A plan to search for a tetraneutron state in the ^{4}He(π^{-},π^{+}) reaction at J-PARC

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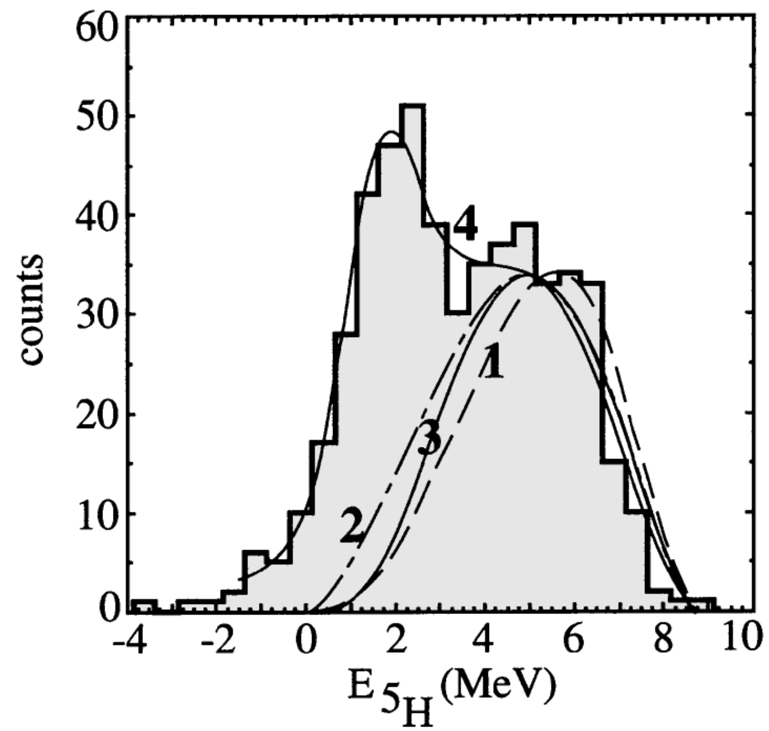
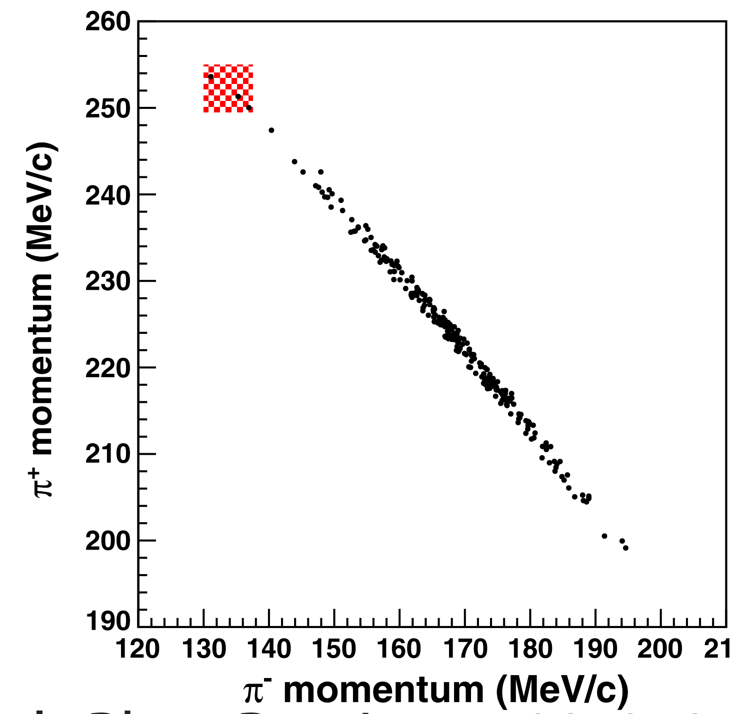
GRADUATE SCHOOL OF SCIENCE
FACULTY OF SCIENCE
KYOTO UNIVERSITY

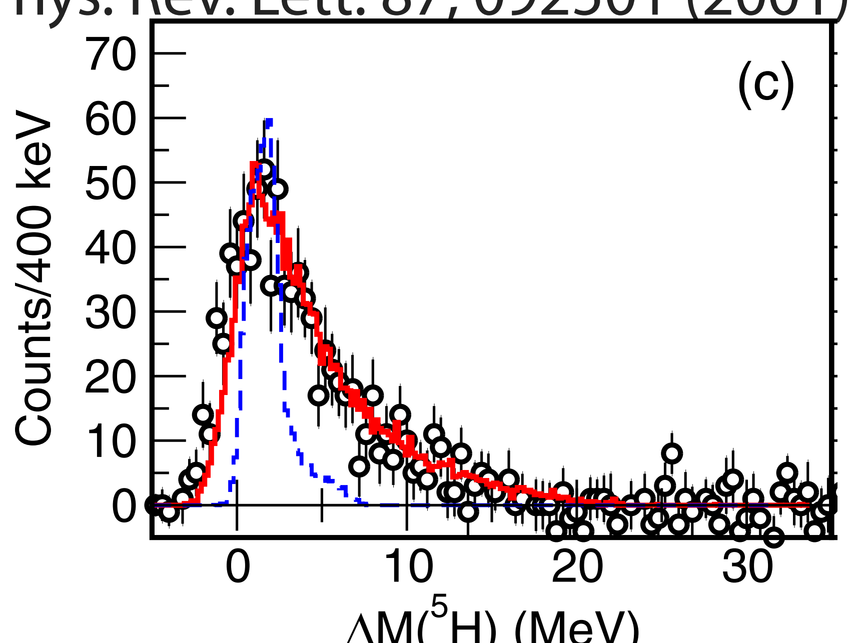
$^{4}n \xleftarrow{-p} {}^{5}H \underset{-\Lambda}{\overset{+\Lambda}{\rightleftarrows}} {}^{6}_{\Lambda}H$



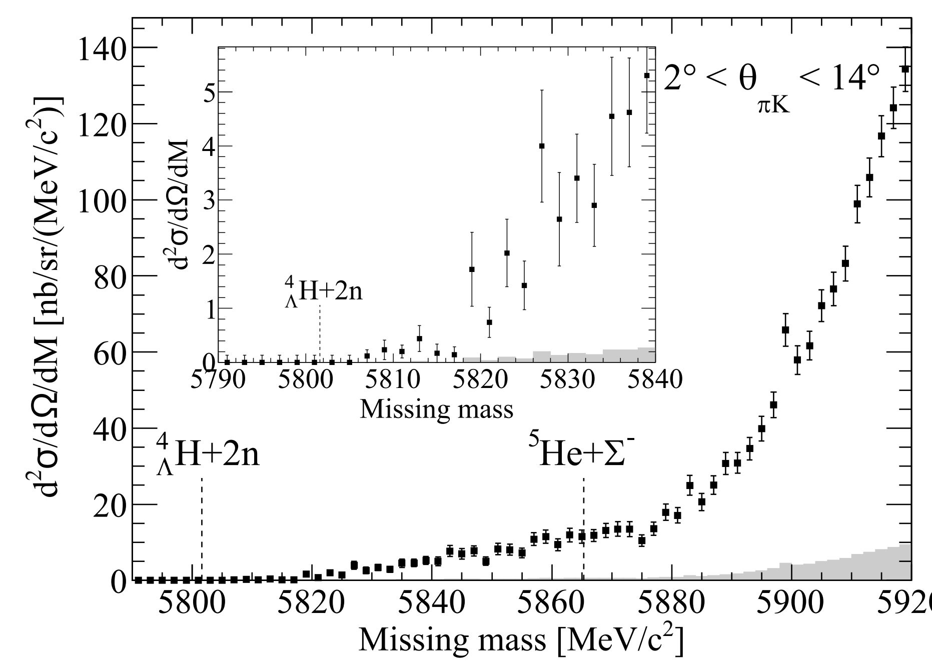
A. A. Korsheninnikov et al., Phys. Rev. Lett. 87, 092501 (2001)



M. Agnello et al., Phys. Rev. Lett. 108, 042501 (2012)



A. H. Wuosmaa et al., Phys. Rev. C 95, 014310 (2017)



R. Honda, et al., arXiv:1703.00623

today's talk based on …

Letter of Intent for J-PARC 50 GeV Synchrotron

Search for tetraneutron by pion double charge exchange reaction on ^{4}He

H. Fujioka,* S. Kanatsuki, T. Nagae, and T. Nanamura
Department of Physics, Kyoto University

T. Fukuda and T. Harada
Osaka Electro-Communication University

E. Hiyama, K. Itahashi,† and T. Nishi
RIKEN Nishina Center

(Dated: June 27, 2016)

Candidates of a tetraneutron resonance state, composed of four neutrons, have been observed in a heavy-ion double charge exchange reaction at RIBF. We would like to investigate this exotic state by a pion double charge exchange reaction at the High-Intensity High-Resolution beamline in an extended Hadron Experimental Facility, which is currently in a planning stage.

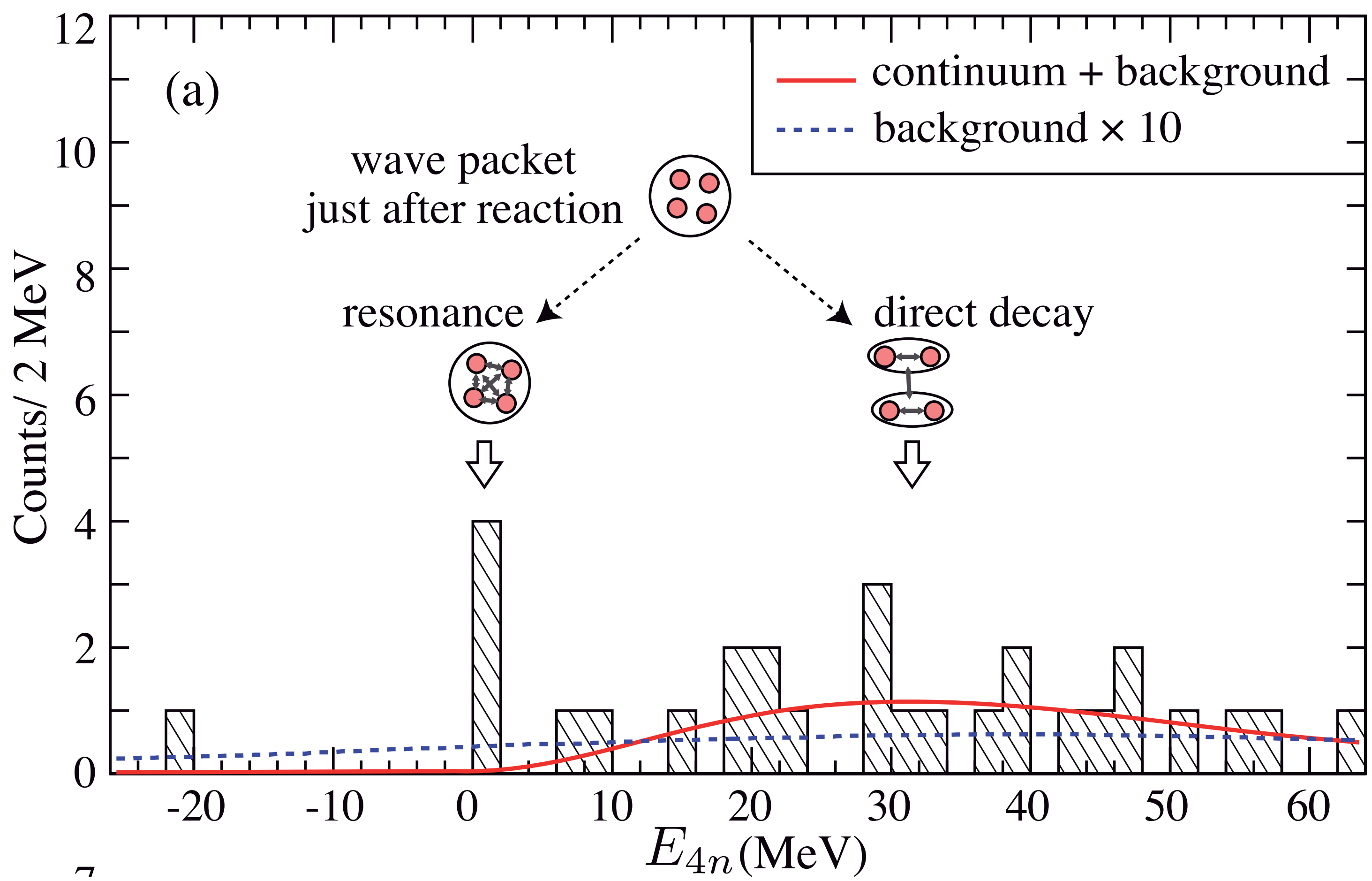
http://j-parc.jp/researcher/Hadron/en/pac_1607/pdf/LoI_2016-18.pdf

motivated by …

Selected for a Viewpoint in *Physics*
PRL **116,** 052501 (2016) PHYSICAL REVIEW LETTERS week ending 5 FEBRUARY 2016

Candidate Resonant Tetraneutron State Populated by the ^{4}He(^{8}He,^{8}Be) Reaction

K. Kisamori,[1,2] S. Shimoura,[1] H. Miya,[1,2] S. Michimasa,[1] S. Ota,[1] M. Assie,[3] H. Baba,[2] T. Baba,[4] D. Beaumel,[2,3] M. Dozono,[2] T. Fujii,[1,2] N. Fukuda,[2] S. Go,[1,2] F. Hammache,[3] E. Ideguchi,[5] N. Inabe,[2] M. Itoh,[6] D. Kameda,[2] S. Kawase,[1] T. Kawabata,[4] M. Kobayashi,[1] Y. Kondo,[7,2] T. Kubo,[2] Y. Kubota,[1,2] M. Kurata-Nishimura,[2] C. S. Lee,[1,2] Y. Maeda,[8] H. Matsubara,[12] K. Miki,[5] T. Nishi,[9,2] S. Noji,[10] S. Sakaguchi,[11,2] H. Sakai,[2] Y. Sasamoto,[1] M. Sasano,[2] H. Sato,[2] Y. Shimizu,[2] A. Stolz,[10] H. Suzuki,[2] M. Takaki,[1] H. Takeda,[2] S. Takeuchi,[2] A. Tamii,[5] L. Tang,[1] H. Tokieda,[1] M. Tsumura,[4] T. Uesaka,[2] K. Yako,[1] Y. Yanagisawa,[2] R. Yokoyama,[1] and K. Yoshida[2]



Today's talk

We propose to investigate

pion DCX (≡ **D**ouble **C**harge e**X**change) reaction

$$\pi^- + {}^4\mathrm{He} \to \pi^+ + {}^4\mathrm{n}$$

T=850 MeV
(~ 980 MeV/c)

at J-PARC.

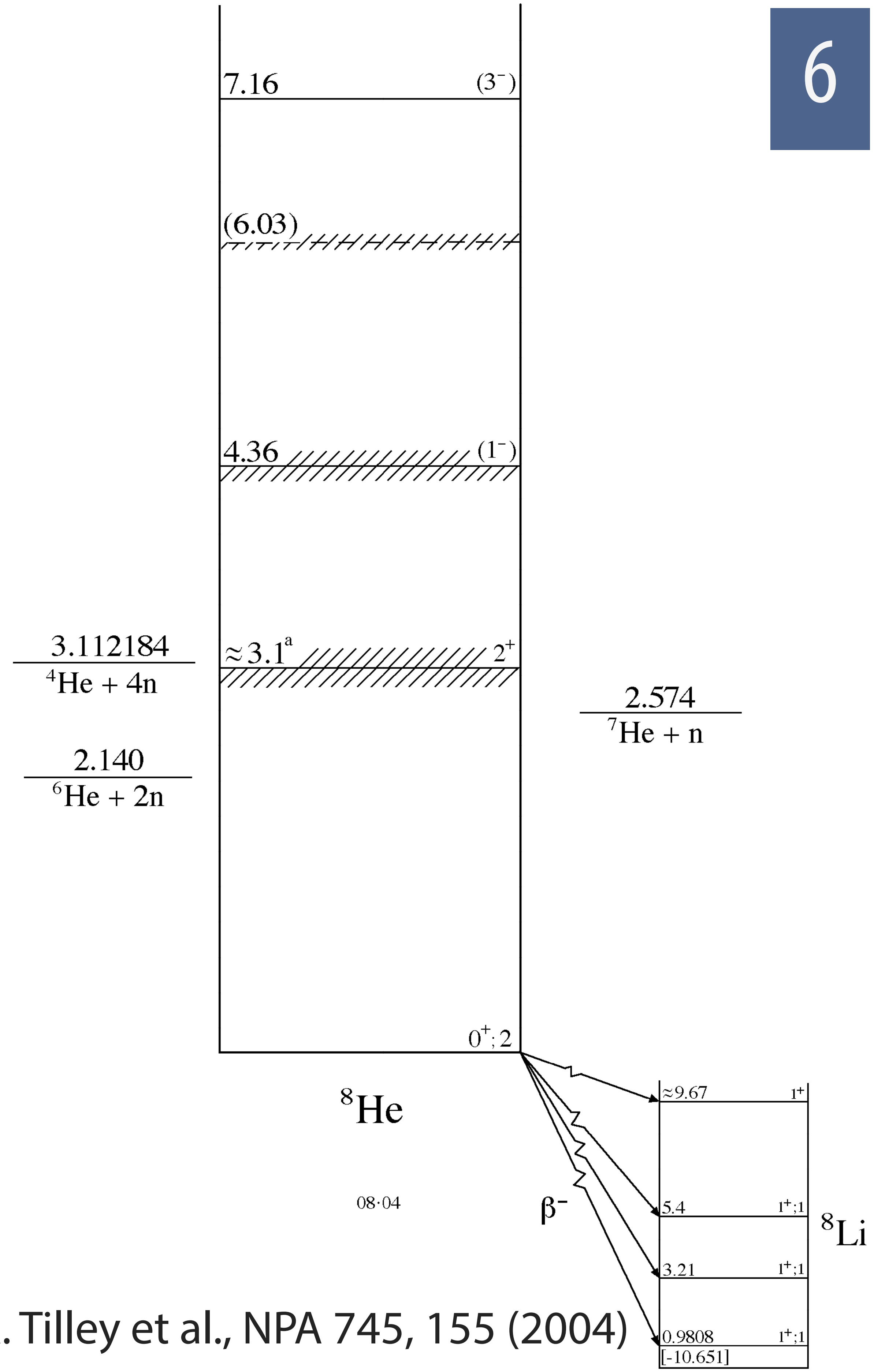
1. **Brief history of pion DCX reaction (until 1980's)**
2. **Proposed experiments at J-PARC**
   (a) analog transition: ^{18}O → ^{18}Ne
   (b) non-analog transition: ^{4}He → ^{4}n

constraint on tetraneutron

- $^8He \rightarrow {}^4He + {}^4n$ forbidden
  $\Rightarrow$ B.E.(^{4}n)<3.1MeV

- $^6He + 2n$ dominance in ^8He break-up
  $\Rightarrow$ B.E.(^{4}n)<1MeV

- unbound ^5H ($\rightarrow {}^3H + 2n$)
  $\Rightarrow$ bound ^{4}n unlikely

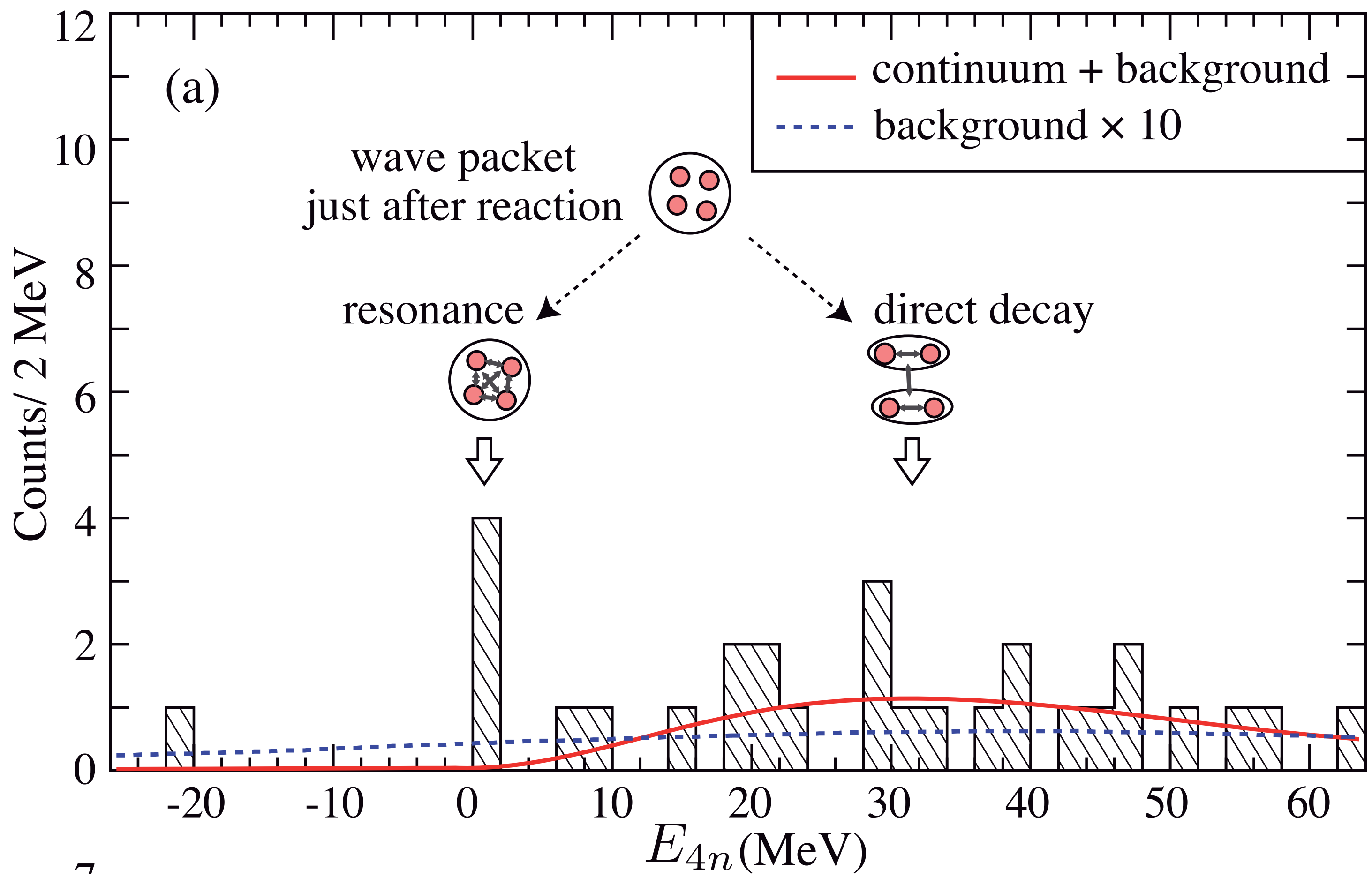


D.R. Tilley et al., NPA 745, 155 (2004)

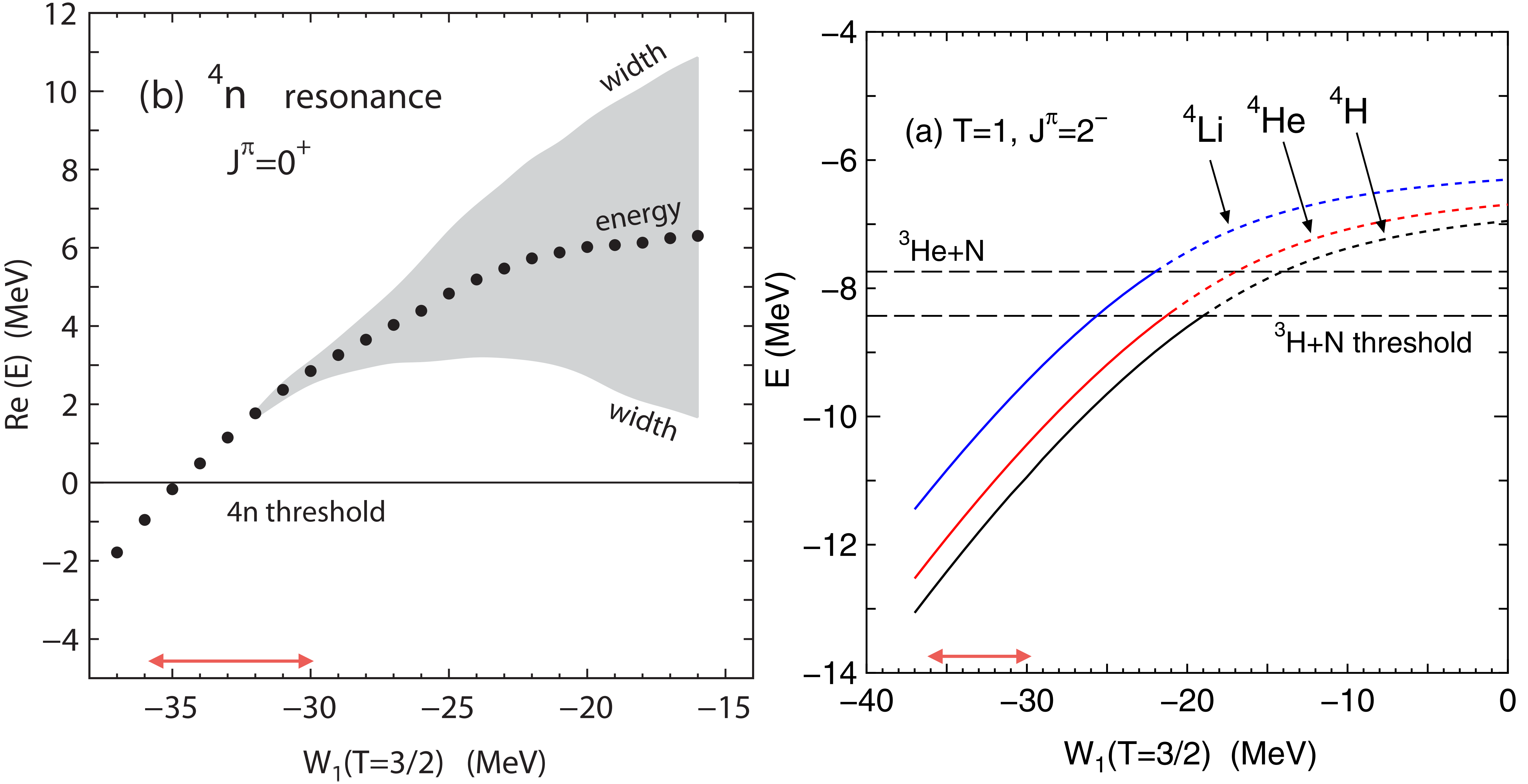
K. Kisamori et al., PRL 116, 052501 (2016)

significance: 4.9 σ (incl. look-elsewhere effect)
energy: 0.83±0.65±1.25 MeV
width : <2.6MeV (FWHM)

above 4n threshold (or not)?



ab-initio 4N calculation



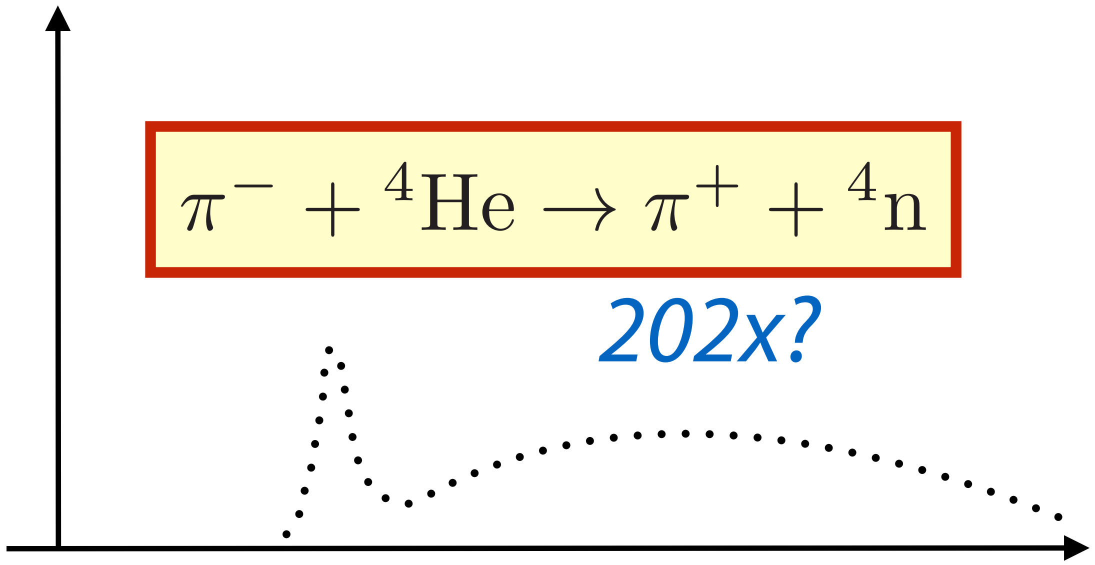
introduction of strong 3N force (T=3/2)

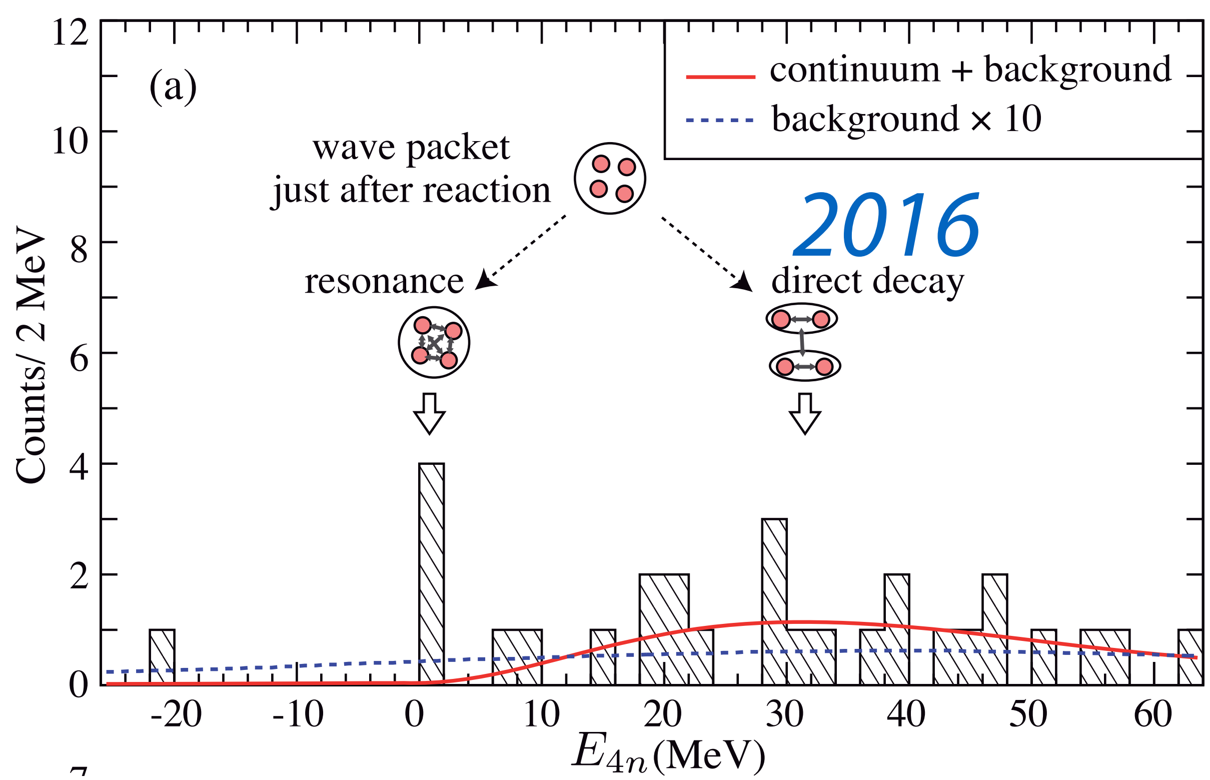
→ ^{4}H, ^{4}He (I=1), ^{4}Li below ^{3}H(^{3}He)+N threshold

E. Hiyama, R. Lazauskas, J. Carbonell, and M. Kamimura, PRC 93, 044004 (2016)

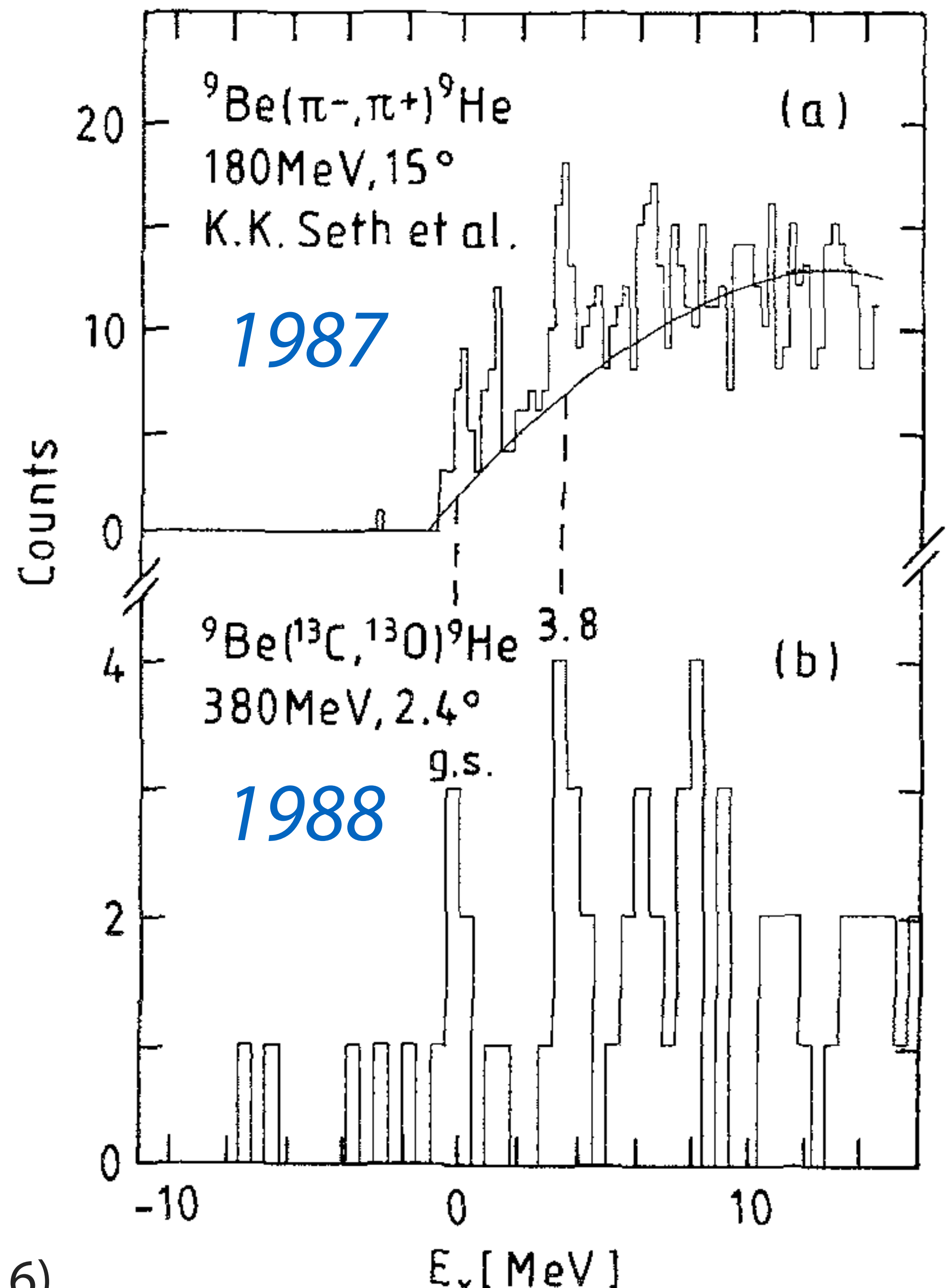
HI DCX and pion DCX

$^4He \rightarrow {}^4n$





$^9Be \rightarrow {}^9He$



K. Kisamori et al., Phys. Rev. Lett. 116, 052501 (2016)

H. G. Bohlen et al., Z. Phys. A. Atomic Nuclei 330, 227 (1988)

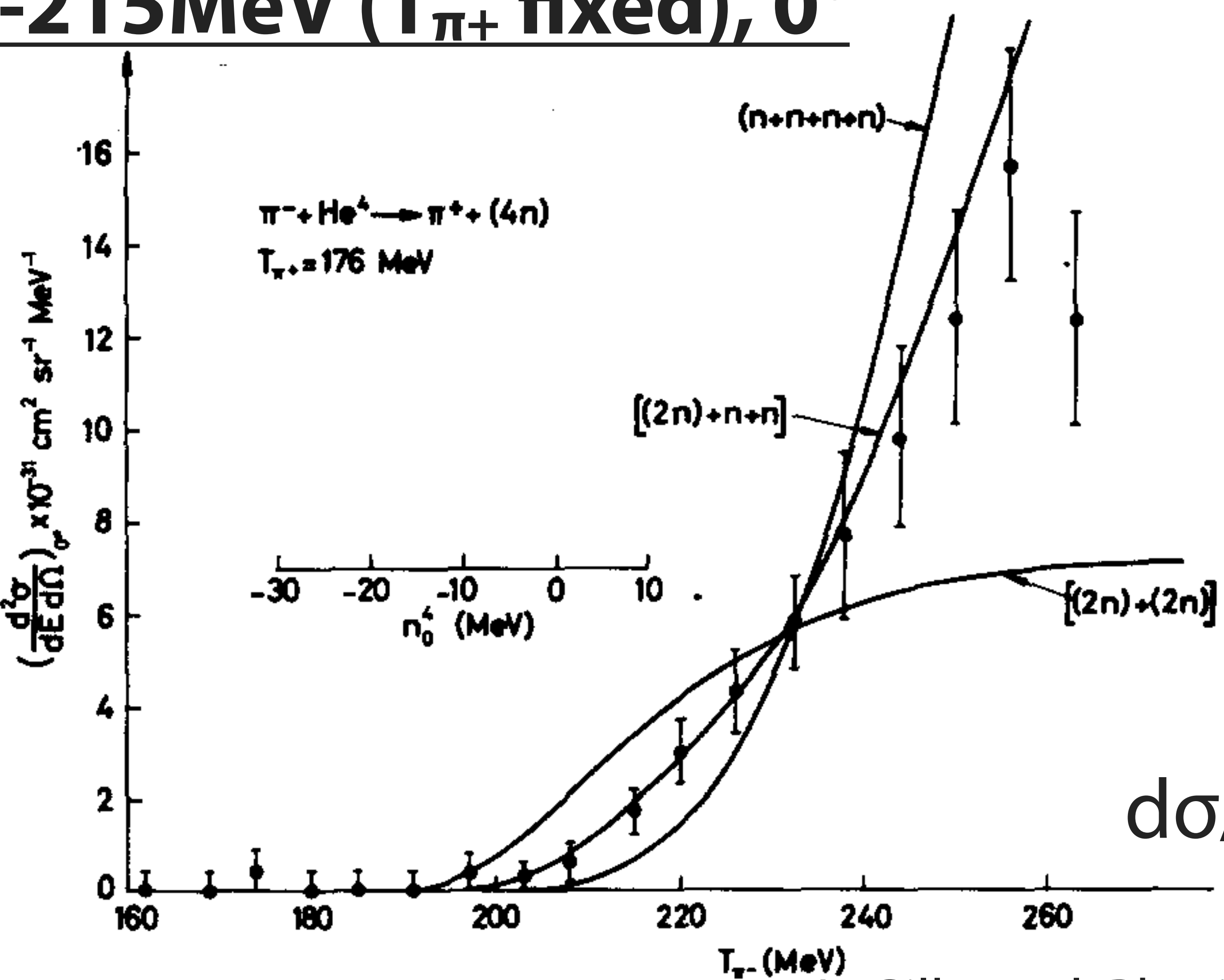
1. Brief history of pion DCX reaction

Negative results in search of ^{4}n

$$\pi^- + {}^4\text{He} \rightarrow \pi^+ + {}^4\text{n}$$

the same reaction but at low energies, different angles

170-215MeV ($T_{\pi+}$ fixed), 0°



dσ/dΩ<200 nb/sr

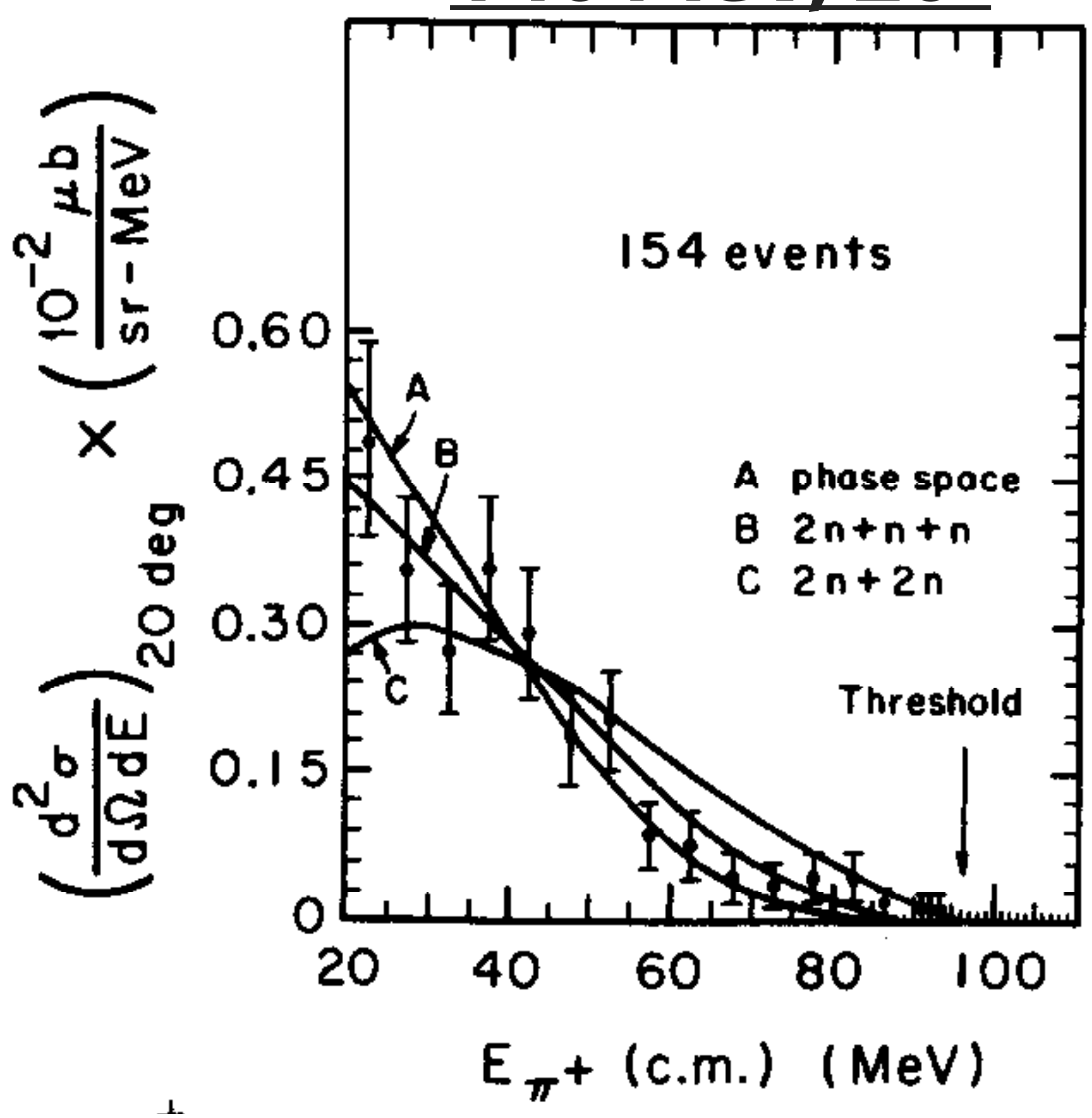
L. Gilly et al.,Physics Letters 19, 335 (1965)

Negative results in search of ^{4}n

$$\pi^- + {}^4\mathrm{He} \rightarrow \pi^+ + {}^4\mathrm{n}$$

the same reaction but at low energies, different angles

140 MeV, 20°



dσ/dΩ<(0.138±0.069) nb/sr

L. Kaufman et al. Physics Letters B 25, 536 (1967)

caution:

the cross section was underestimated by a factor of 100

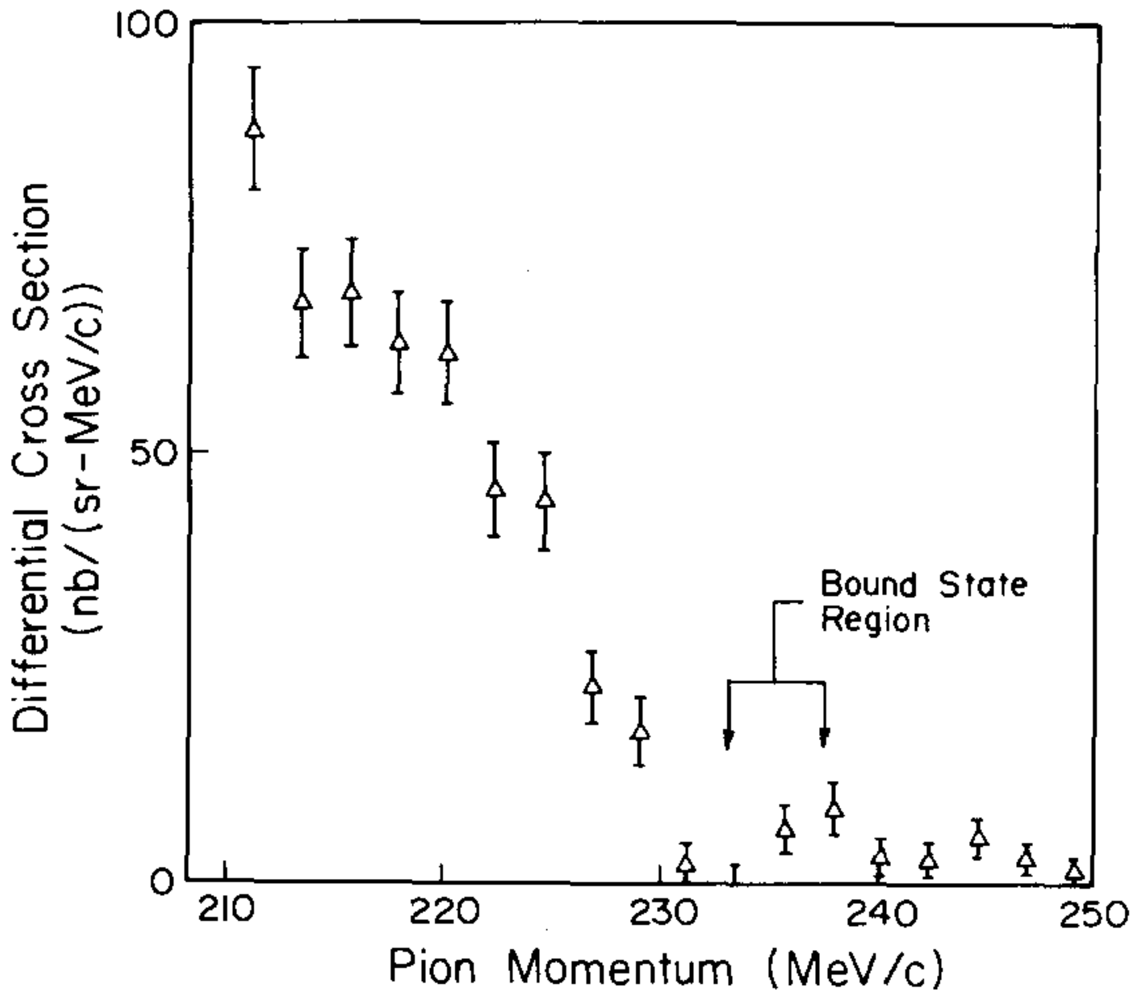
A. Stetz et al., Phys. Rev. Lett. 47, 782 (1981)

Negative results in search of ^{4}n

$$\pi^- + {}^4\mathrm{He} \rightarrow \pi^+ + {}^4\mathrm{n}$$

the same reaction but at low energies, different angles

165 MeV, 0°



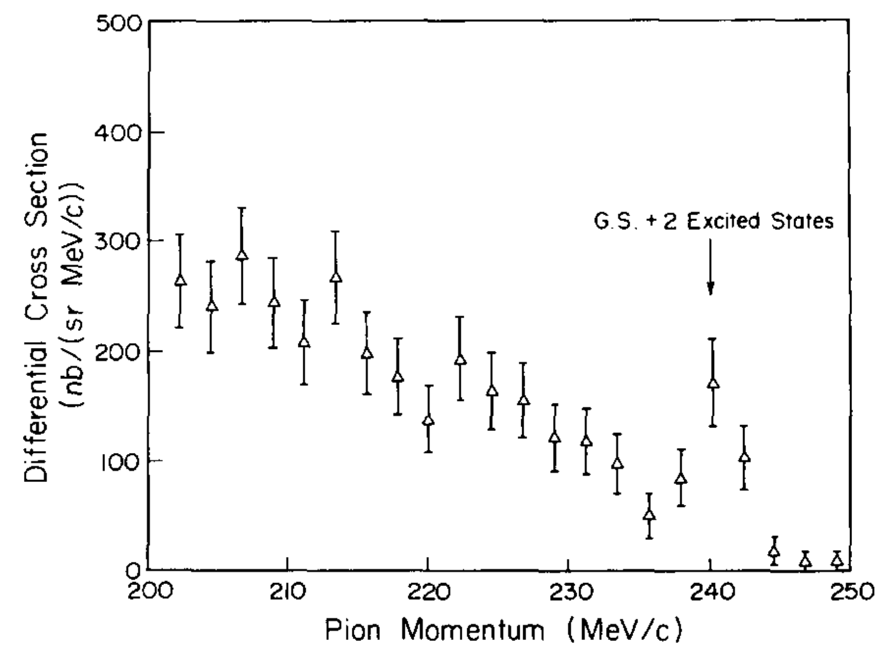


Fig. 2. The $d\sigma/d\Omega dP$ (lab frame) data for $^{12}C(\pi^-, \pi^+)^{12}Be$ at 8° and $T_\pi^- = 165$ MeV. The peak corresponding to the transition to the ^{12}Be ground and first two excited states has been indicated.

(0, 2.1, 2.7MeV)

$d\sigma/d\Omega = 7 \pm 15$ nb/sr

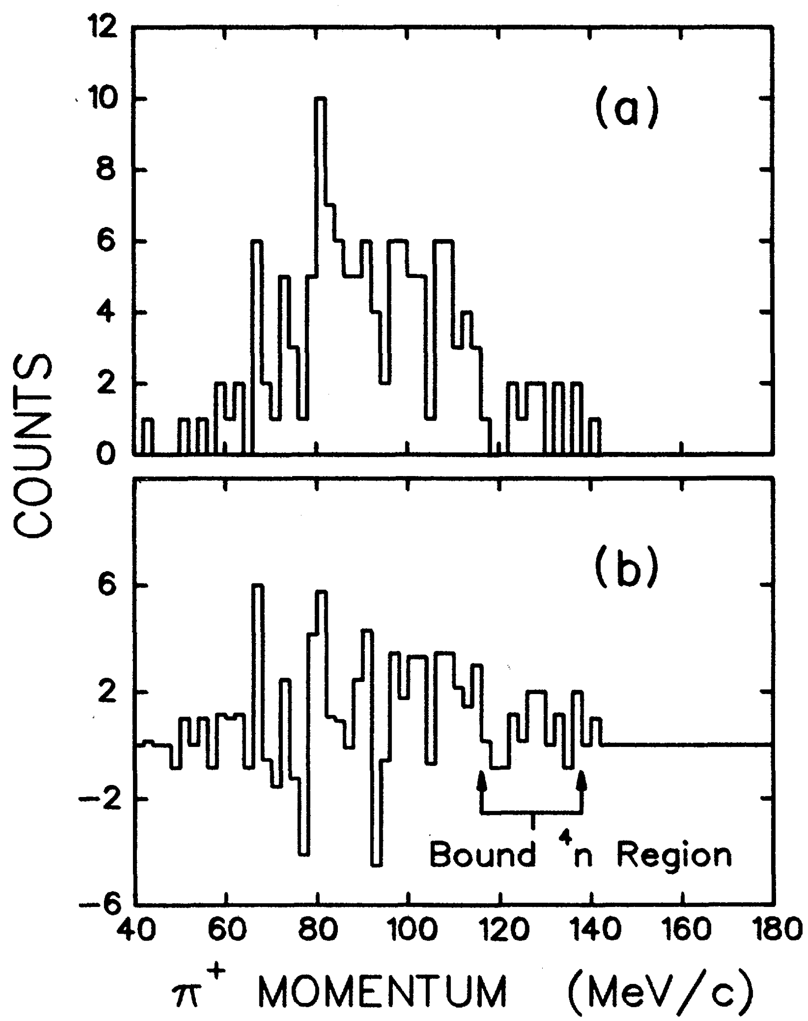
J. E. Ungar et al., Physics Letters B 144, 333 (1984)

Negative results in search of ^{4}n

$$\pi^- + {}^4\mathrm{He} \rightarrow \pi^+ + {}^4\mathrm{n}$$

the same reaction but at low energies, different angles

80 MeV, 50°–130°

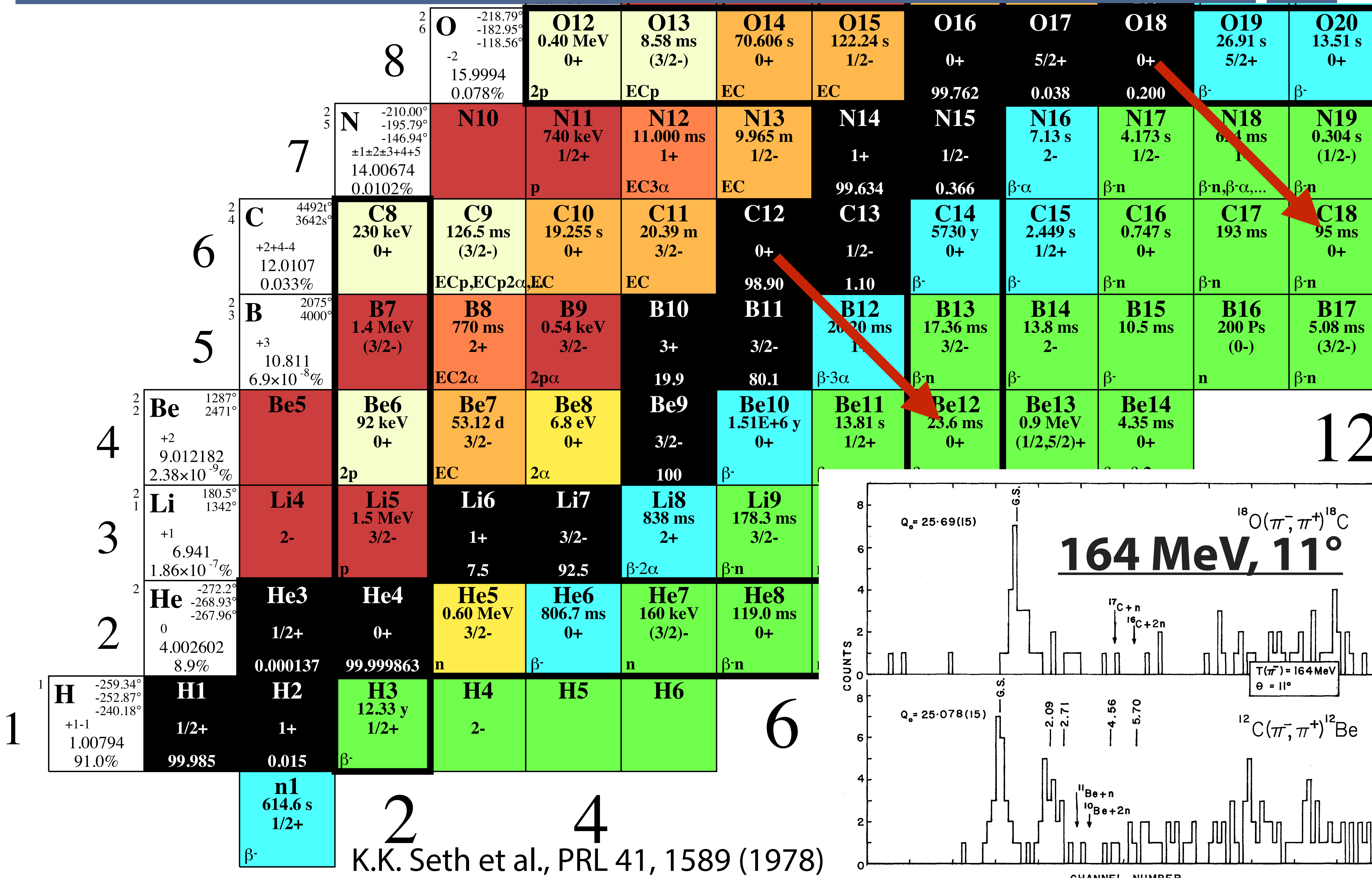


dσ/dΩ<13 nb/sr

T. P. Gorringe et al., Phys. Rev. C 40, 2390 (1989)

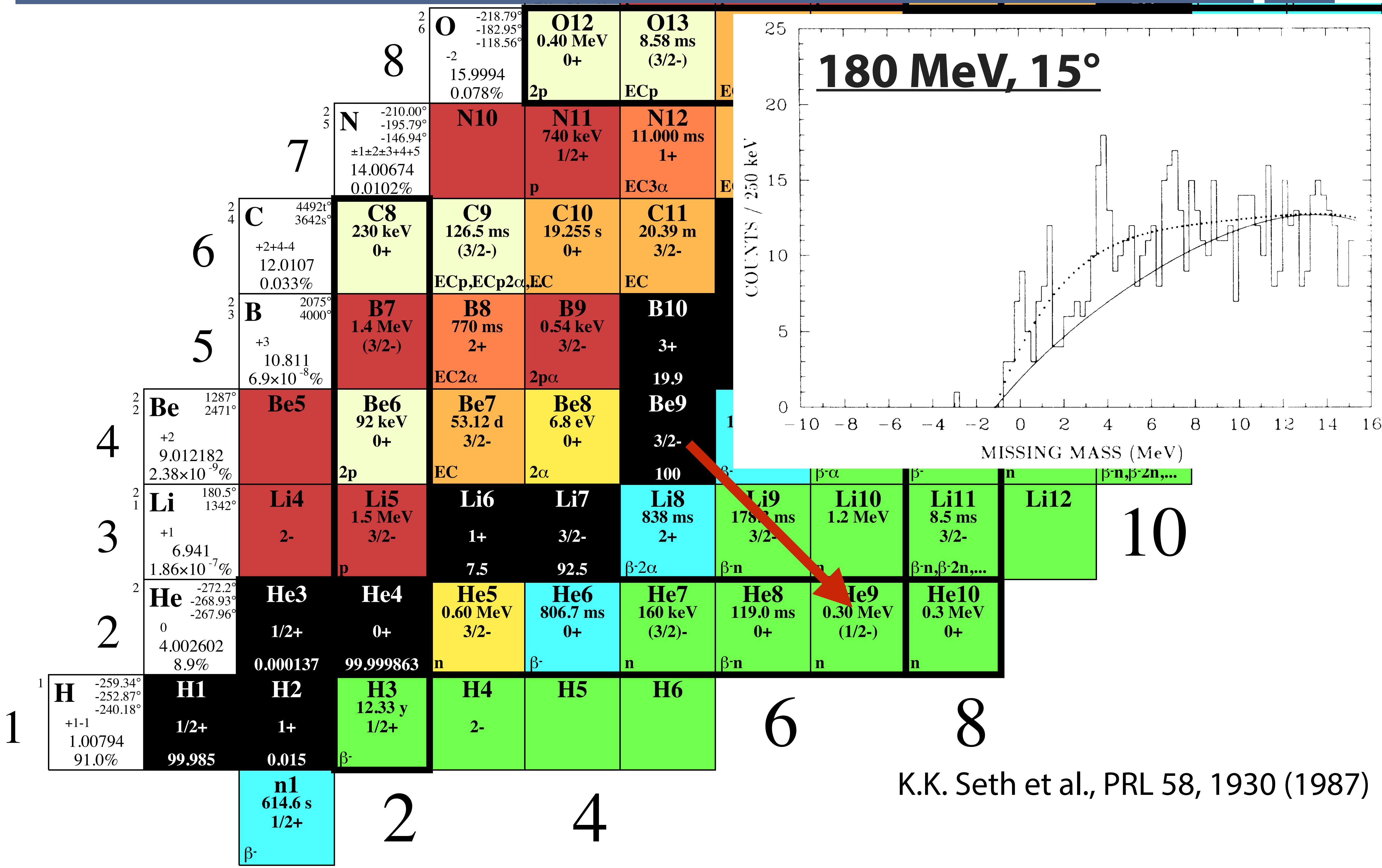
DCX measurements other than $^{4}He \rightarrow {}^{4}n$

Some examples…



K.K. Seth et al., PRL 41, 1589 (1978)

Some examples…



K.K. Seth et al., PRL 58, 1930 (1987)

Pion DCX reaction in light nuclei

accessible / **observed**
in pion DCX reaction

					^{15}Ne	^{16}Ne	^{17}Ne	^{18}Ne	^{19}Ne	^{20}Ne	^{21}Ne	^{22}Ne
					^{14}F	^{15}F	^{16}F	^{17}F	^{18}F	^{19}F	^{20}F	^{21}F
				^{12}O	^{13}O	^{14}O	^{15}O	^{16}O	^{17}O	^{18}O	^{19}O	^{20}O
			^{10}N	^{11}N	^{12}N	^{13}N	^{14}N	^{15}N	^{16}N	^{17}N	^{18}N	^{19}N
		^{8}C	^{9}C	^{10}C	^{11}C	^{12}C	^{13}C	^{14}C	^{15}C	^{16}C	^{17}C	^{18}C
		^{7}B	^{8}B	^{9}B	^{10}B	^{11}B	^{12}B	^{13}B	^{14}B	^{15}B	^{16}B	^{17}B
		^{6}Be	^{7}Be	^{8}Be	^{9}Be	^{10}Be	^{11}Be	^{12}Be	^{13}Be	^{14}Be	^{15}Be	^{16}Be
	^{4}Li	^{5}Li	^{6}Li	^{7}Li	^{8}Li	^{9}Li	^{10}Li	^{11}Li	^{12}Li	^{13}Li		
	^{3}He	^{4}He	^{5}He	^{6}He	^{7}He	^{8}He	^{9}He	^{10}He				
^{1}H	^{2}H	^{3}H	^{4}H	^{5}H	^{6}H	^{7}H						
	^{1}n		^{3}n?	^{4}n?								

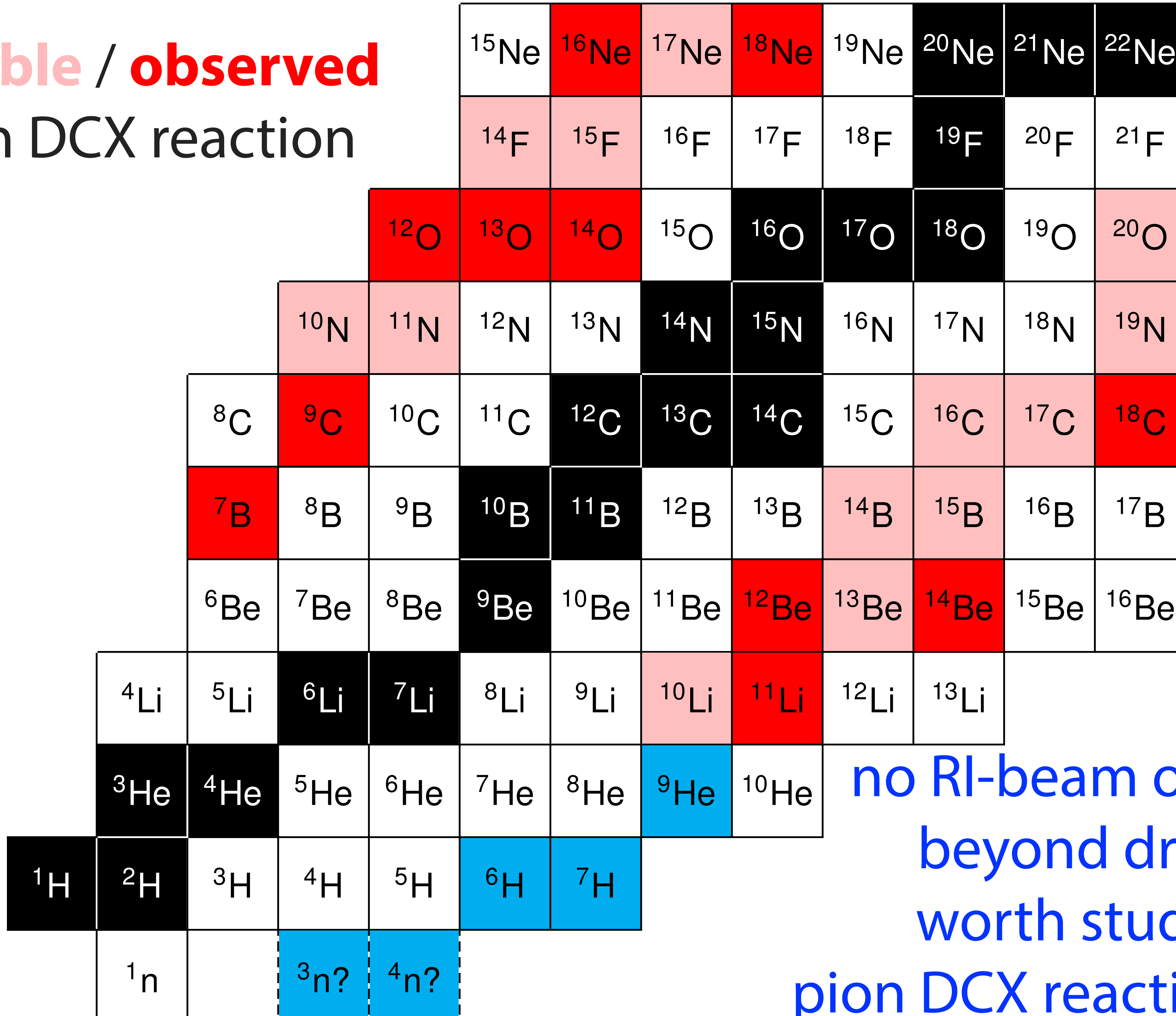
disadvantage:

only (N,Z)→(N±2, Z∓2) possible

⇒ activities in RI-beam facilities

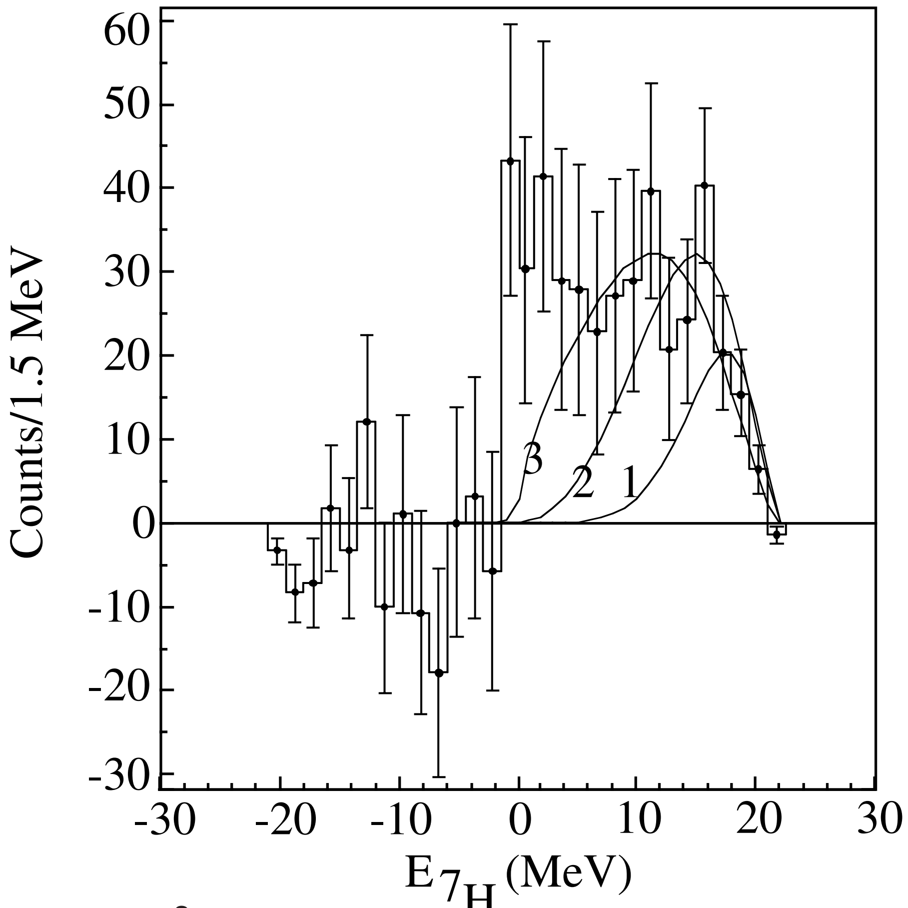
Pion DCX reaction in light nuclei

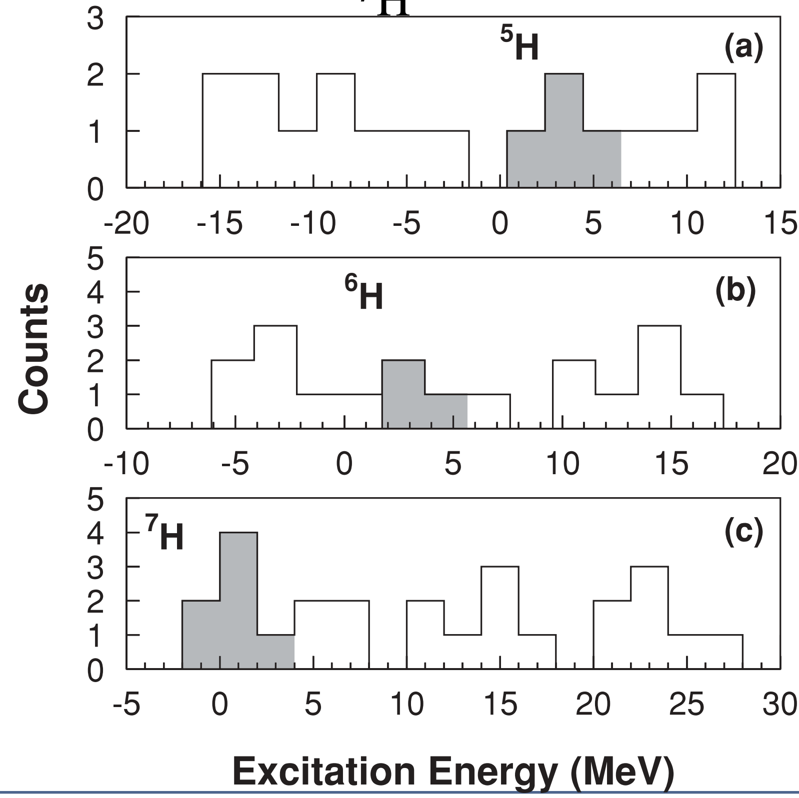
accessible / **observed**
in pion DCX reaction



no RI-beam of nuclides
beyond drip line !
worth studying in
pion DCX reactions (again)?

Case for Hydrogen-7





p(^{8}He,pp)^{7}H RIKEN

A. A. Korsheninnikov et al., Phys. Rev. Lett. 90, 082501 (2003)

GANIL

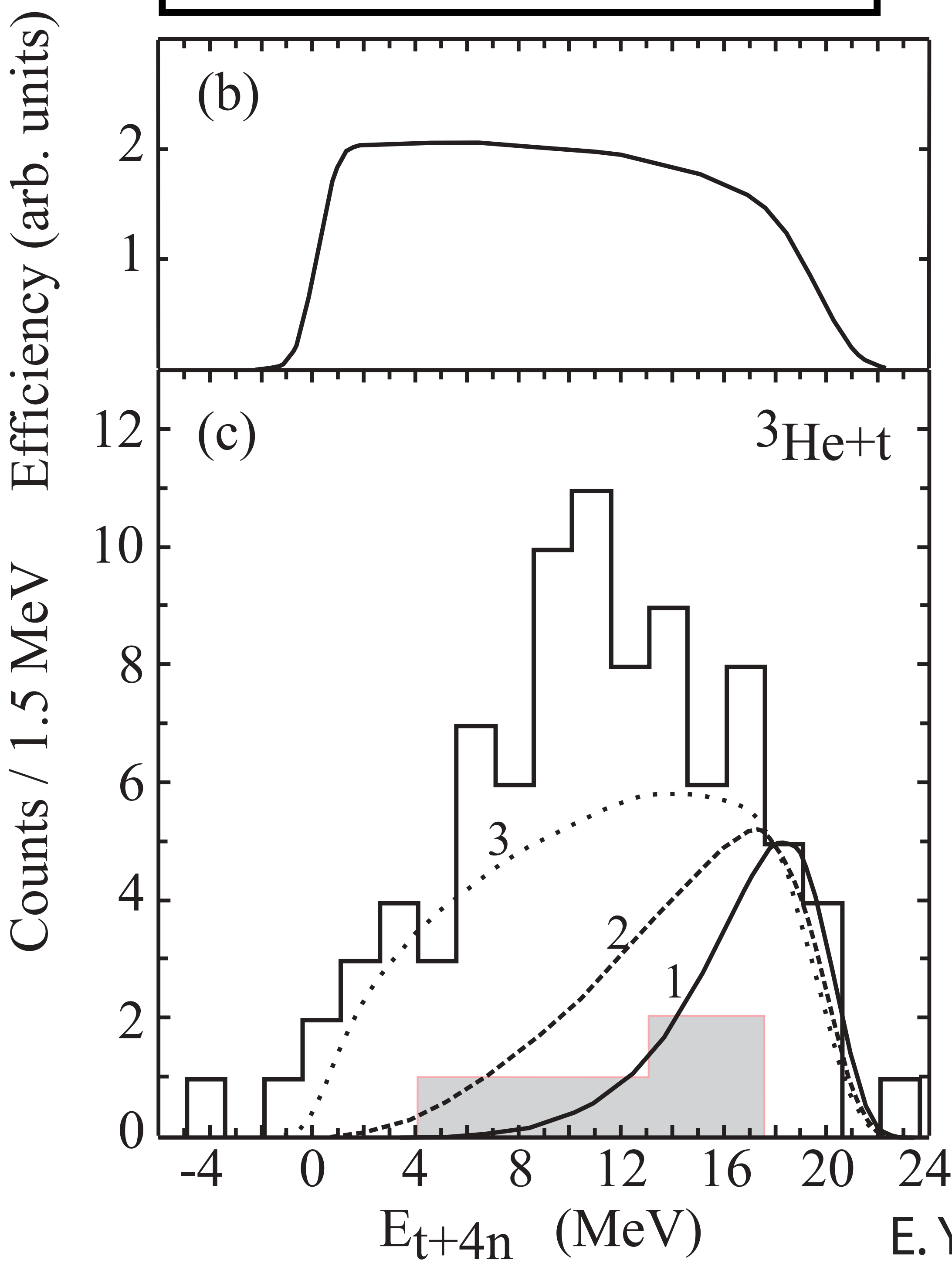
^{12}C(^{8}He,^{7}H→^{3}H+4n)^{13}N

M. Caamaño et al., Phys. Rev. C 78, 044001 (2008)

relation to tetraneutron,
as ^{7}H decays into ^{3}H+4n (^{4}n)???

Case for Hydrogen-7

$^2H(^8He,^3He)^7H$



1: t+n+n+n+n (five-body)

2: t+^{2}n+^{2}n (three-body)

3: t+^{4}n (two-body)

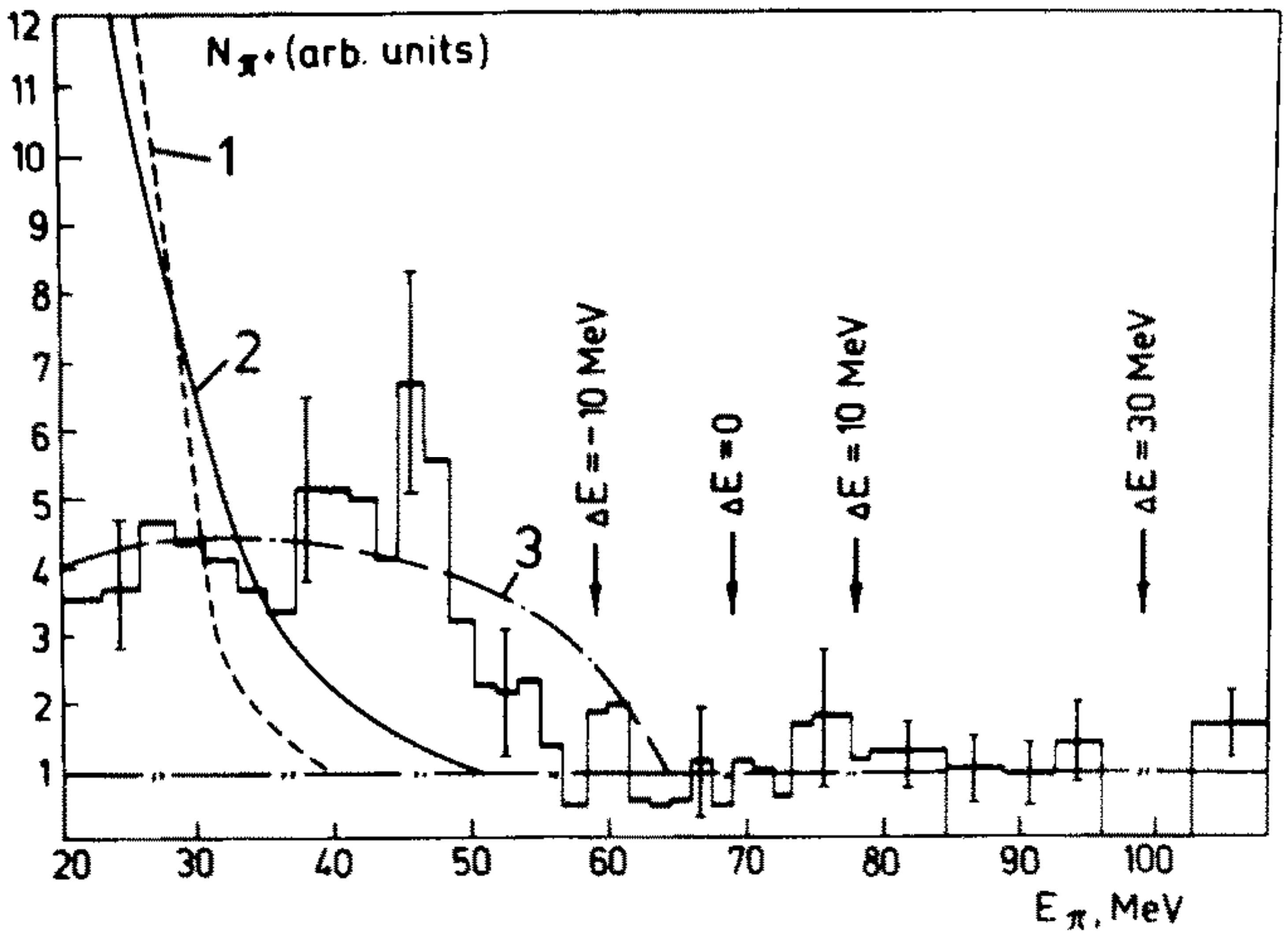
Despite the low number of accumulated statistics, some remarkable features inherent to the missing-mass spectrum in Fig. 3(c) should be noted. No clear evidence for a ^{7}H peak is seen at low energies; however, close to $E_{t+4n} = 0$ MeV, the experimental spectrum is much steeper than that of Curve 2, which is an extreme case. Furthermore, below 5 MeV, the spectrum exhibits a "shoulder" centered at ~2 MeV. One could say that the low-energy part of the spectrum looks similar to that of Curve 3, which assumes the existence of a hypothetical quasibound tetraneutron. However, the explanation of a peculiar threshold behavior in the missing-mass spectrum of ^{7}H seems unrealistic due to the lack of any reliable experimental proofs, suggesting that any bound or narrow quasibound ^4n state exists. Modern theoretical approaches [18,19] do not predict a ^4n nucleus either. Therefore, it is justified to regard the observed shape of the experimental spectrum near the $t + 4n$ threshold as an indication of a ^{7}H state. The reaction cross section of the ^{7}H production in the low-energy region is determined to be $\sim 5\ \mu$b/sr per unit count in the spectrum within the angular range of $\simeq 6^\circ$–14° in the center-of-mass system.

E. Y. Nikol'Skiĭ et al., Phys. Rev. C 81, 064606 (2010)

Case for Hydrogen-7

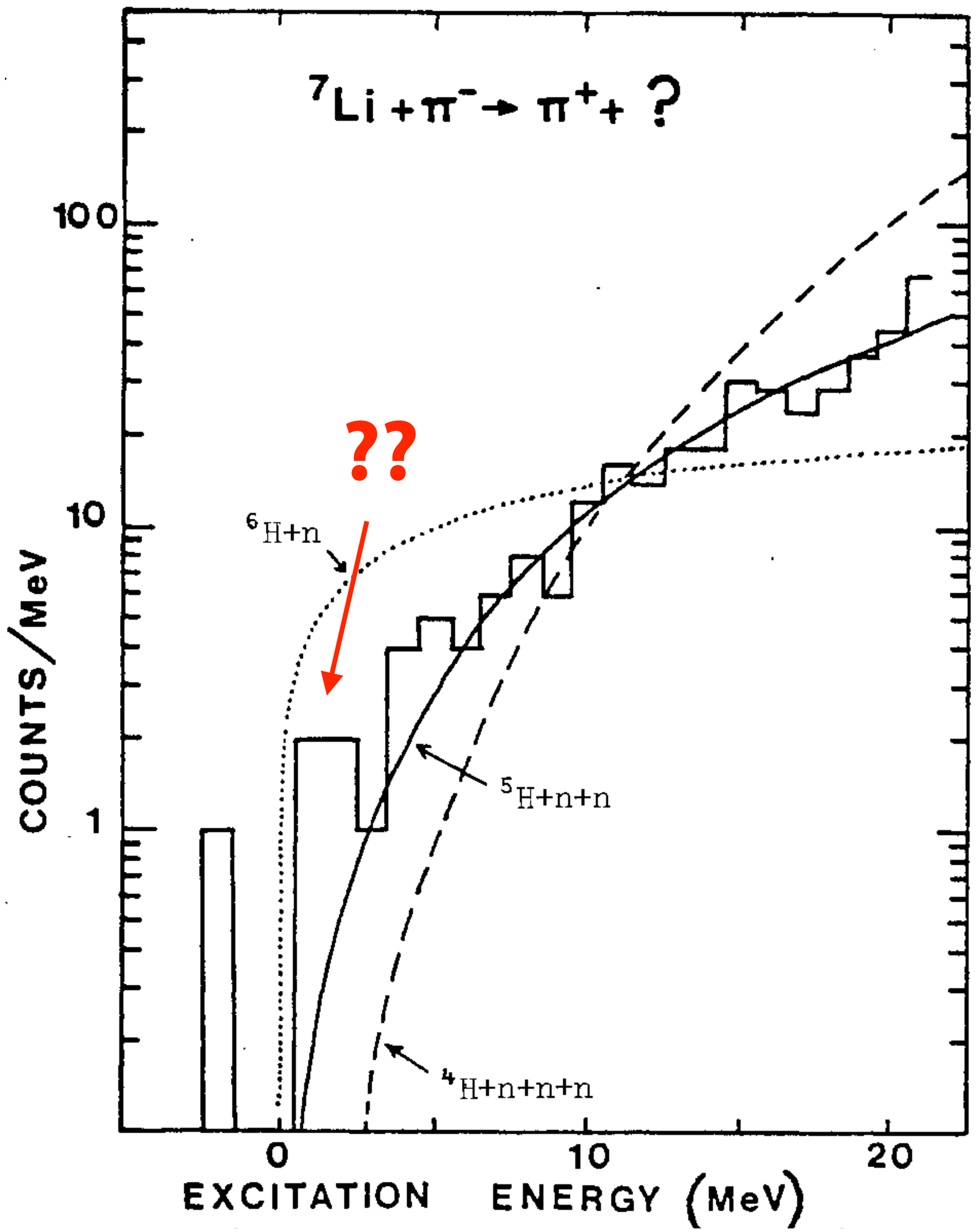
$^{7}Li(\pi^{-},\pi^{+})^{7}H$

102 MeV, 30°



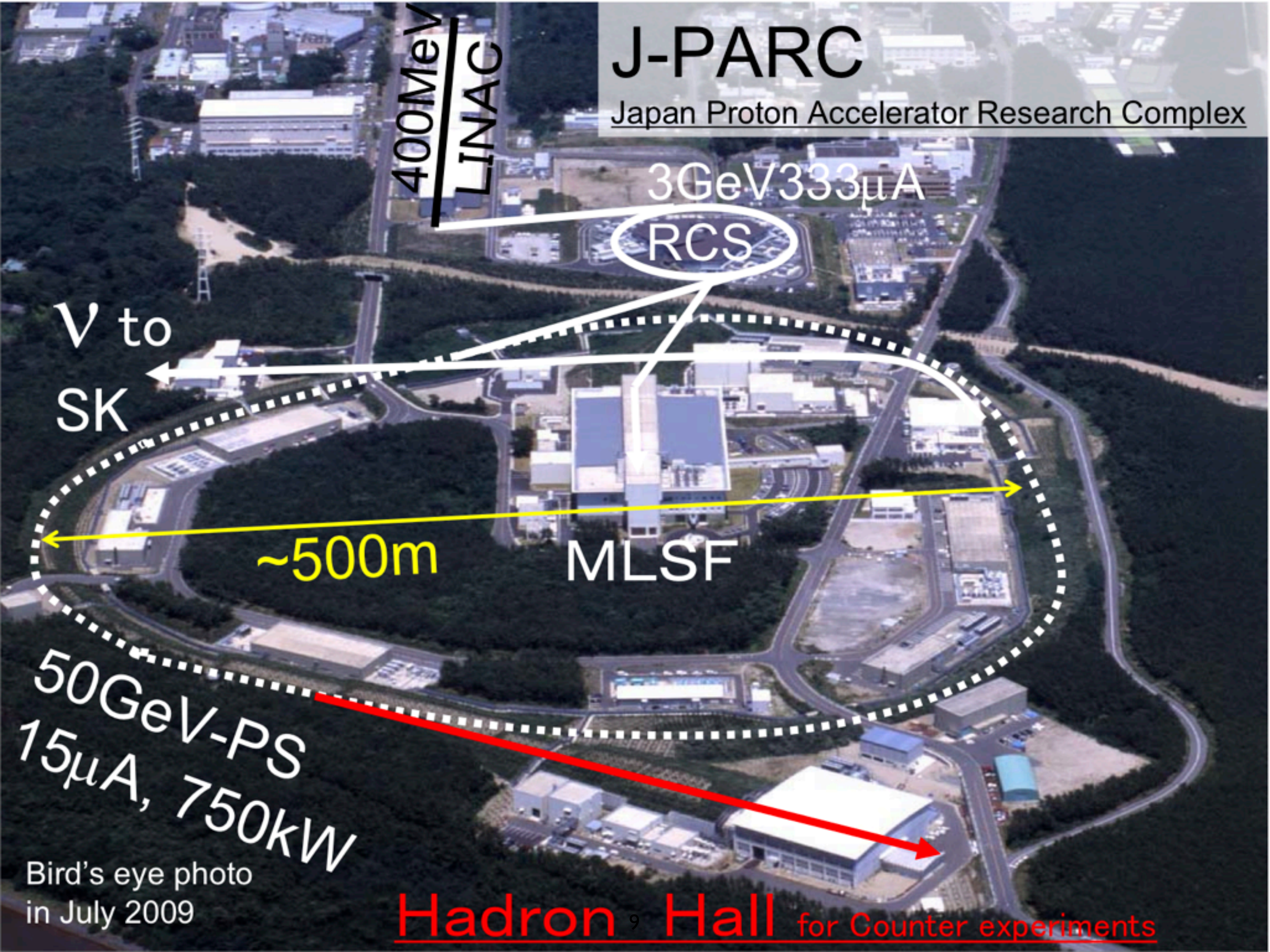
V. S. Evsee et al., Nucl. Phys. 352, 379 (1981)

192 MeV, 15°

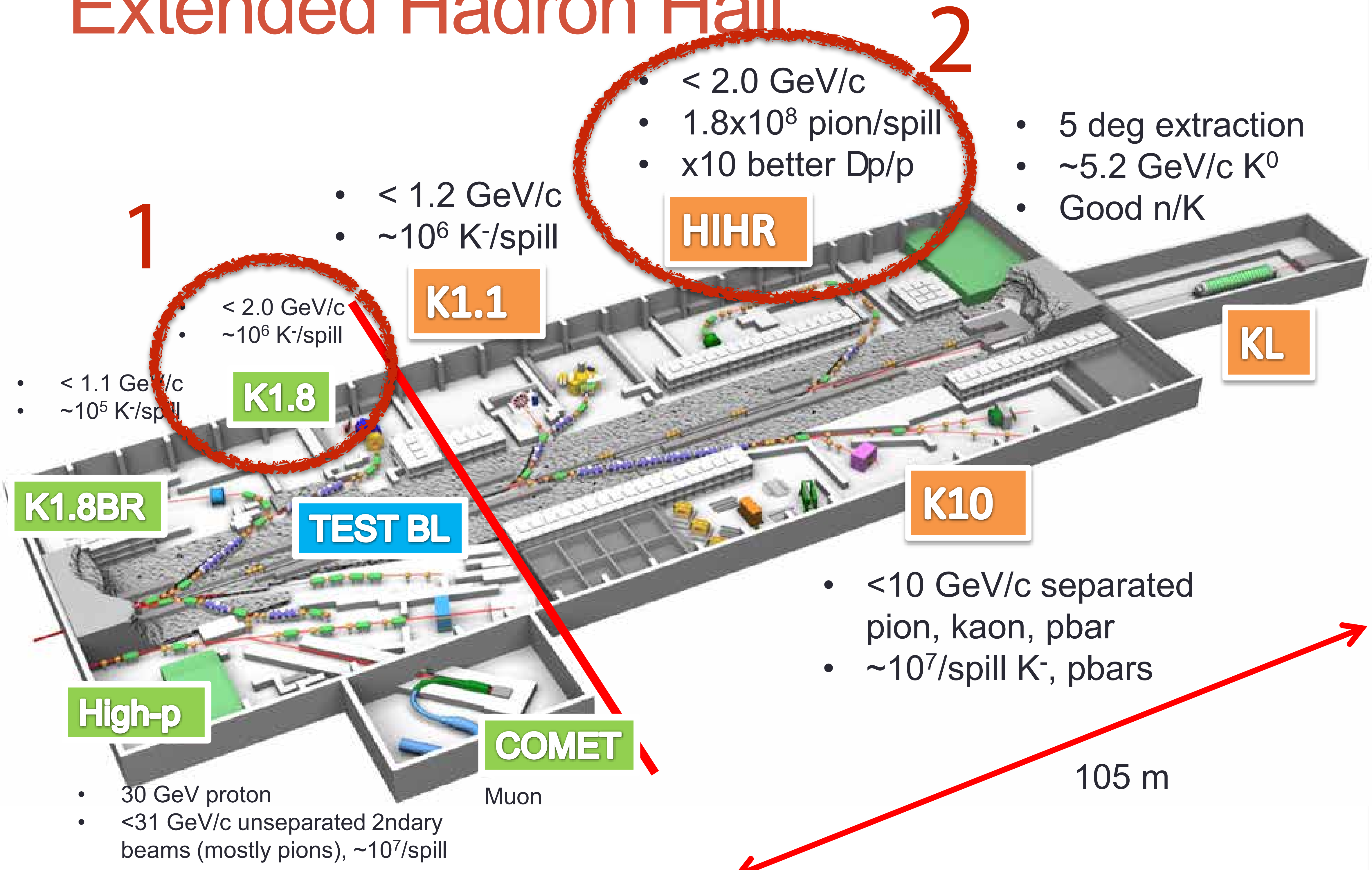


K.K. Seth, CERN 81-09, p.655 (1981)

2. Proposed experiments at J-PARC

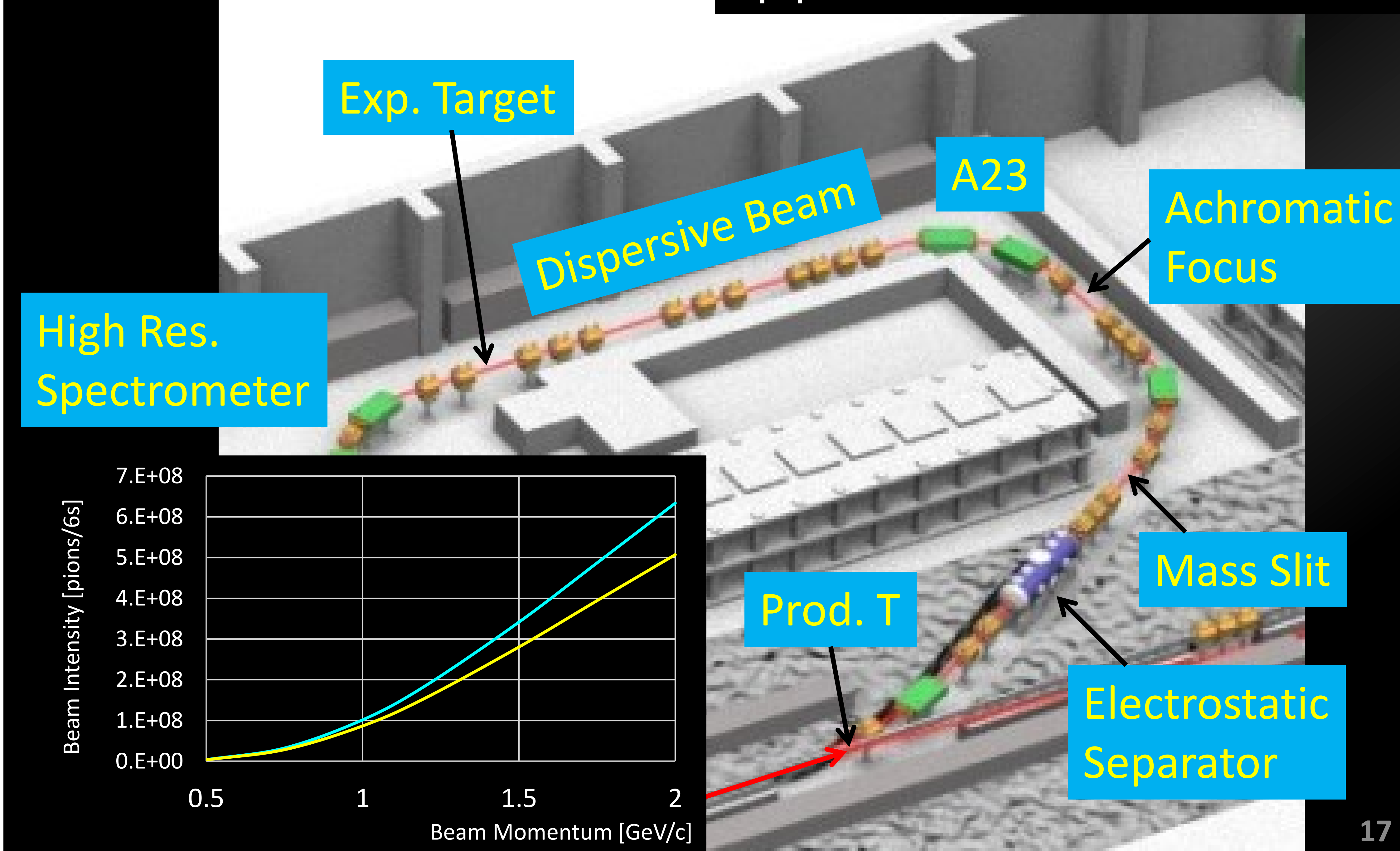

J-PARC
Japan Proton Accelerator Research Complex
400MeV
LINAC
3GeV333μA
RCS
ν to
SK
~500m
MLSF
50GeV-PS
15μA, 750kW
Bird's eye photo
in July 2009
Hadron Hall for Counter experiments

Extended Hadron Hall



HIHR Line
J-PARC ExHH

Intensity: ~ 1.8×10^{8} pion/pulse
(1.2 GeV/c, 58 m, 1.4msr*%,
100kW, 6s spill, Pt 60mm)
$\Delta p/p$ ~ 1/10000



17

H. Noumi, "International workshop on physics at the extended hadron experimental facility of J-PARC"

Staging strategy (tentative)

- If the ^{4}n peak is confirmed in the latest SHARAQ/RIBF experiment…
  - phase-1: analog transition of $^{18}O \rightarrow ^{18}Ne_{g.s.}$ (DIAS) at the existing K1.8 beamline
  - phase-2: non-analog transition of $^{4}He \rightarrow ^{4}n$ at the HIHR beamline
    - high intensity and high resolution with dispersion matching technique

Two Letters of Intent submitted

Letter of Intent for J-PARC 50 GeV Synchrotron

Letter of Intent for J-PARC 50 GeV Synchrotron

Investigation of Pion Double Charge Exchange Reaction with S-2S Spectrometer

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Department of Physics, Kyoto University

T. Fukuda and T. Harada
Osaka Electro-Communication University

E. Hiyama, K. Itahashi, and T. Nishi
RIKEN Nishina Center

(Dated: June 27, 2016)

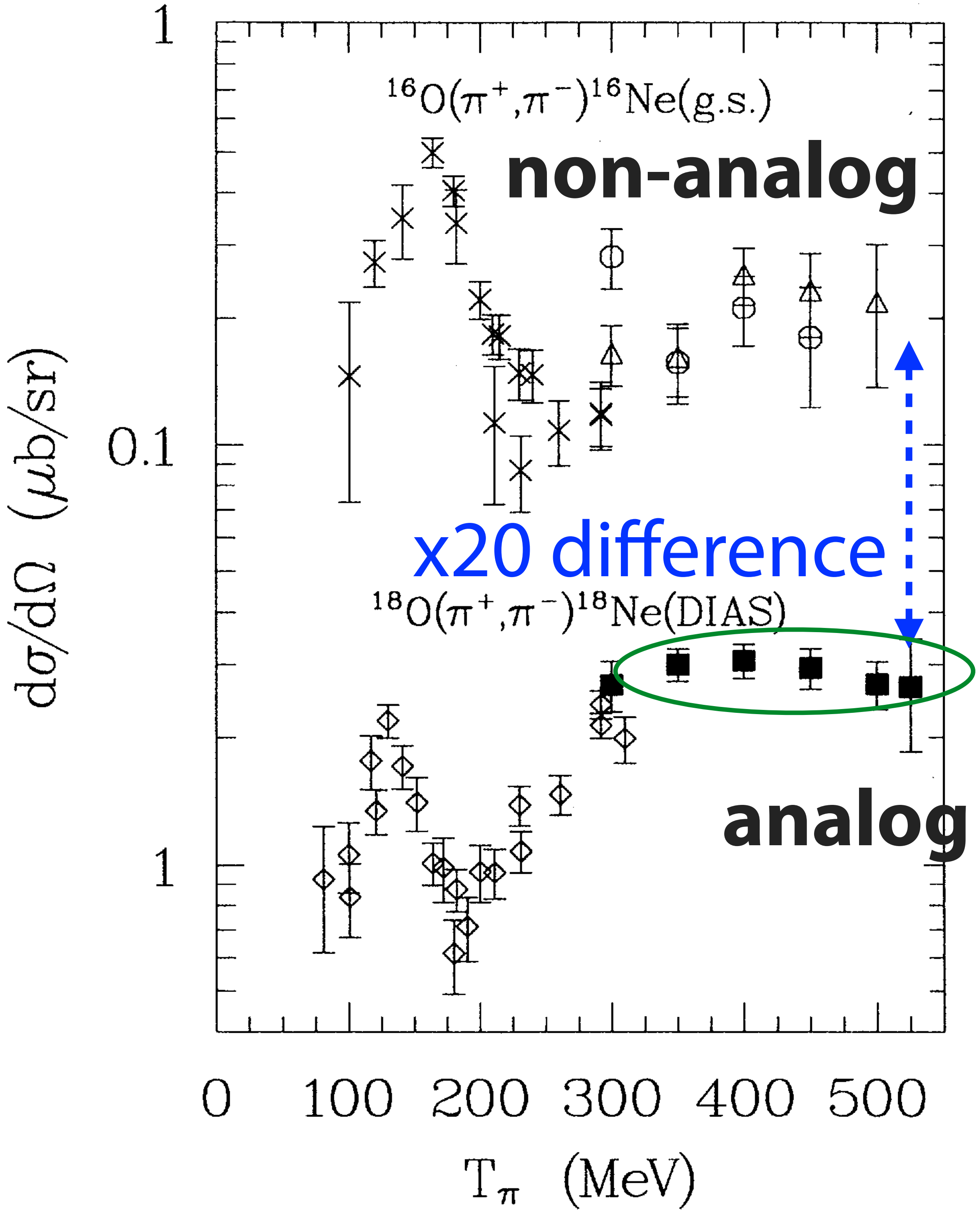
We will study pion double charge exchange $(\pi^{\pm}, \pi^{\mp})$ reactions with approximately 850 MeV (980 MeV/c) π beams at J-PARC. The ultimate goal is to search for a tetraneutron resonance state (^{4}n), whose candidates have been observed in the ^{4}He(^{8}He, ^{8}Be) reaction at RIBF. First of all, an analog transition, the ^{18}O$(\pi^{+}, \pi^{-})^{18}$Ne (g.s.) reaction, will be investigated at the existing K1.8 beamline with the S-2S spectrometer. It will be an important step toward a non-analog transition, the ^{4}He$(\pi^{-}, \pi^{+})^{4}$n reaction, with much smaller cross section.

http://j-parc.jp/researcher/Hadron/en/pac_1607/pdf/LoI_2016-18.pdf

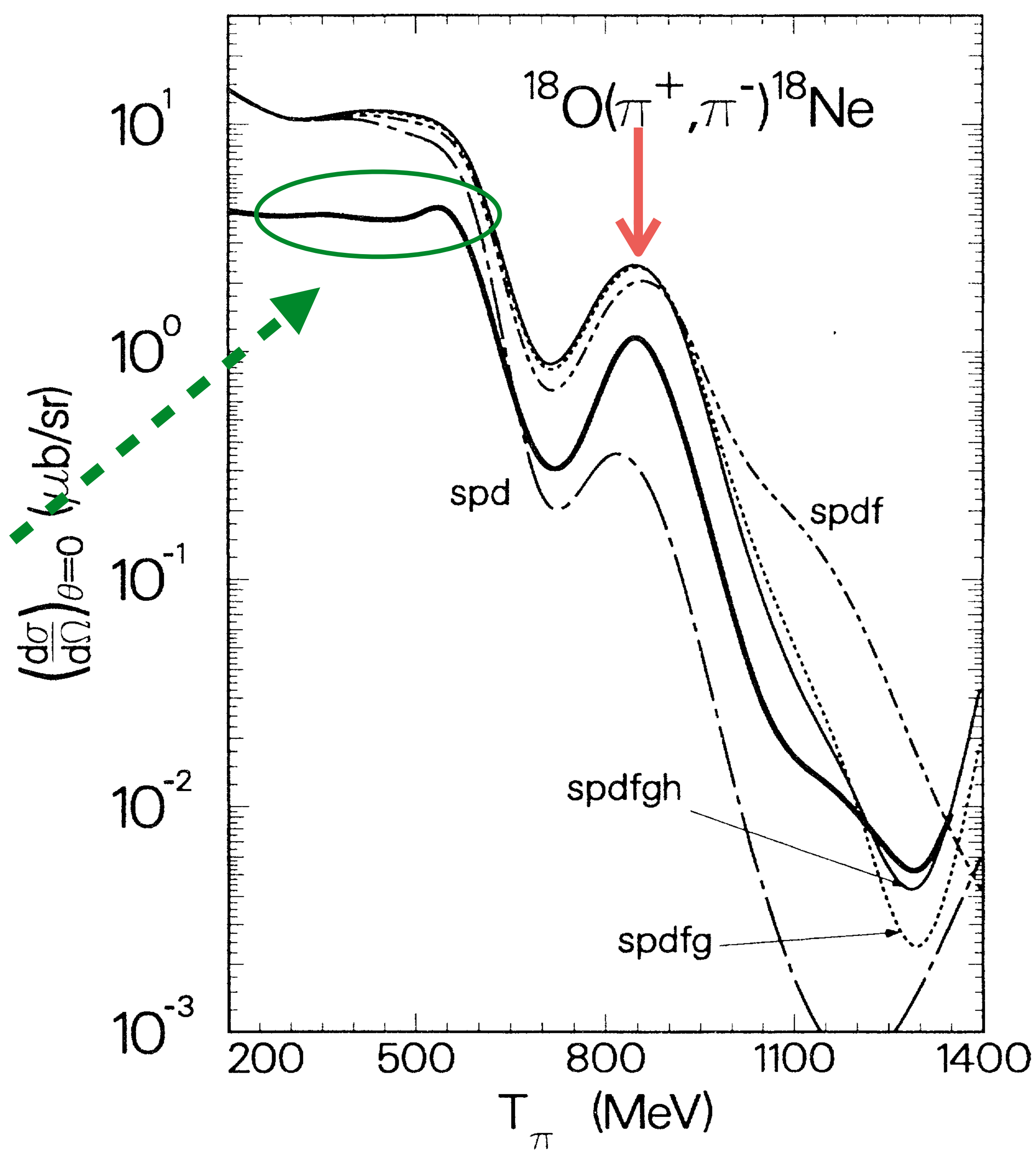
http://j-parc.jp/researcher/Hadron/en/pac_1607/pdf/LoI_2016-19.pdf

Pion DCX far above Δ region

available data < 550MeV (LAMPF)



theory

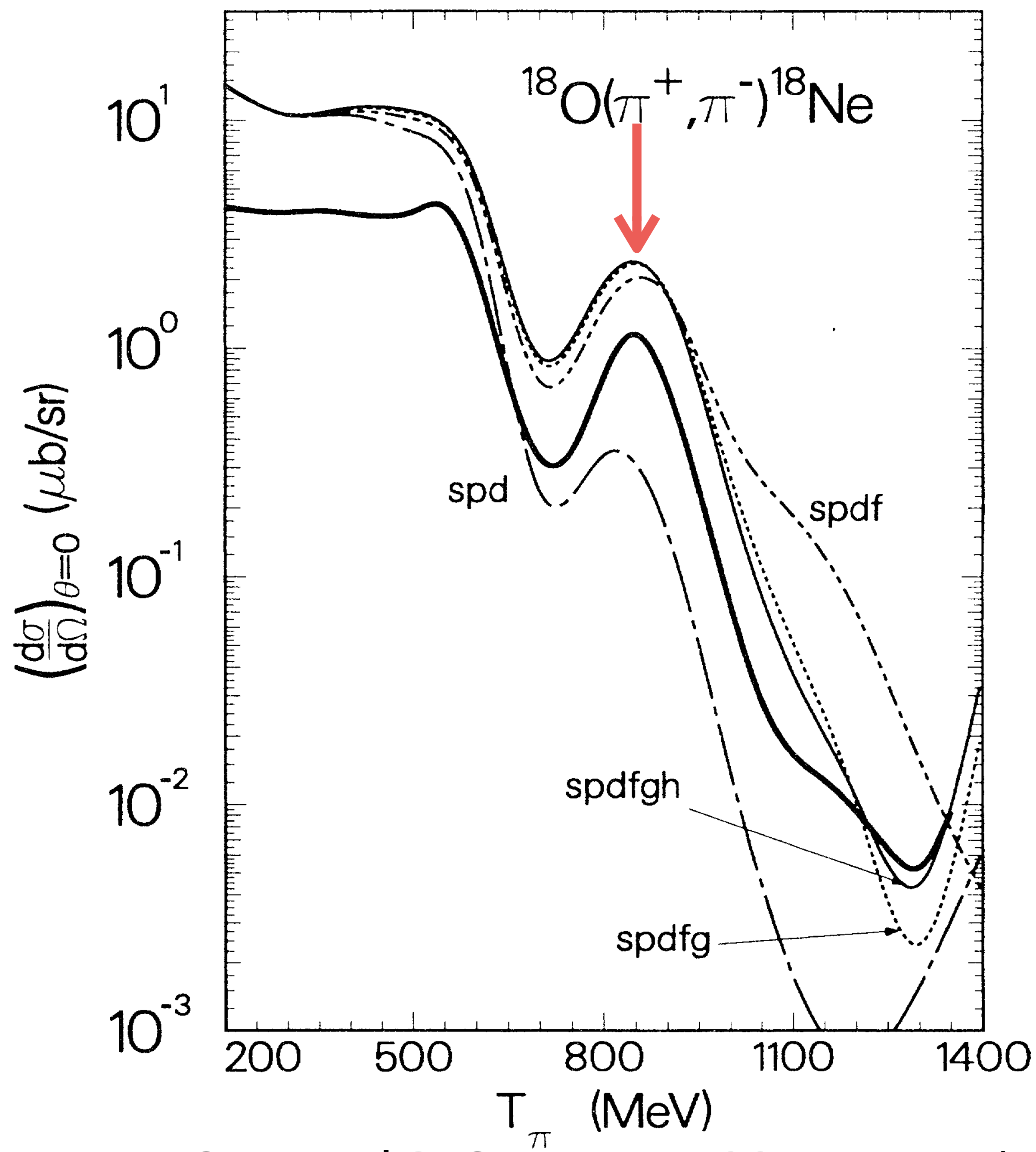


D.P. Beatty et al., PRC 48, 1428 (1993)

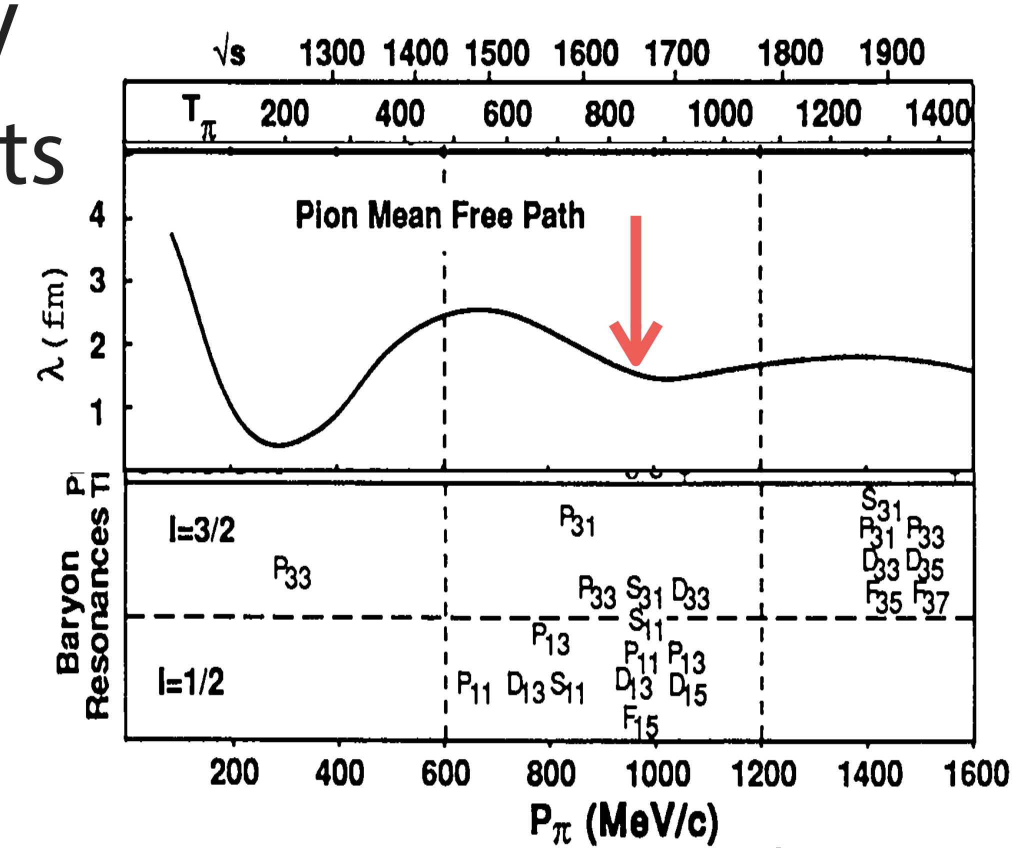
E. Oset and D. Strottman, PRL 70, 146 (1993)

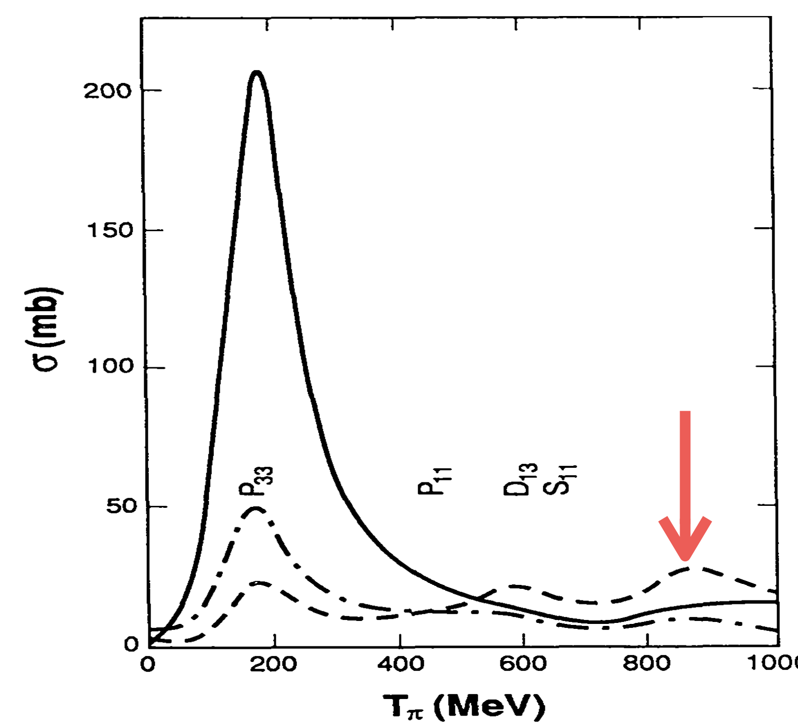
Pion DCX in the third resonance region

No measurement above 0.5 GeV except for inclusive measurements



E. Oset and D. Strottman, PRL 70, 146 (1993)





"PILAC Users Group Report on the Physics with PILAC" (1991)

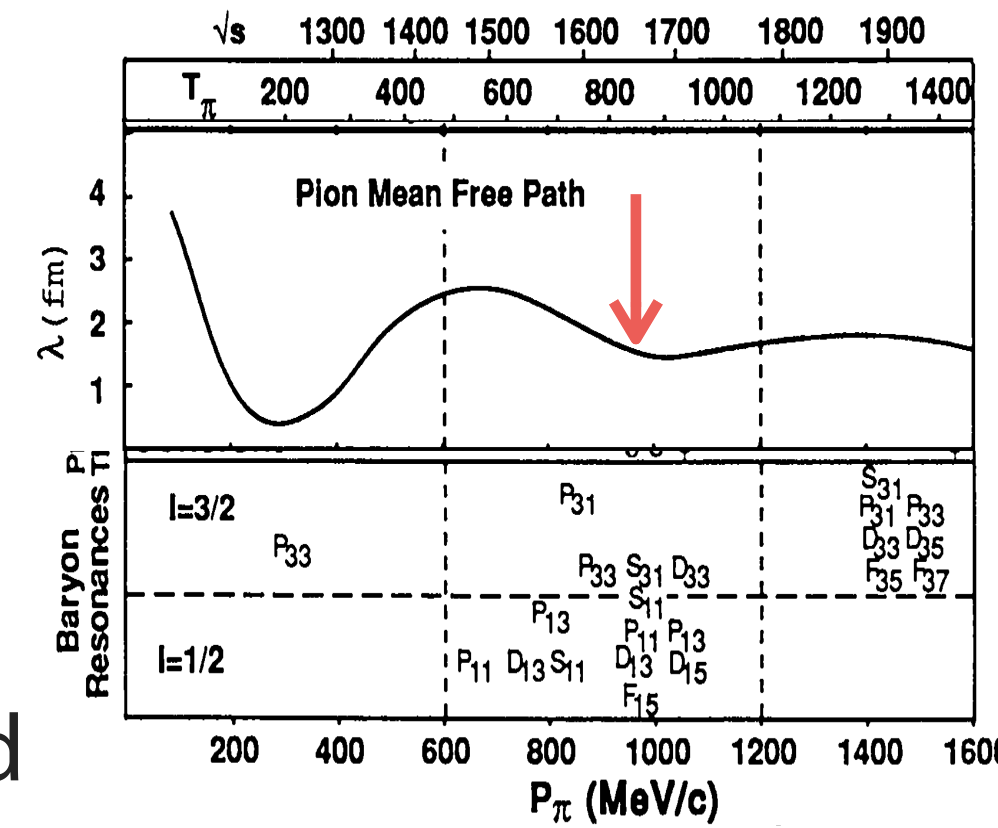
Pion DCX in the third resonance region

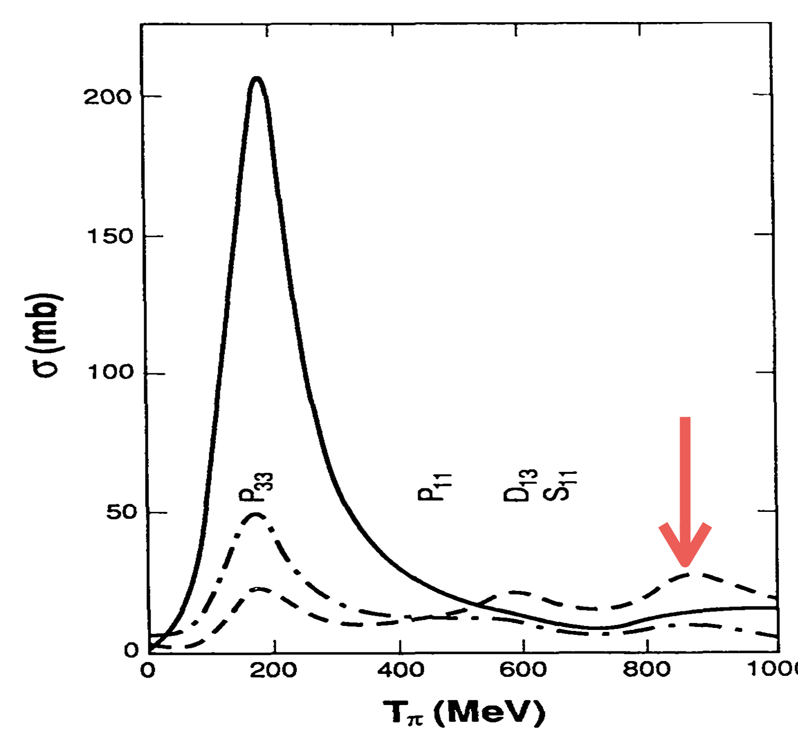
moderately small mean free path

↓

the spectrum will be less distorted by final state interaction.

(may be important for a fragile tetraneutron)





"PILAC Users Group Report on the Physics with PILAC" (1991)

Comparison with other measurements

Reaction	q (MeV/c)	Q-value (MeV)	
^{4}He(^{8}He, ^{8}Be)[a]	14.2	−3.2	← SHARAQ/RIBF
^{4}He(π^-,π^+)[b]	130.7–266.3	−30.9	← TRIUMF (Gorringe et al.)
^{4}He(π^-,π^+)[c]	35.5	−30.9	← LAMPF (Ungar et al.)
^{4}He(π^-,π^+)[d]	32.9	−30.9	
^{4}He(π^-,π^+)[e]	31.7	−30.9	
^{4}He(π^-,π^+)[f]	31.3	−30.9	← J-PARC

[a] Same condition as in Ref. [1]
[b] $T_{\pi^-} = 80\,\mathrm{MeV}$ ($p_{\pi^-} = 170\,\mathrm{MeV}/c$) and $\theta_{\pi^+} = 50°–130°$. Same condition as in Ref. [21]
[c] $T_{\pi^-} = 165\,\mathrm{MeV}$ ($p_{\pi^-} = 271\,\mathrm{MeV}/c$). Same condition as in Ref. [20]
[d] $T_{\pi^-} = 300\,\mathrm{MeV}$ ($p_{\pi^-} = 417\,\mathrm{MeV}/c$)
[e] $T_{\pi^-} = 550\,\mathrm{MeV}$ ($p_{\pi^-} = 675\,\mathrm{MeV}/c$)
[f] $T_{\pi^-} = 850\,\mathrm{MeV}$ ($p_{\pi^-} = 980\,\mathrm{MeV}/c$) (to be proposed in the letter of intent)

	π^- energy	intensity	π^+ acceptance
LAMPF [20]	165 MeV	10^6/sec	25 msr
TRIUMF [21]	80 MeV	2×10^6/sec	$\sim 2\pi$ sr
J-PARC HIHR	850 MeV	2.7×10^7/sec[a]	~ 10 msr

[a] averaged per spill (6 sec).

- With 2 g/cm^2 liquid ^{4}He target,
  formation cross section 1nb/sr ⇒ 97 events in 2 weeks

http://j-parc.jp/researcher/Hadron/en/pac_1607/pdf/LoI_2016-18.pdf

Concept of Phase-1 experiment

- analog transition: $\pi^- + {}^{18}O \rightarrow \pi^+ + {}^{18}Ne_{g.s.}$

  - target: ${}^{18}O$-enriched water

  - spectrometer:
    K1.8 beamline + S-2S spectrometer (under construction)
    T. Nagae et al. Spectroscopy of Ξ-hypernuclei with the ${}^{12}C(K^-,K^+){}^{12}_{\Xi}Be$ reaction

  - 400 counts per day expected
    (with 10^7 π^+/spill beam
    impinging on 2 g/cm^2 $H_2{}^{18}O$ target)

  - to establish a method of pion DCX measurement

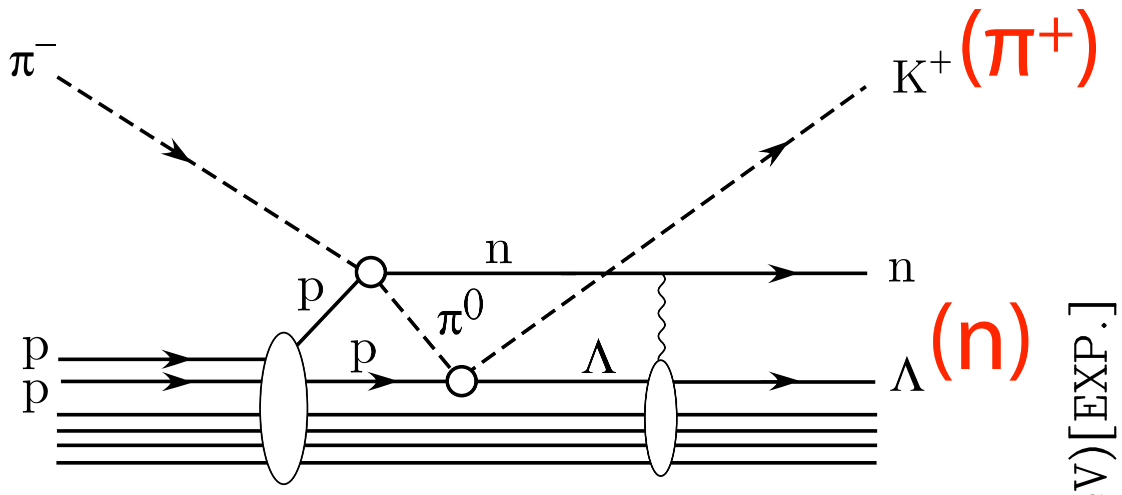
- beam-energy scan?
  comparison with non-analog transition (${}^{16}O$, ${}^{12}C$, …)?

Experimental background

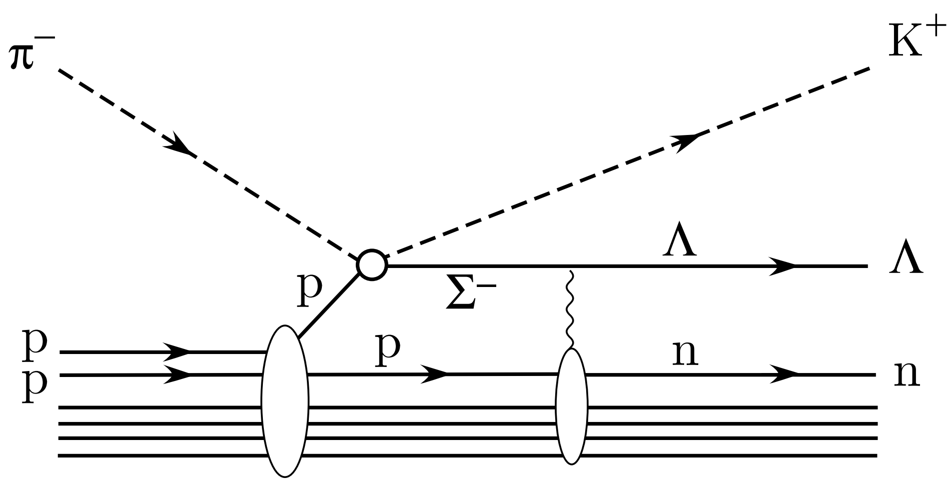
- e^+/π^+ separation will be very important.
  - no detector installed for this purpose at present (ToF/ΔE doesn't help because of high momentum.)
  - Lead glass Cherenkov counters as a promising candidate
- $\pi^- \to \pi^0$: single charge exchange on target
  $\pi^0 \to 2\gamma$: instantaneous decay
  $\gamma \to e^+e^-$: pair creation (near the target)
  The momentum of positrons can be inside the region of interest (around the 4n threshold in DCX reaction).
- In-flight decay of π will be insignificant.

Relevance to hypernuclear physics

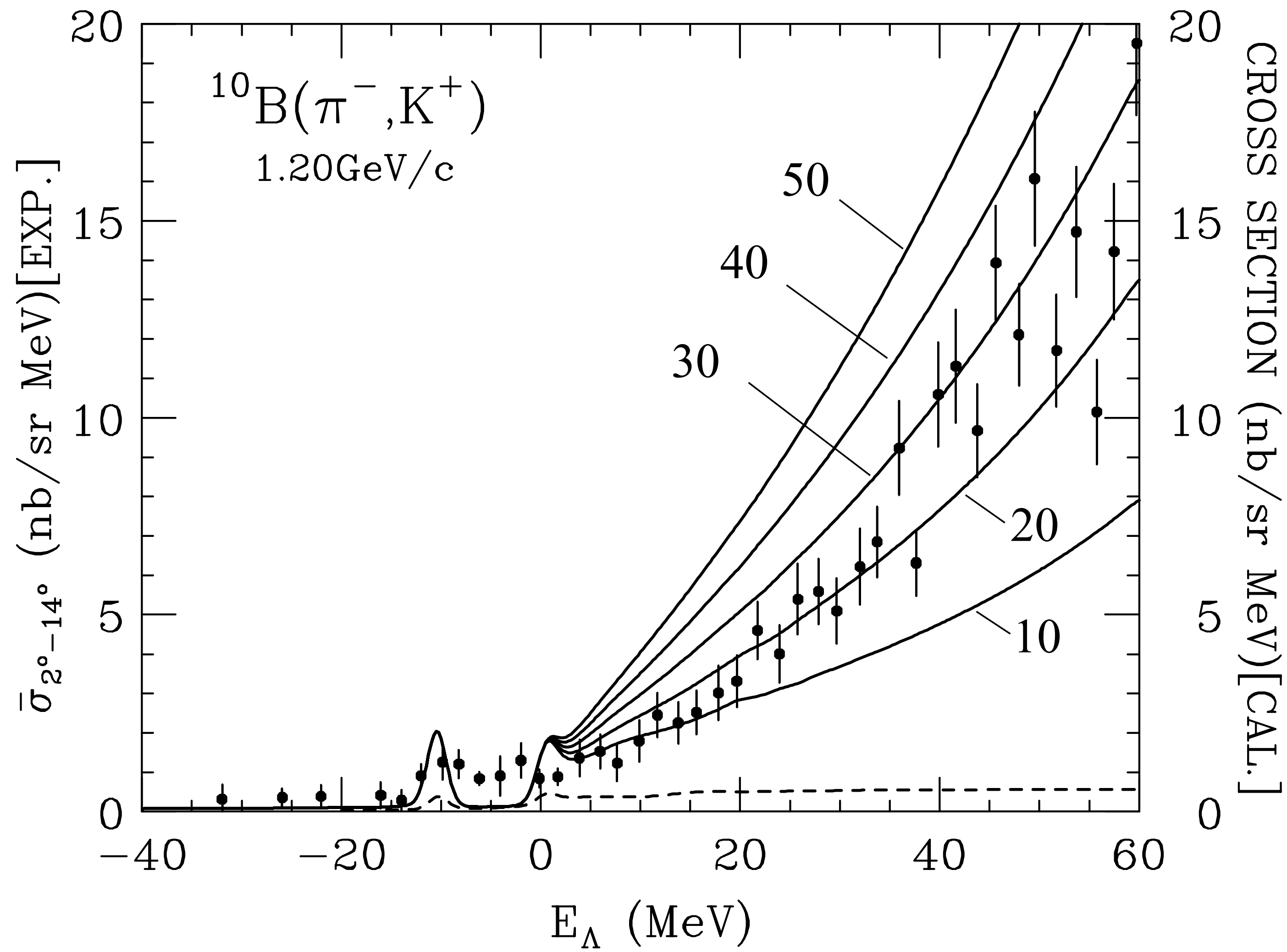
neutron-rich Λ-hypernuclei produced in (π^-,K^+) DCX reaction



(a)



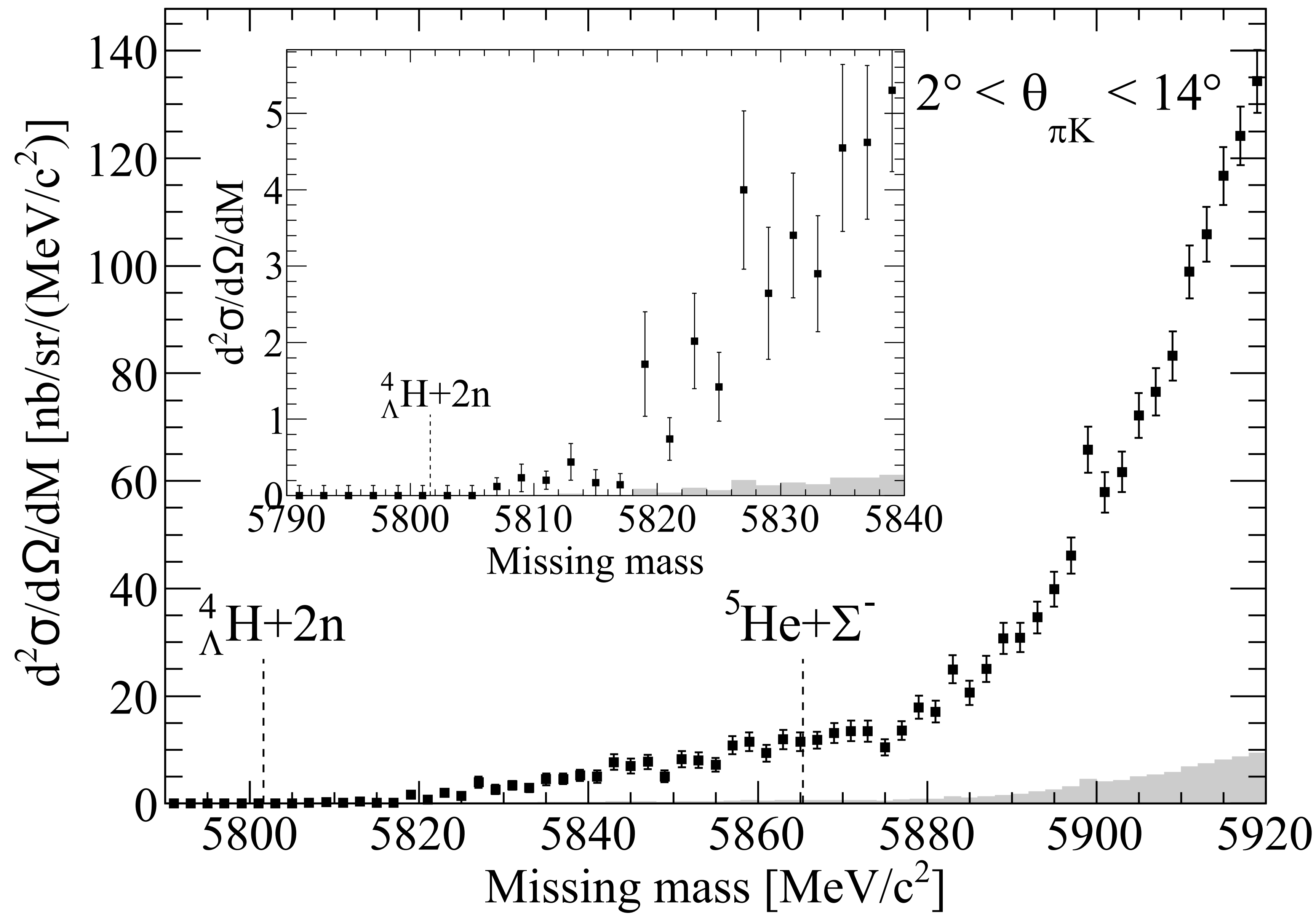
(b)



Comparison between experimental data
and theoretical calculations

T. Harada et al., Phys. Rev. C 79, 014603 (2009)

Recent result on $^{6}_{\Lambda}H$



R. Honda, et al., arXiv:1703.00623

We expect to achieve a comparable sensitivity in the (π^{-},π^{+}) measurement

Conclusion

- Candidate events of a resonant tetraneutron state were recently observed at SHARAQ/RIBF.
- Pion DCX reaction was utilized for populating neutron(proton)-rich nuclides.
- We propose to investigate a pion DCX reaction at J-PARC in search of tetraneutron (and ^{7}H, ^{9}He, trineutron).
    - at much higher energy (850MeV) than in past experiments (<200MeV)
    - starting from analog-transition measurement with a ^{18}O target, because of its large cross section.