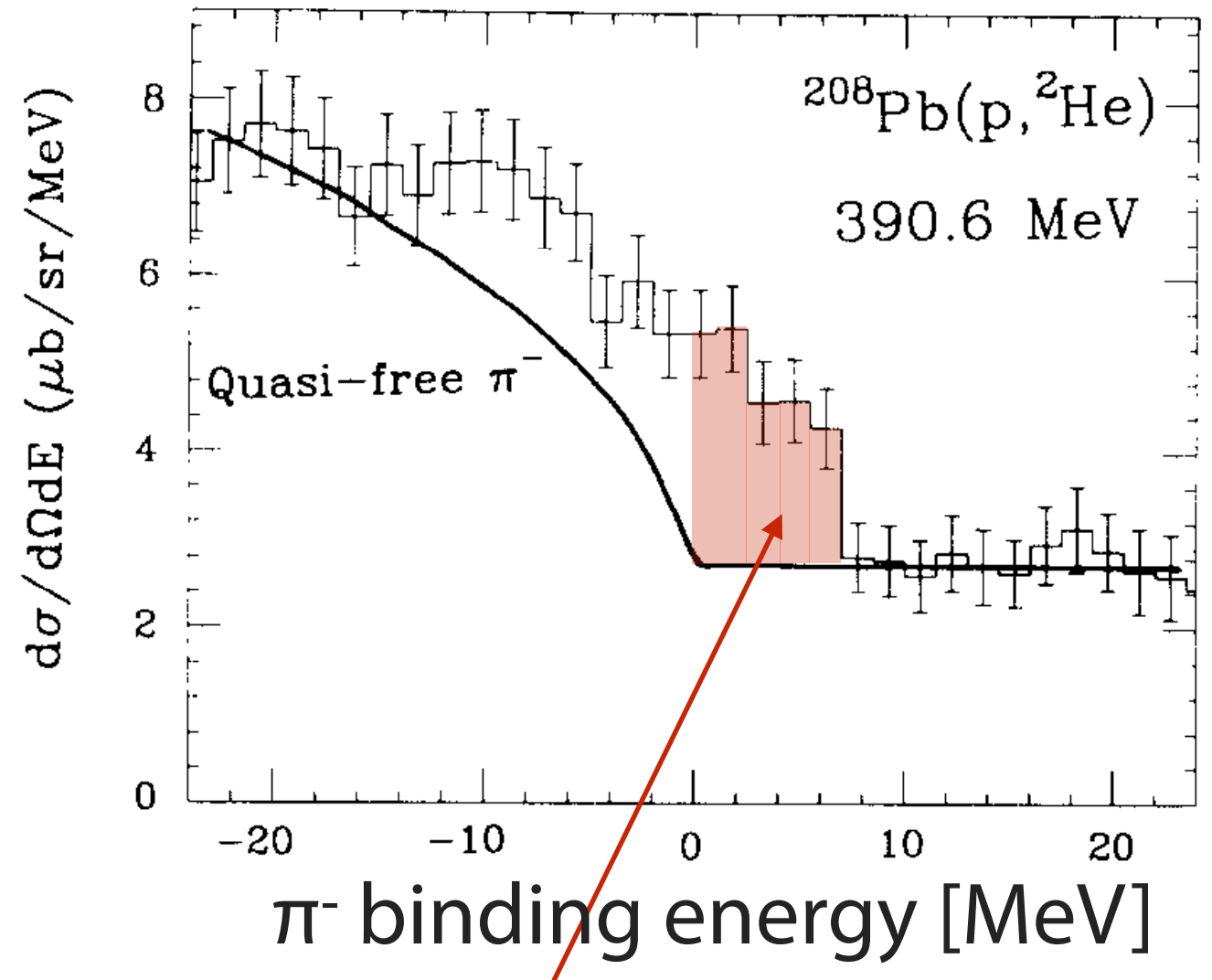
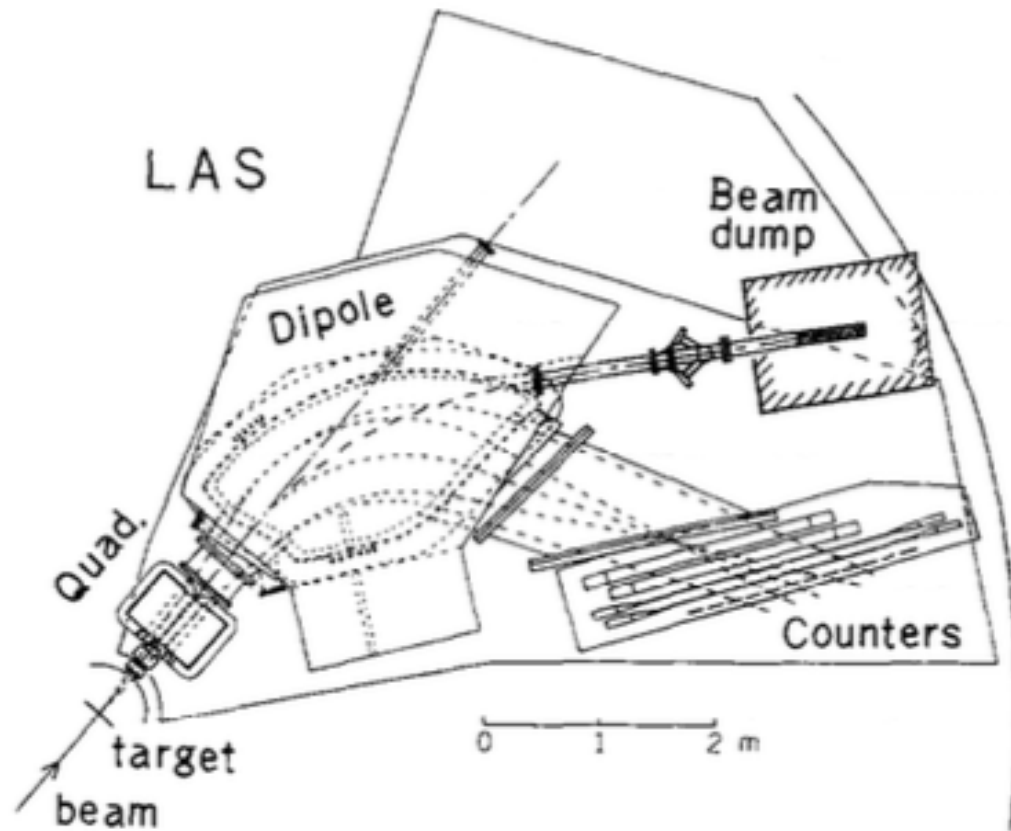
compared with (d,³He) reaction

advantage: high-resolution spectrometer “Grand Raiden”
+ dispersion matching (planned)

disadvantage: small detection efficiency for two particles

note: production cross section is *not* largely different

N. Matsuoka et al., PLB 359 (1995) 39



LAS at 0 degrees

beam intensity : 0.5-1 nA

target : 22.3mg/cm² ²⁰⁸Pb

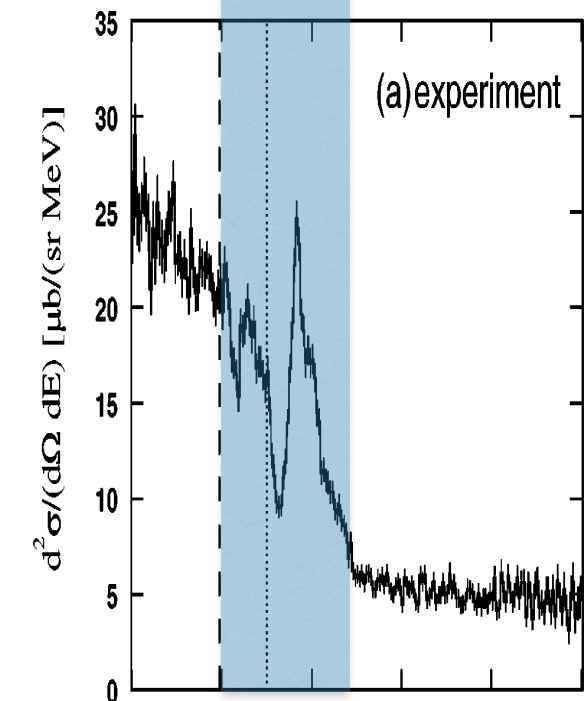
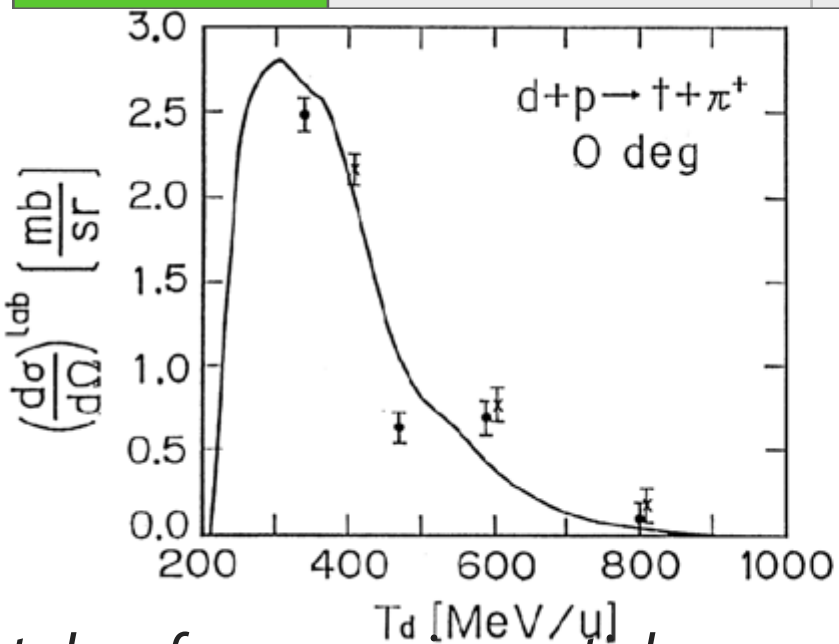
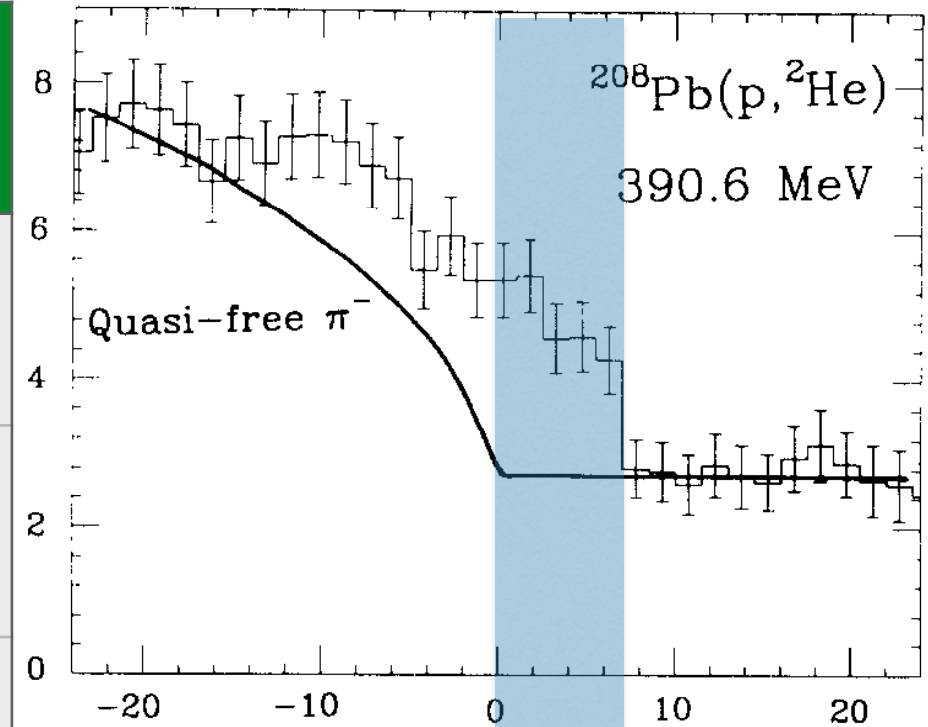
resolution : 700 keV (FWHM)

“the contribution from π⁻ bound states is observed”

$$d\sigma/d\Omega (0 < B < 7 \text{ MeV}) = 16 \pm 1.4 \text{ } \mu\text{b/sr}$$

N. Matsuoka et al., PLB 359 (1995) 39

	elementary cross section	integrated cross section	momentum transfer
(p, ² He) 390.6 MeV	137.8 ± 4.0 μb/sr	16 ± 1.4 μb/sr	49 MeV/c
	↓ ×20	↓ ×5	
(d, ³ He) 600 MeV	~2800 μb/sr	~76 μb/sr	56 MeV/c
(d, ³ He) 500 MeV	~2200 μb/sr	—	9 MeV/c

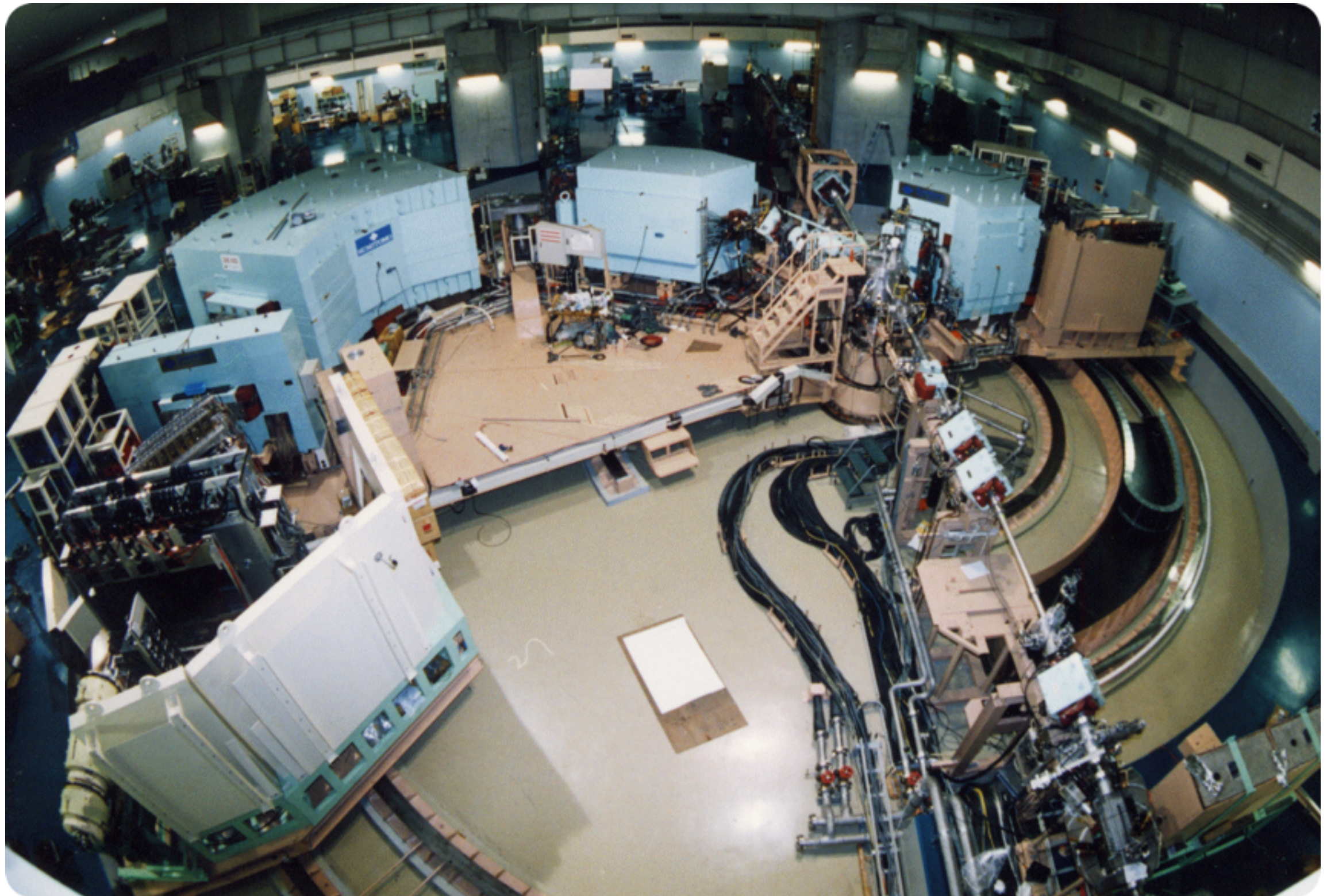


taken from a review article

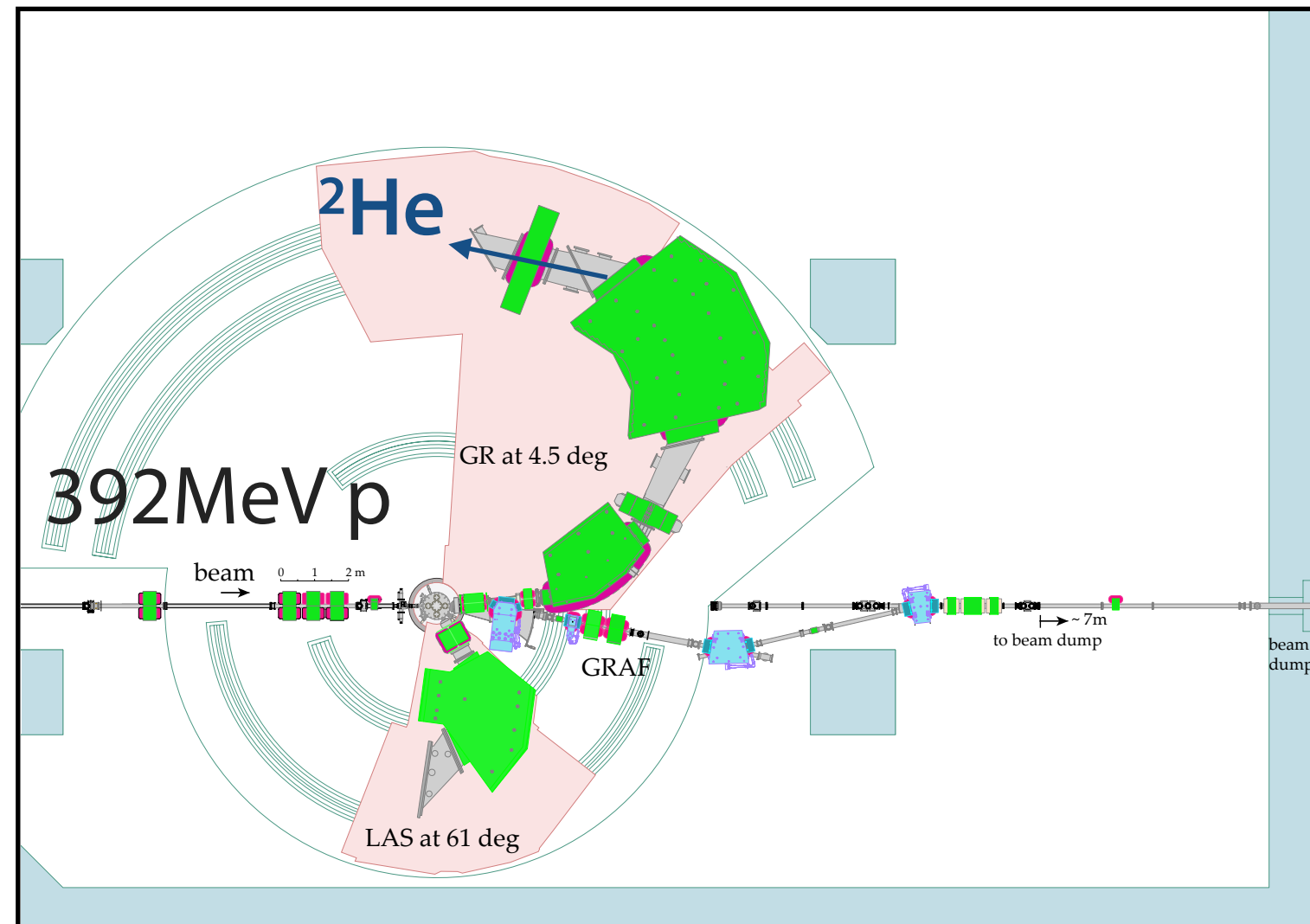
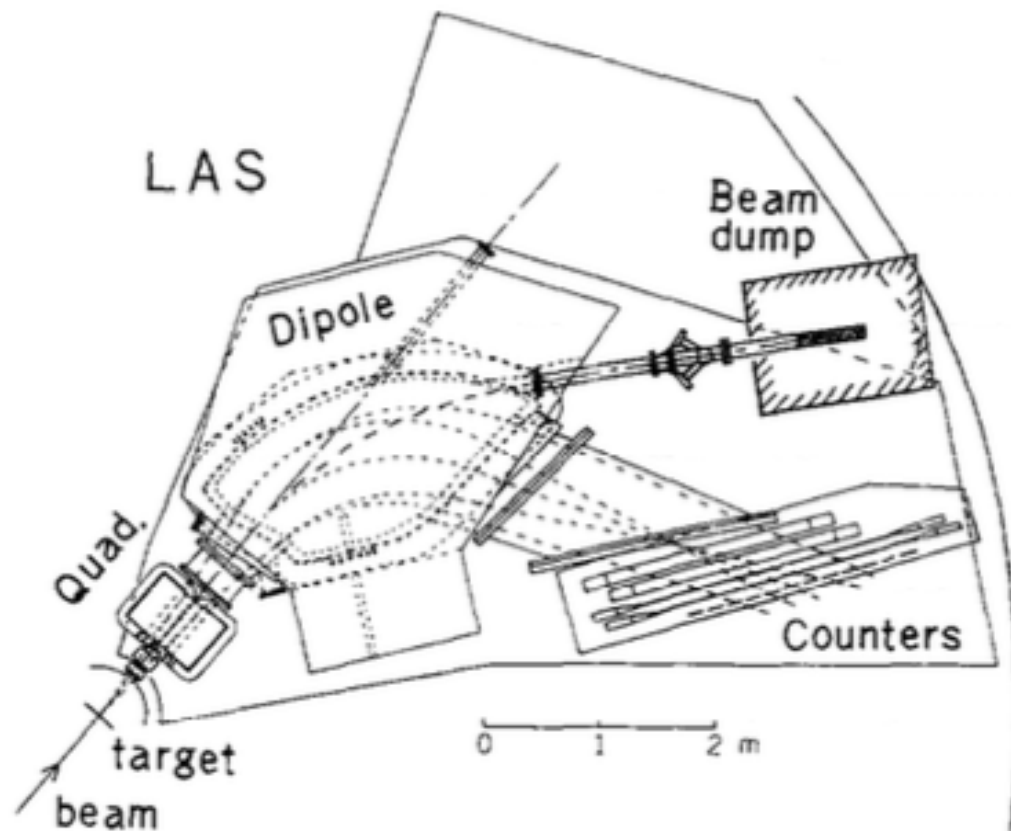
(T. Yamazaki et al., Phys. Rep. 514 (2012) 1)

H. Gilg et al., PRC 62 (2000) 025201

K. Itahashi et al., PRC 62 (2000) 025202

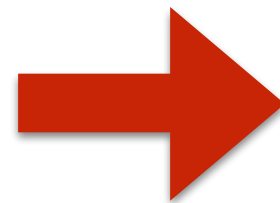


N. Matsuoka et al., PLB 359 (1995) 39



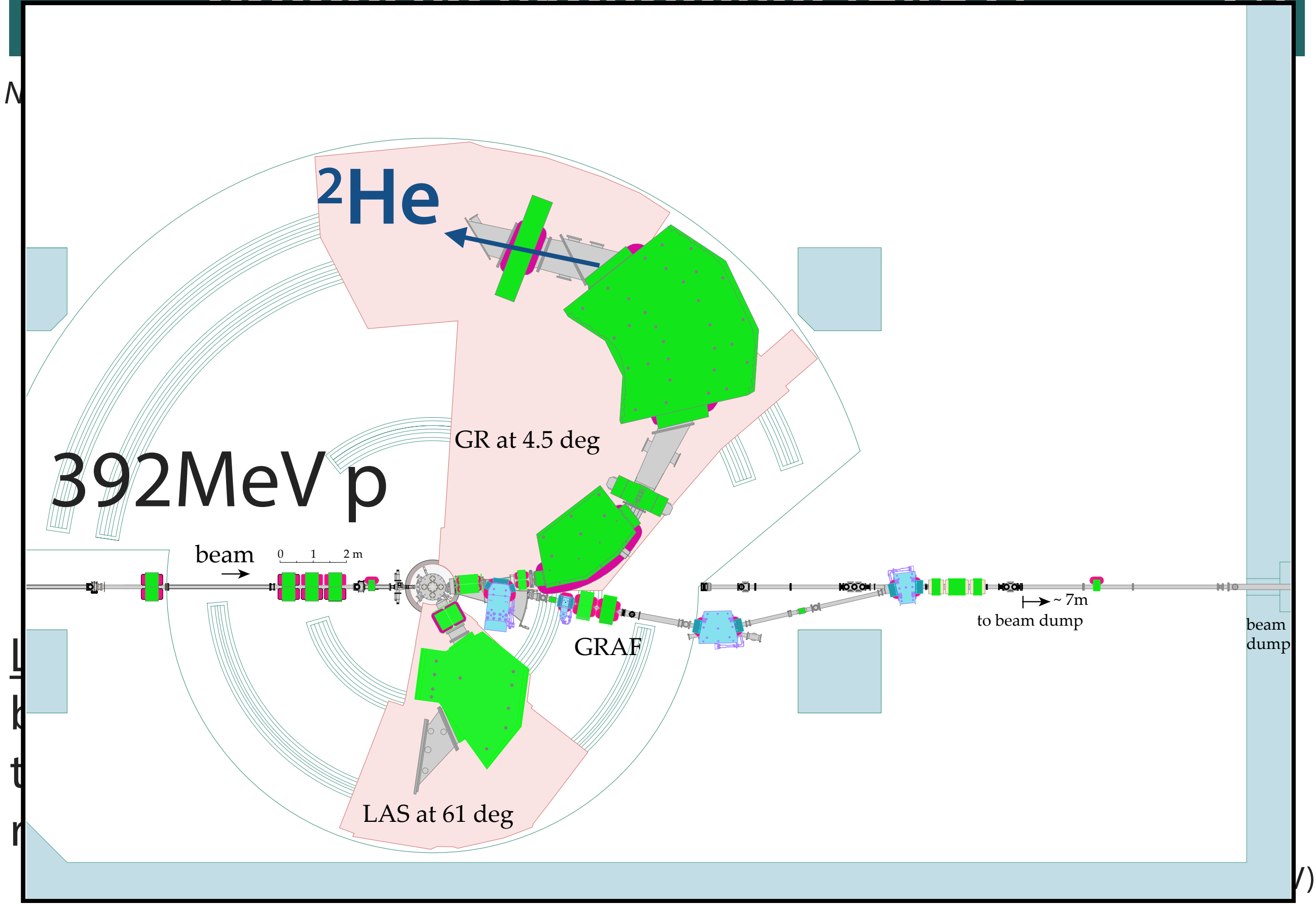
LAS at 0 degrees

beam intensity : 0.5-1 nA
target : 22.3 mg/cm^2 ^{208}Pb
resolution : 700 keV (FWHM)

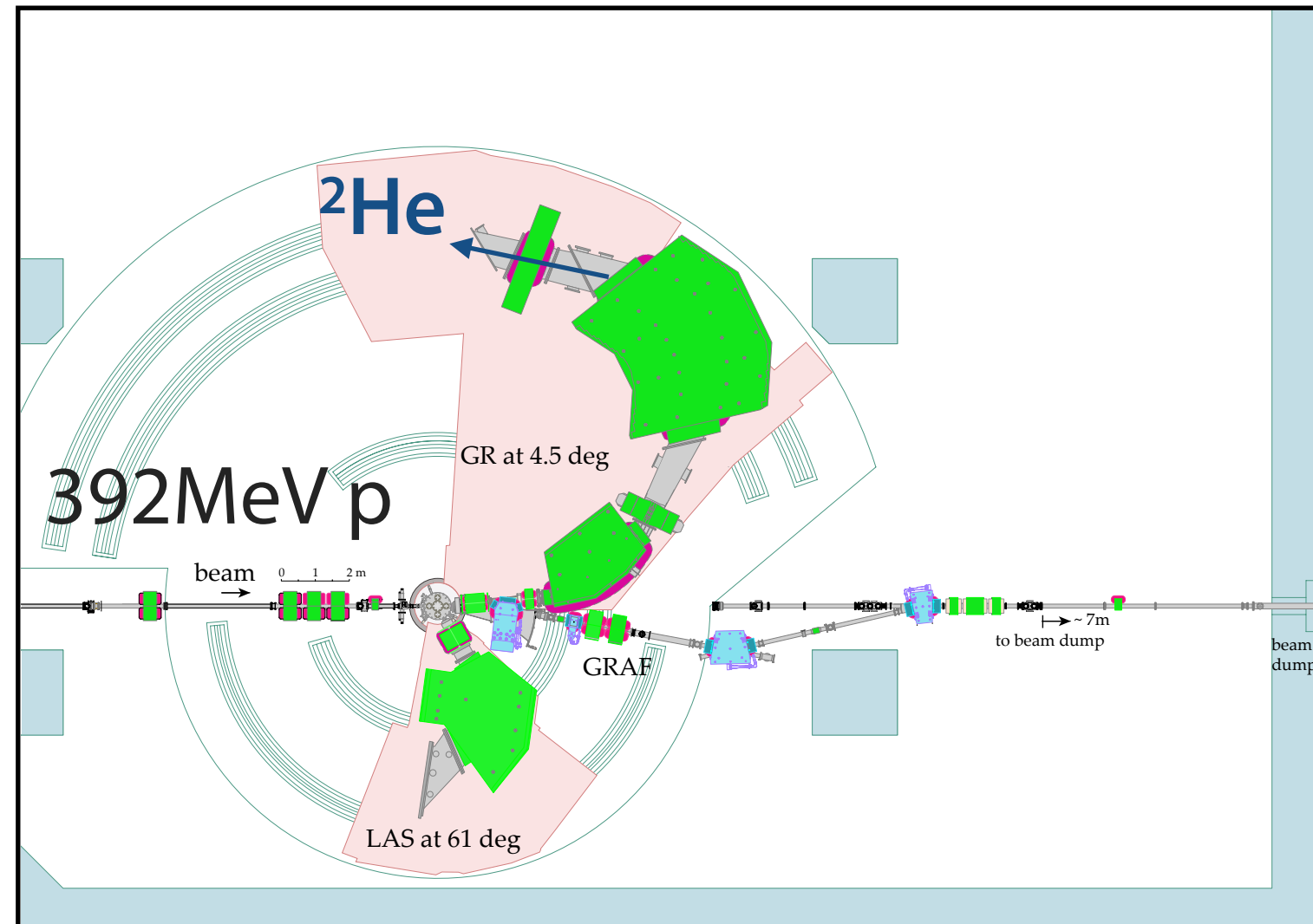
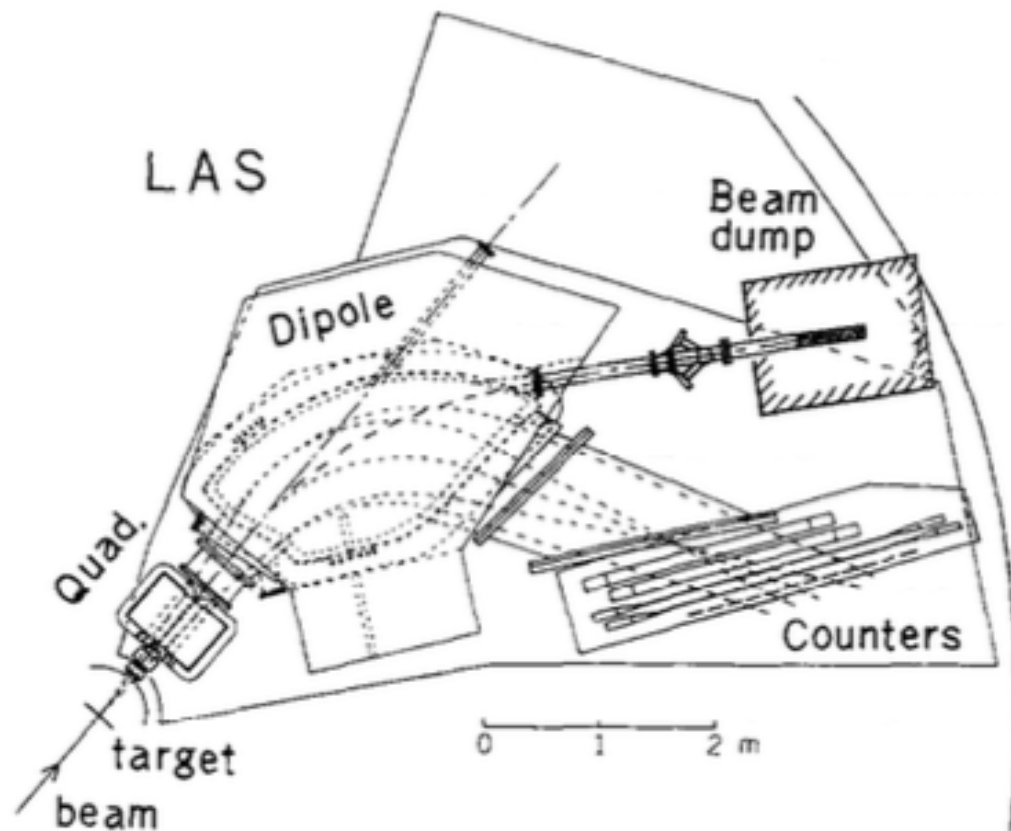


Grand Raiden at 4.5 degrees

beam intensity : ~ 100 nA
target : $\sim 20 \text{ mg/cm}^2$ ^{208}Pb
resolution : 200 keV (FWHM)
(beam width ~ 150 keV, $\Delta E_{\text{diff.}} \sim \Delta E_{\text{strag.}} \sim 100$ keV)

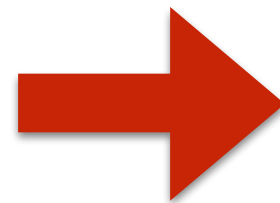


N. Matsuoka et al., PLB 359 (1995) 39



LAS at 0 degrees

beam intensity : 0.5-1 nA
target : 22.3 mg/cm^2 ^{208}Pb
resolution : 700 keV (FWHM)

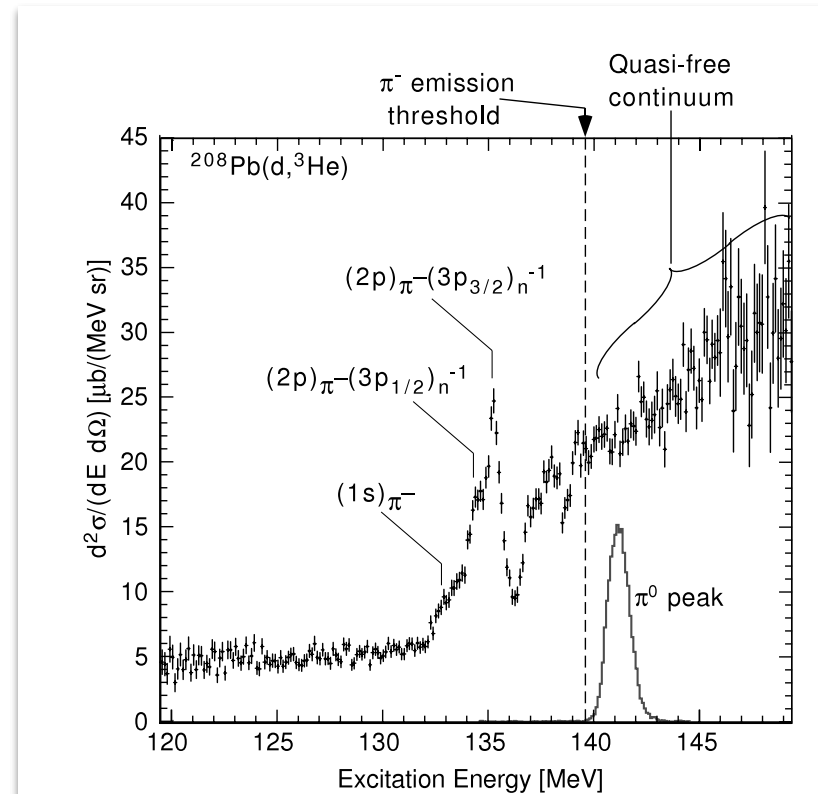
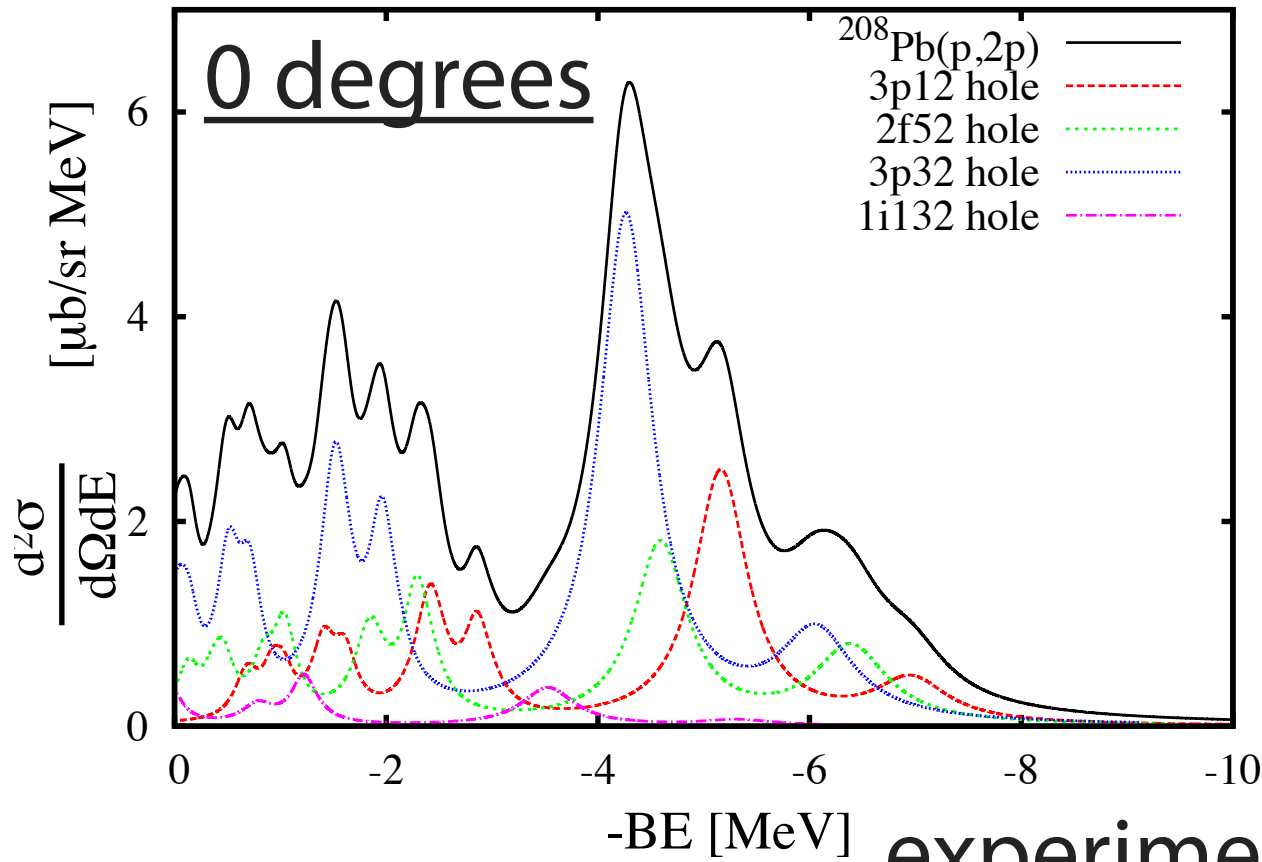


Grand Raiden at 4.5 degrees

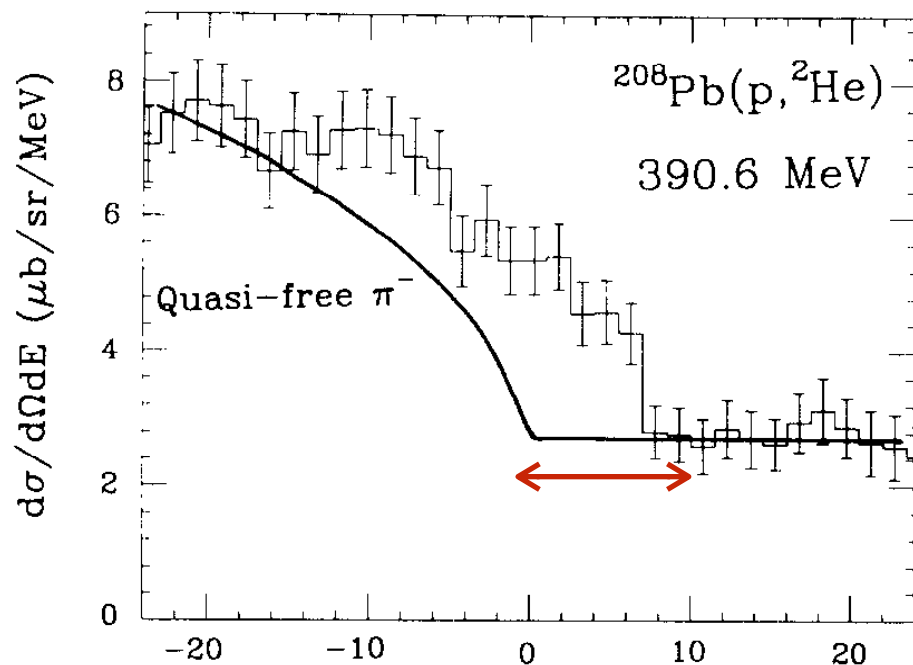
beam intensity : ~ 100 nA
target : $\sim 20 \text{ mg/cm}^2$ ^{208}Pb
resolution : 200 keV (FWHM)
(beam width ~ 150 keV, $\Delta E_{\text{diff.}} \sim \Delta E_{\text{strag.}} \sim 100$ keV)

J. Yamagata-Sekihara, N. Ikeno, S. Hirenzaki

cf. (d,³He)



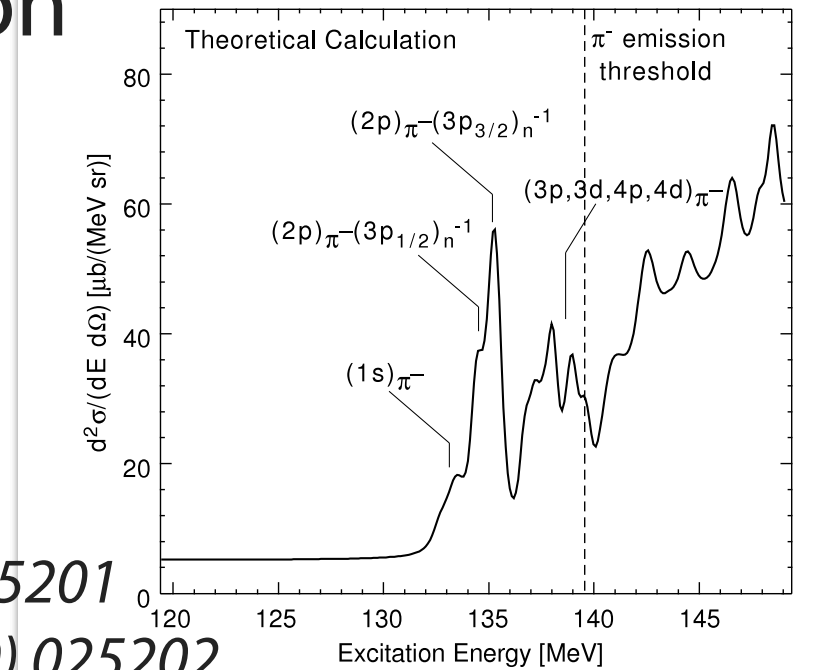
experimental resolution
= 200keV FWHM



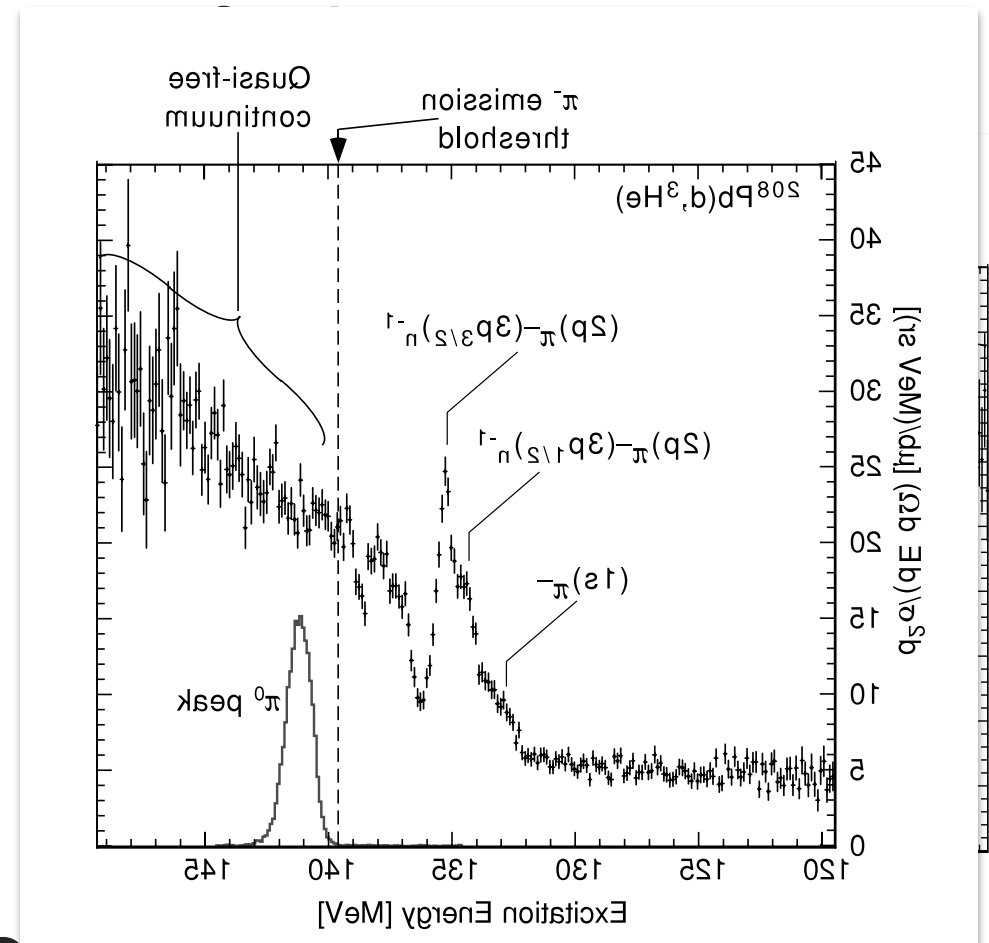
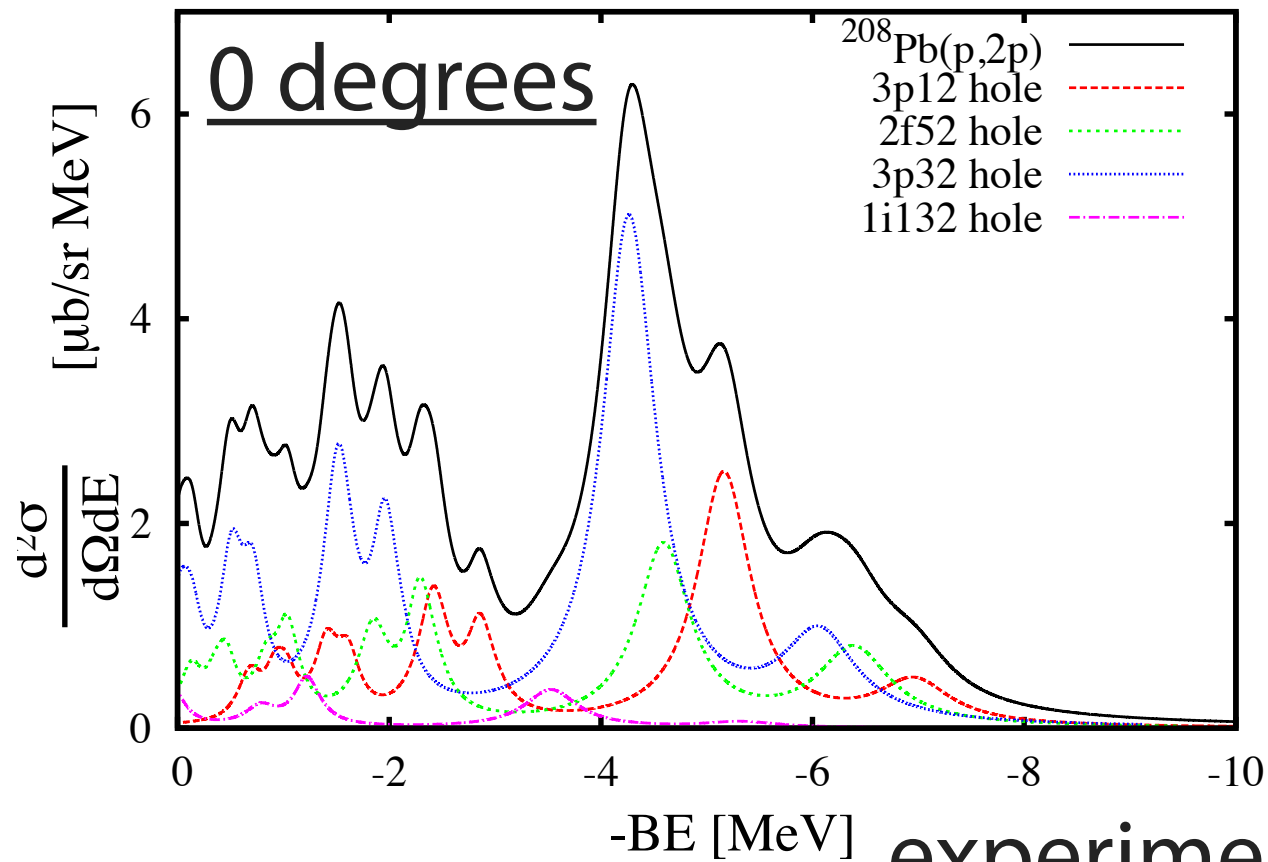
(700keV FWHM)

H. Gilg et al., PRC 62 (2000) 025201

K. Itahashi et al., PRC 62 (2000) 025202



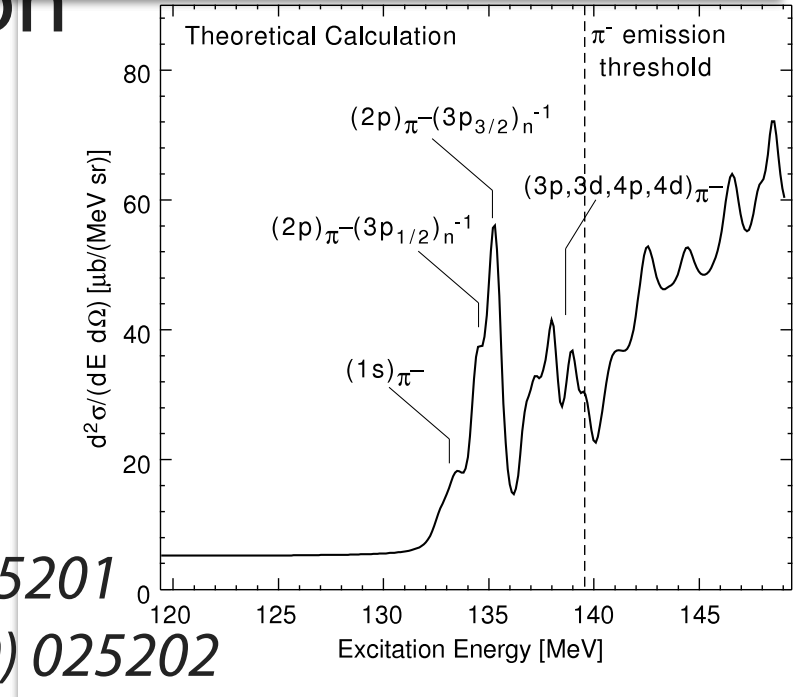
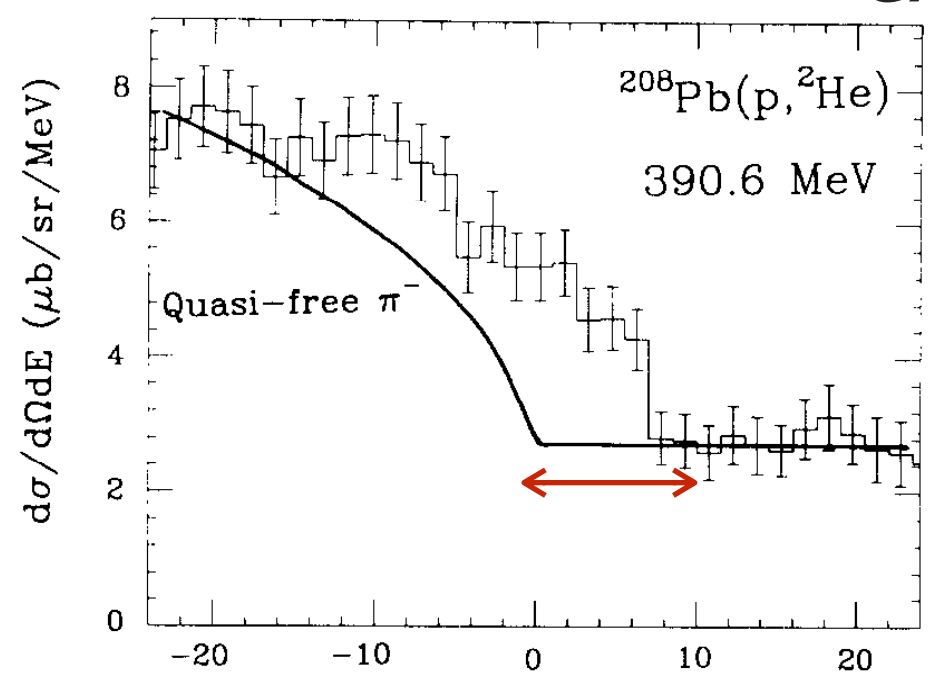
J. Yamagata-Sekihara, N. Ikeno, S. Hirenzaki



experimental resolution

= 200keV FWHM

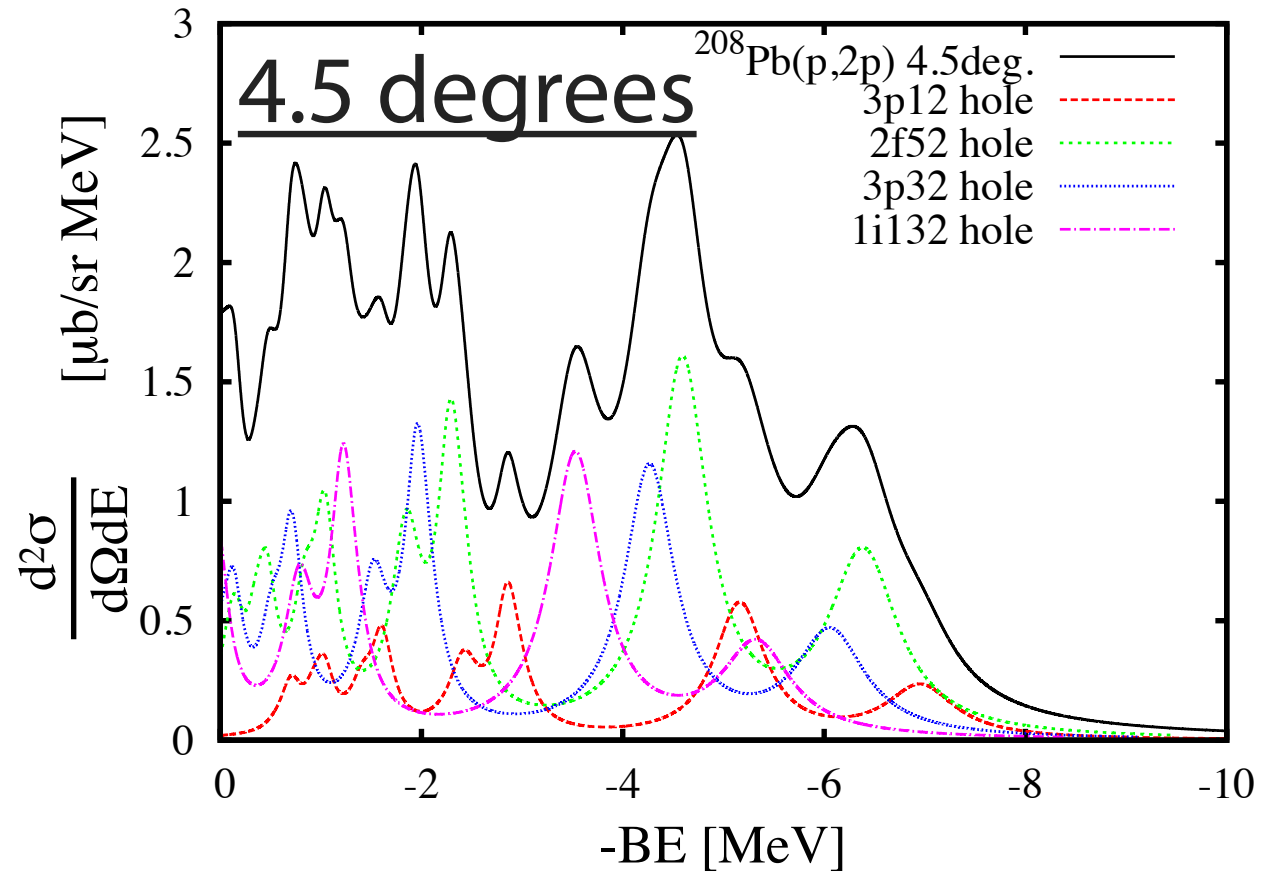
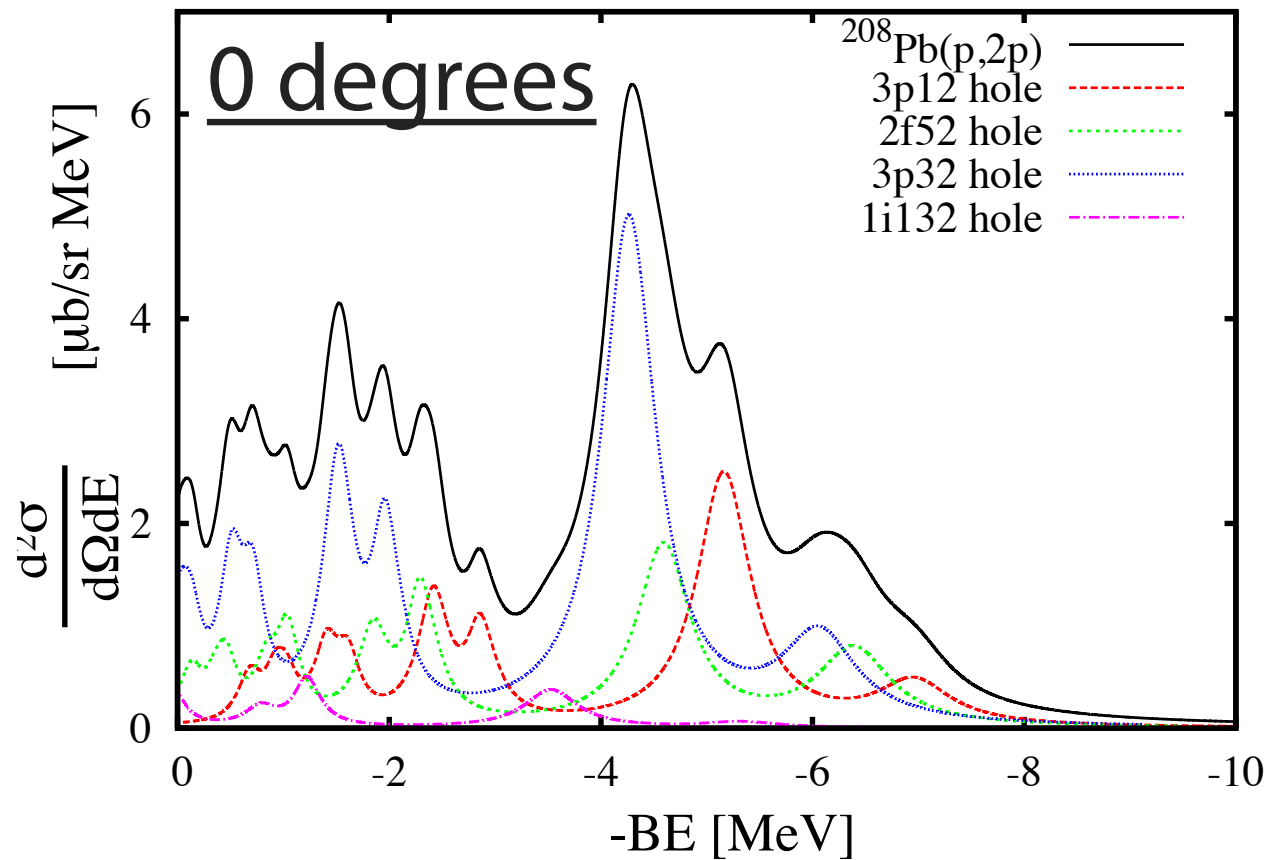
(700keV FWHM)



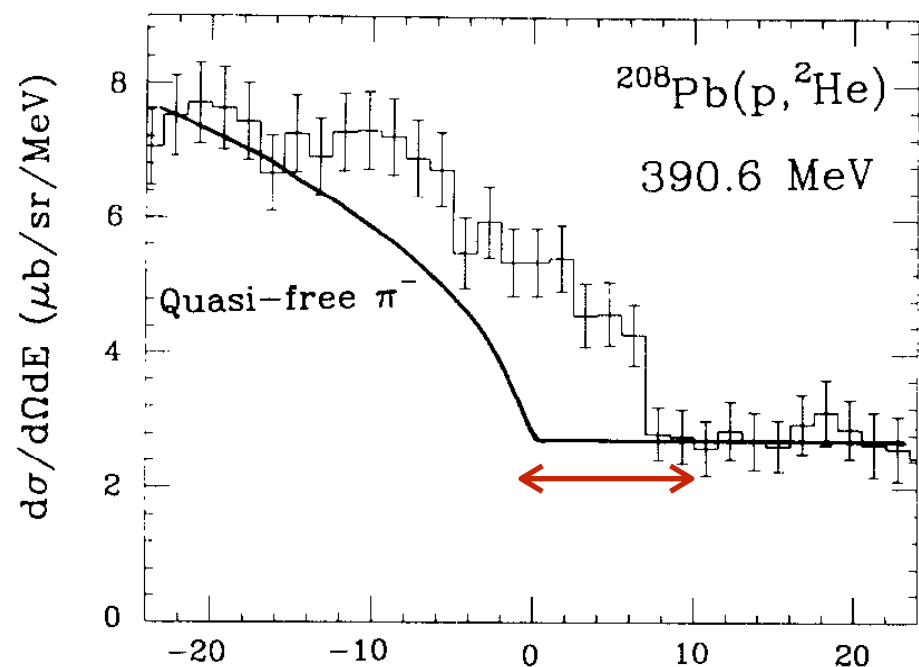
H. Gilg et al., PRC 62 (2000) 025201

K. Itahashi et al., PRC 62 (2000) 025202

J. Yamagata-Sekihara, N. Ikeno, S. Hirenzaki



experimental resolution = 200keV FWHM



assumption:

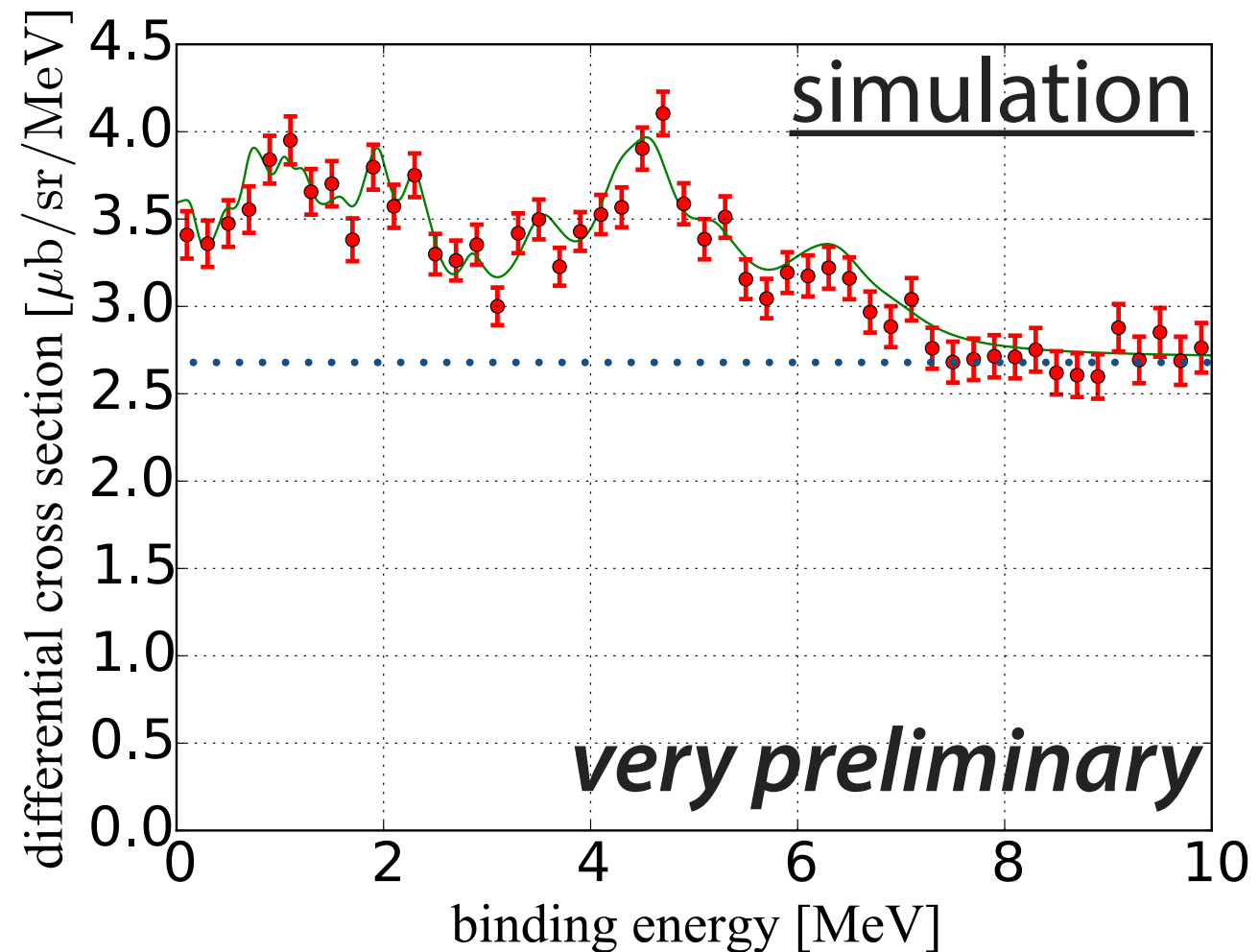
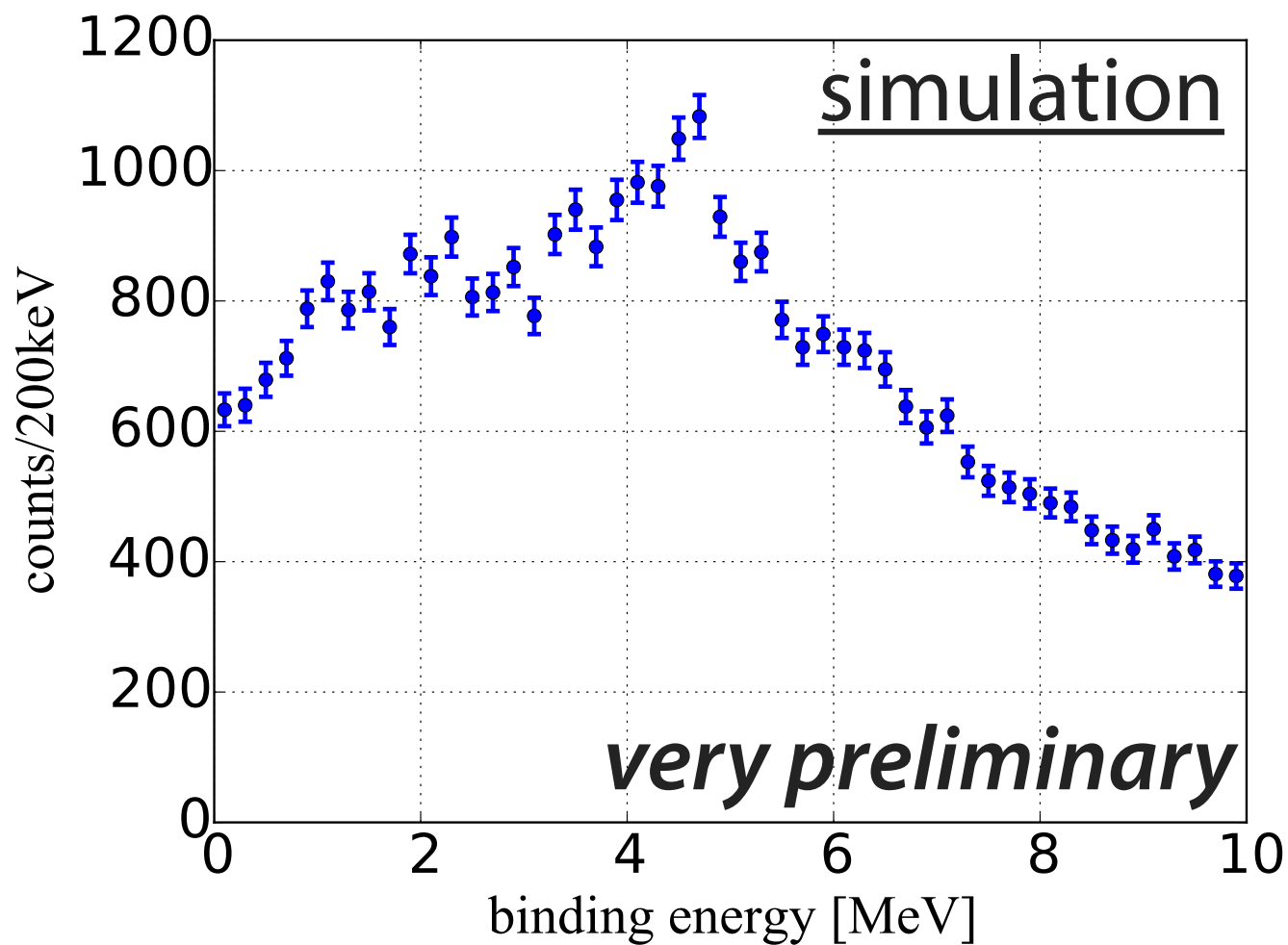
$$d\sigma/d\Omega^{\text{lab}}(pn \rightarrow ^2\text{He}\pi^-) = 137.8 \mu\text{b/sr}$$

for $\theta = 0^\circ$ and 4.5°

100nA proton beam on 20mg/cm² Pb target for 5 days

same background level as E29 (at 0 degrees)

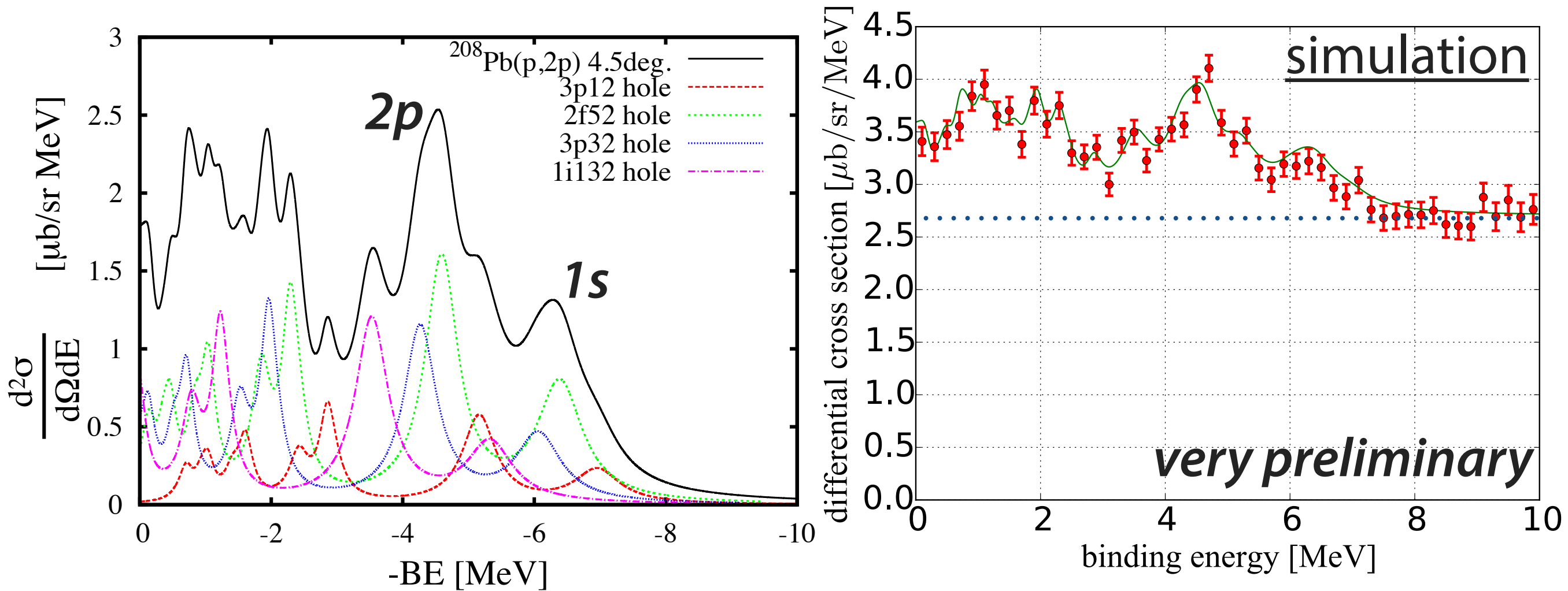
acceptance maximum at B=4MeV



100nA proton beam on 20mg/cm² Pb target for 5 days

same background level as E29 (at 0 degrees)

acceptance maximum at B=4MeV



- ❖ determination of absolute beam energy
- ❖ (p,²He) measurement with Grand Raiden
 - ▶ $^{209}\text{Bi}(p,^2\text{He})^{208}\text{Pb}_{\text{g.s.}}$
 - ▶ $p(p,^2\text{He})\pi^0$
 - ▶ $^{208}\text{Pb}(p,^2\text{He})^{207}\text{Pb}\times\pi^-$
 - ▶ accidental coincidence of two protons

4-day beamtime approved in B-PAC77 (RCNP E451)

- ❖ pionic atom production by (p,²He) reaction
 - ▶ ²⁰⁸Pb target at first → different targets such as Sn
- ❖ aiming at 200 keV resolution (FWHM)
 - ▶ improved by dispersion matching? (future plan)
- ❖ small acceptance compensated by intense beam
 - ▶ beam dumped via newly-constructed GRAF beamline
- ❖ 2p states may be observed by 5-day data acquisition