January 31, 2017

Workshop on

Espace de Structure et de réactions Nucléaires Théorique

Revisiting 3n System
and
Possible New Measurements

H. Sakai

RIKEN Nishina Center

Aim

Fujita-Miyazawa(1957) 3NF

$$V(123) = -\frac{\mu}{(4\pi)^2}\left\{\delta_{ab}\left[a\,\mu - b\,\mu^3\ \boldsymbol{\nabla}_{23}\cdot\boldsymbol{\nabla}_{31}\right] + d\,\mu^3\ i\,\epsilon_{bac}\,\tau_c^{(2)}\ i\,\boldsymbol{\sigma}^{(2)}\cdot\boldsymbol{\nabla}_{23}\times\boldsymbol{\nabla}_{31}\right\}$$

$$\times\left\{\frac{g_A\,\mu}{2f_\pi}\,\tau_a^{(1)}\,\boldsymbol{\sigma}^{(1)}\cdot\boldsymbol{\nabla}_{13}\right\}\left\{\frac{g_A\,\mu}{2f_\pi}\,\tau_b^{(3)}\,\boldsymbol{\sigma}^{(3)}\cdot\boldsymbol{\nabla}_{23}\right\}\ Y(x_{23})\,Y(x_{31})$$

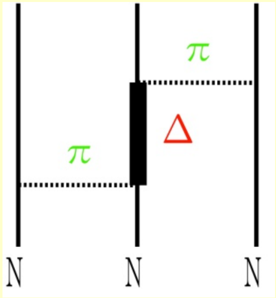
=0 for T=3/2

M.R. Robilotta (FM50)

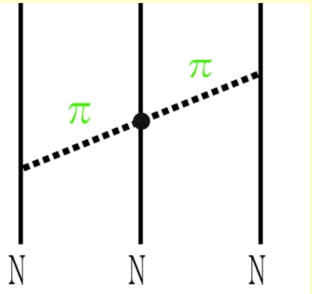
3NP	$a\,\mu$	$b\,\mu^3$	$c\,\mu^3$	$d\,\mu^3$
FM-57	-0.274	-1.237	0	-0.3091
O-77	-0.91	-0.81	0	-
TM-79	1.13	-2.58	-1.05	-0.75
BR-83	-1.05	-2.29	0	-0.77
TM'-93	-0.74	-2.53	0	-0.72
TM'-99	-1.12	-2.79	0	-0.75
Texas-99	-1.87	-3.82	0	-1.12

- **Most exp. studies are on T=1/2 3NF**
  - Due to experimental difficulties
- **Study on T=3/2 3NF via 3n system**
  - Are we sure for a- and b-terms?
- **Modern 3NF**
  - χPT (new structure appears)

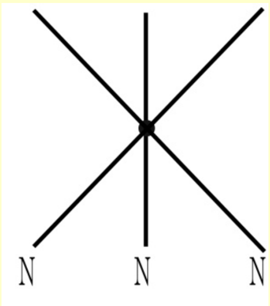
b, d **p-wave**



a **s-wave**



c



Brief history of ^{3}n search

Short list of 3n search

Author(1st)	Article	Reaction	Energy (E/A MeV)	Angle	3n	Comment
Fujikawa	NP A115(68)1	7Li(n,3n)	~40	integrated	No	Activation method
Koral	NP A175(71)156	7Li(n,3n)	19	38°>θ>4°	No	
Heavy-ion						
Cerny	RL 53B(74)247	7Li(7Li,11C)3n	11	10°	No	
Belozyorov	NP A477(88)131	7Li(11B,15O)3n	7	8°	No	
Pion DCX						
Sperinde	PL 32B(70)185	3He(π-,π+)3n	140	θ>15°	Yes	Er=13 MeV, Γ=12 MeV
Stetz	NPA457(86)669	3He(π-,π+)3n	120	θ>20°	No	
Yuly	PR C55(97)1848	3He(π-,π+)3n	240	θ>25°	No	
Graeter	EPJ A4(99)5	3He(π-,π+)3n	120	Integrated	No	
3p search						
Williams	PRL 23(69)156	3He(p,n)3p	50	θ>20°	Yes	Er=9 MeV, Γ=11 MeV

History of bound ^{3}n search by activation

2.A.1

Nuclear Physics **A115** (1968) 1—13; © *North-Holland Publishing Co., Amsterdam*

^{7}Li(p,xn)^{7}Be → ^{7}Li(n,^{3}n)^{5}Li → ^{138}Ba(^{3}n,n)^{140}Ba

- INS, UT
- Activation method
- No evidence found

SEARCH FOR TRI-NEUTRONS

K. FUJIKAWA † and H. MORINAGA

Department of Physics, University of Tokyo
Bunkyo-ku, Tokyo, Japan

Received 26 July 1967

Abstract: A search for bound tri-neutrons in the reaction ^{7}Li(n, ^{3}n)^{5}Li has been made with neutrons produced by a 55 MeV proton beam incident on a thick metallic lithium target. The detection of the tri-neutron was attempted with the reaction ^{138}Ba(^{3}n, n)^{140}Ba, whose yield of ^{140}La, the β-decay product of ^{140}Ba, was measured with a low-background counting apparatus. No evidence for the existence of the bound tri-neutron was found within the limits of experimental error. The upper limit was determined at 1 mb for the total cross section of the reaction ^{7}Li (n, ^{3}n)^{5}Li at the neutron energies $E_n \approx$ 14–19 MeV, where its values were expected to become the highest.

History of bound ^{3}n search by ^{7}Li(n,^{3}n)

1.B: 2.A.1

Nuclear Physics **A175** (1971) 156—166; *North-Holland Publishing Co., Amsterdam*

- **CWRU**
- **Van de Graaff**
- **No evidence found**

A SEARCH FOR THE BOUND TRINEUTRON FROM ^{7}Li+n REACTIONS

KENNETH F. KORAL †, E. A. SILVERSTEIN †† and P. R. BEVINGTON
Case Western Reserve University, Cleveland, Ohio †††

Received 18 May 1971

Abstract: A search was made for bound trineutrons produced by bombardment of a lithium target with 19 MeV neutrons. Direct detection of the trineutrons at forward reaction angles was attempted with a helium-recoil scintillator. Trineutrons could be partially separated from a background of neutrons by correlating the time of flight between target and detector with the pulse height produced by the recoiling ^{4}He ion. No evidence for the existence of a trineutron was found over a binding-energy range of $\approx$ 0 to 7 MeV. The upper limits for the differential and total cross sections are 0.1 mb/sr and 1 mb respectively for the reaction ^{7}Li(n, ^{3}n)^{5}Li and 0.8 mb/sr · MeV and 10 mb respectively for the reaction ^{7}Li(n, p)^{7}He. ^{7}He $\rightarrow$ ^{3}n+^{4}He.

$$^7\text{Li}+\text{n} \rightarrow {}^3\text{n}+{}^5\text{Li} \qquad Q = -12.9 \text{ M}$$

$$^7\text{Li}+\text{n} \rightarrow {}^7\text{He}+\text{p} \qquad Q = -10.4 \text{ M}$$

$$\hookrightarrow {}^3\text{n}+{}^4\text{He} \qquad Q = -\ 0.53 \text{ M}$$

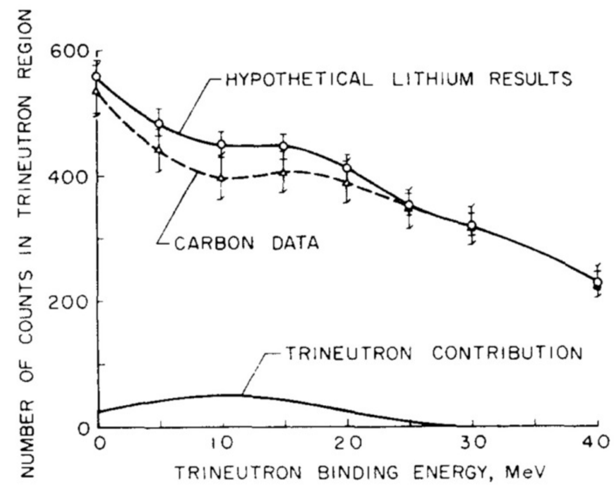


Fig. 7. Hypothetical results with minimum number of trineutrons that produces a discernible difference between the carbon and lithium data for the one-step reaction.

History of ^3n resonance search by $^7Li(^{11}B,^{15}O)$

NP A477(88)131

SEARCH FOR THE TRI- AND TETRA-NEUTRON IN REACTIONS INDUCED BY ^{11}B AND ^{9}Be IONS ON ^{7}Li

A. V. BELOZYOROV, C. BORCEA, Z. DLOUHÝ, A. M. KALININ, NGUYEN HOAI CHAU,

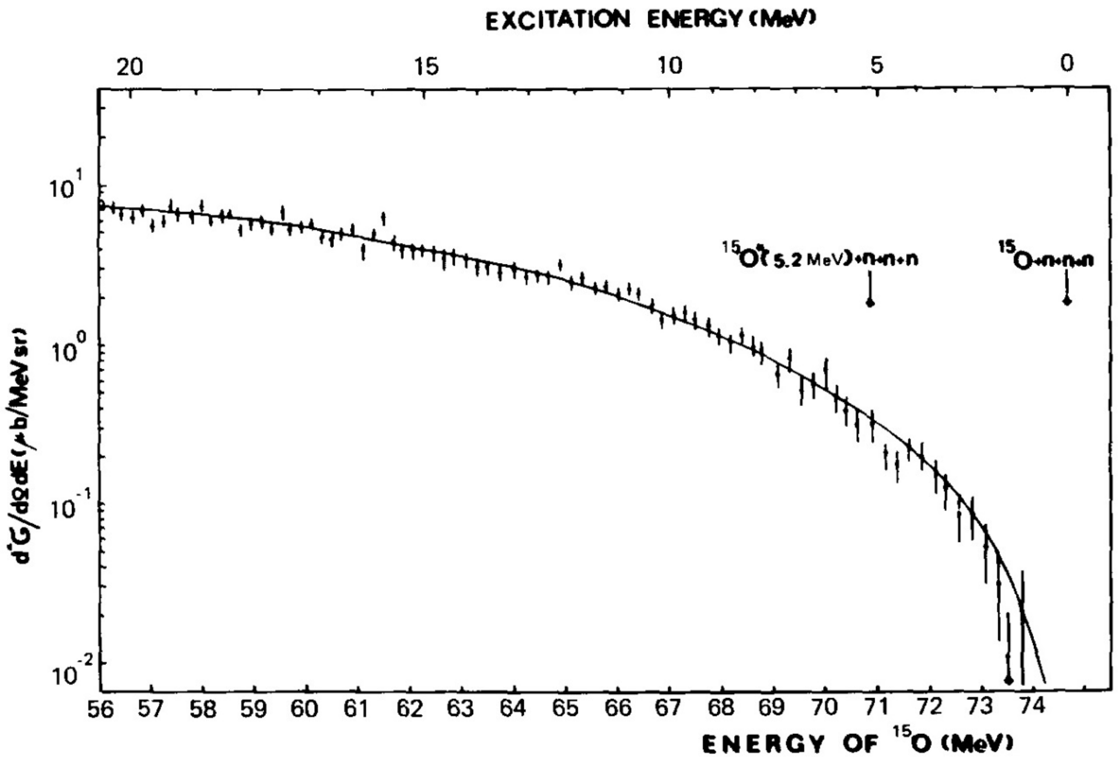


Fig. 3. The ^{15}O energy spectrum for the ^{7}Li(^{11}B, ^{15}O)^{3}n reaction. The full curve is a phase-space calculation that takes into account the following exit channels: ^{15}O + n + n + n and ^{15}O* (E_x = 5.183 MeV) + n + n + n.

- **DUBNA**
- **$^7Li(^{11}B,^{15}O)^3n$**
- **$E(^{11}B)$=88 MeV (low E)**
- **θ =8° (large angle)**
- **MSP-144(mag. Spectr.)**
- **No evidence**

History of ^{3}n resonance search by ^{3}He(π-,π+)

PL 32B(70)185

EVIDENCE FOR A LOW-ENERGY RESONANCE IN THE THREE-NEUTRON SYSTEM *

J. SPERINDE, D. FREDRICKSON, R. HINKINS, V. PEREZ-MENDEZ and B. SMITH
Lawrence Radiation Laboratory, University of California, Berkeley, California, USA

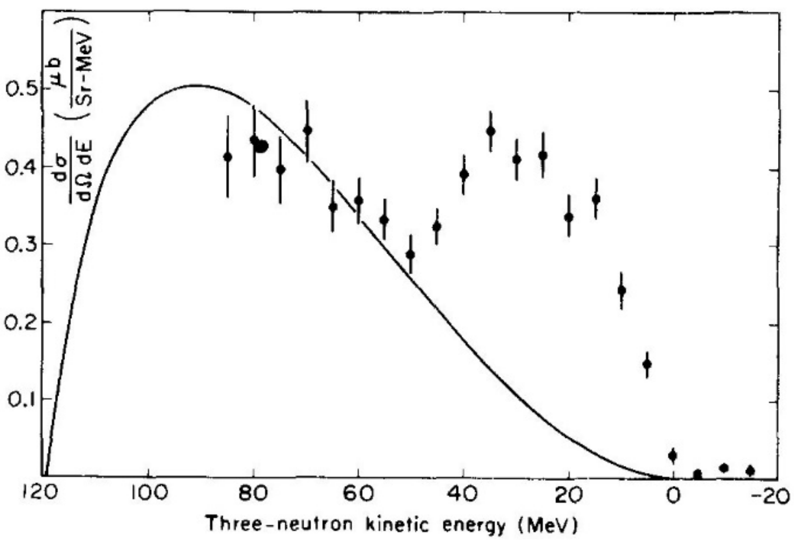


Fig. 1. Differential cross section for the reaction $\pi^- + {}^3He \rightarrow \pi^+ + 3n$ as a function of the kinetic energy of the three-neutron system. The solid line represents four-body phase space normalized to the data in the energy range of 50 to 85 MeV.

- LRL, Barkeley
- 3He(π-,π+)3n
- E(π-)=140 MeV
- θ > 15°
- Evidence Yes
  Er=13 MeV, Γ=12 MeV

History of ^{3}n resonance search by ^{3}He(π-,π+)

NP A457(1986)669

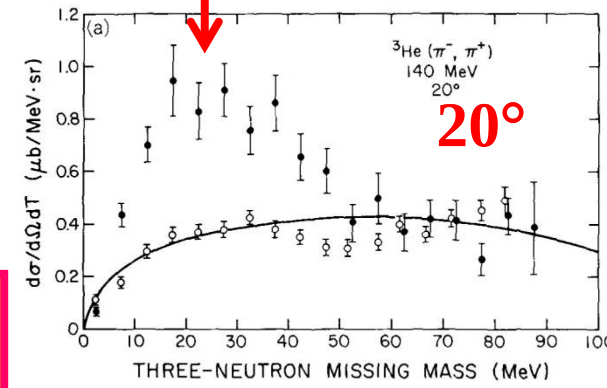
PION DOUBLE CHARGE EXCHANGE ON ^{3}He AND ^{4}He

A. STETZ and L.W. SWENSON

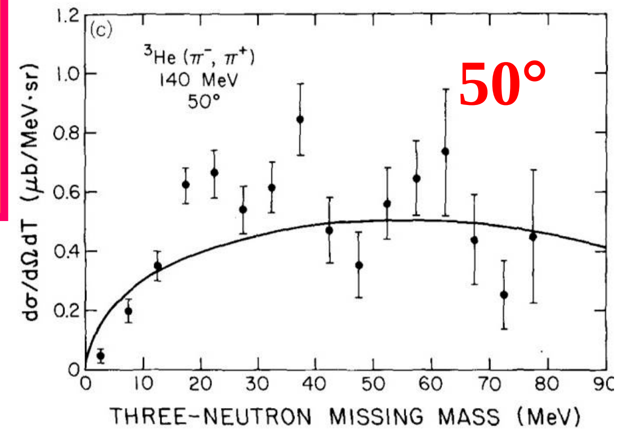
Oregon State University, Corvallis, OR 97331, USA

Abstract: We have measured the differential cross section $d^2\sigma/d\Omega\, dT$ for the double charge exchange reactions ^{4}He(π^+, π^-)4p and ^{3}He(π^-, π^+)3n at 140, 200 and 295 MeV. By fitting this data with a simple phase-space model we have estimated the integrated cross section $d\sigma/d\Omega$ and the total cross section. The ^{4}He data agree qualitatively with the predictions of a meson exchange calculation and with one version of the successive single charge exchange model. The ^{3}He cross sections are considerably larger than those of ^{4}He and in some cases the missing mass plot shows a strong enhancement, which resembles a broad three-nucleon resonance.

q~180 MeV/c



- LAMPF
- EPICS spect.
- E(π-)=140-295 MeV
- θ > 20 degrees
- Evidence ?



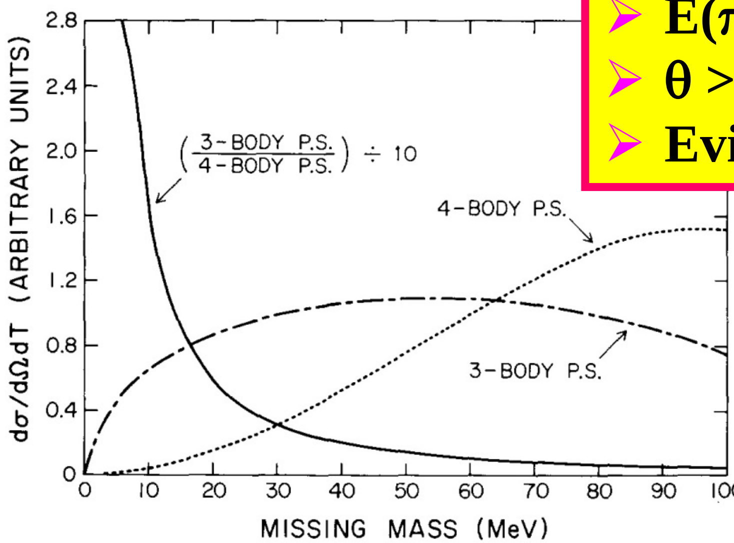


Fig. 6. Three-body (two nucleons and a pion) and four-body (three nucleons and pion) phase space distributions for $d^2\sigma/d\Omega_{c.m.}\, dT$. The two dashed curves are calculated for an incident energy of 140 MeV and normalized to the same total area. The solid curve is the quotient of the two phase space distributions scaled down by 10^{-1}.

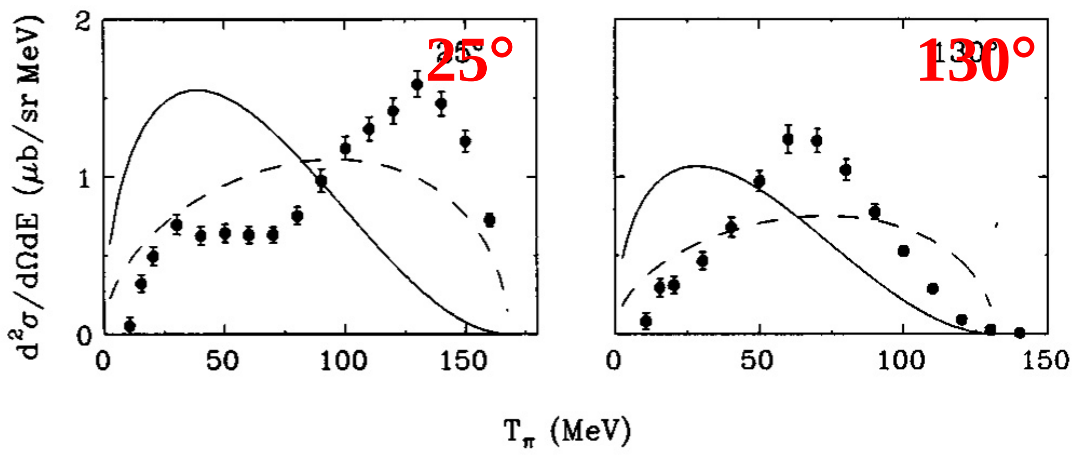
- 3B-PS:n-n-π (Why not n-n-n?)
- 4B-FS:n-n-n-π

History of ^{3}n resonance search by ^{3}He(π-,π+)

PHYSICAL REVIEW C VOLUME 55, NUMBER 4 APRIL 1997

Pion double charge exchange and inelastic scattering on ^{3}He

M. Yuly,* W. Fong,† E. R. Kinney,‡ C. J. Maher,§ J. L. Matthews, T. Soos,‖ J. Vail,¶ M. Y. Wang,** and S. A. Wood††



- LAMPF
- EPICS spect.
- θ > 25 degrees
- E(π-)=120-240 MeV
- No evidence

FIG. 9. A comparison of doubly differential cross sections for ^{3}He(π^-,π^+) with the prediction of three-body (dashed line) and four-body (solid line) phase space at 180 MeV for laboratory angles 25° and 130°. The phase space predictions have been normalized to have the same singly differential cross section as the data. The uncertainty indicated includes the statistical uncertainty and the systematic uncertainties which depend on the outgoing pion energy.

History of bound ^{3}n search ^{3}He(π-,π+)

Graeter et al., EPJ A4(99)5

Short note

Search for a bound trineutron with the ^{3}He(π^-,π^+)nnn reaction

J. Gräter[1], P. A. Amaudruz[2], R. Bilger[1], P. Camerini[3], J. Clark[4], H. Clement[1], E. Friedman[5], L. Felawka[2],

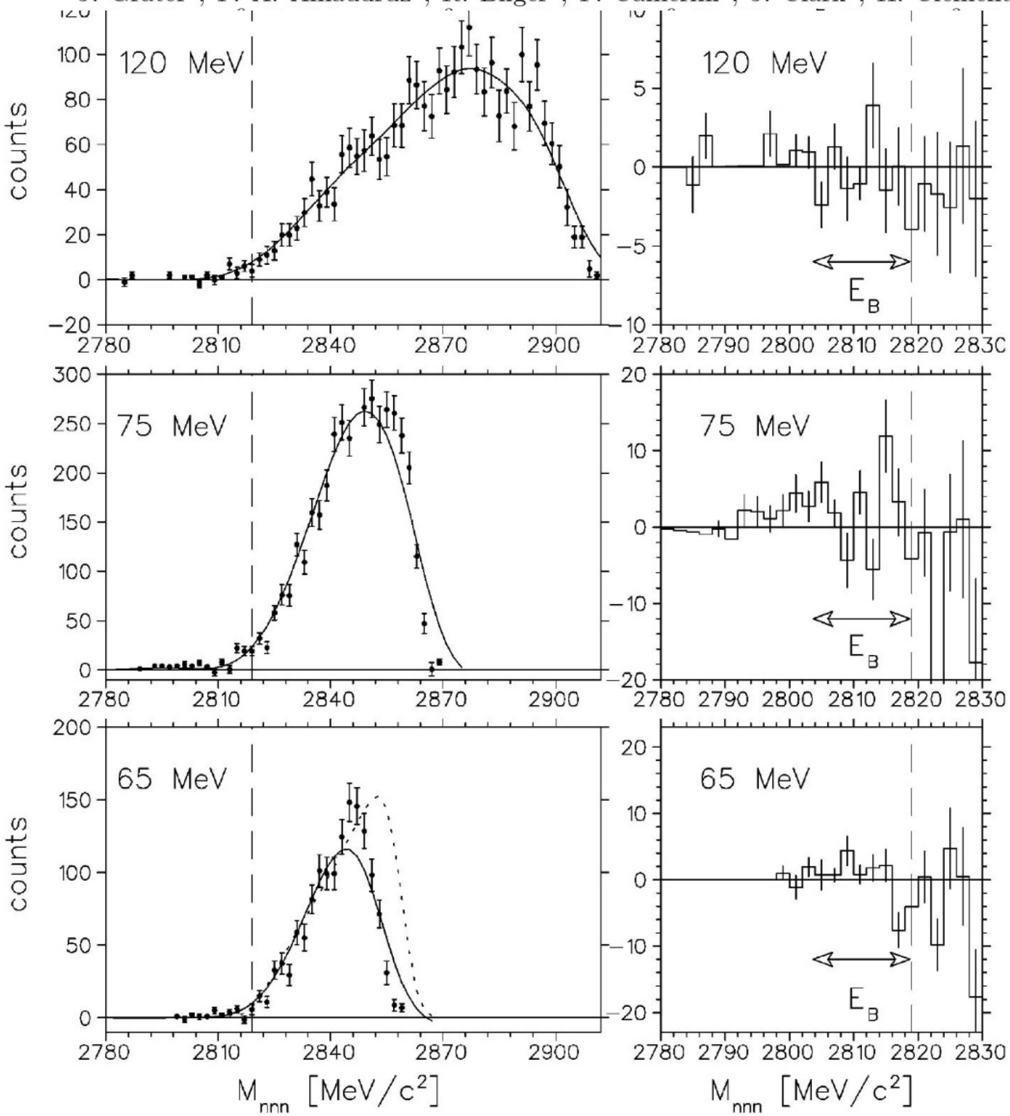


Fig. 1. Invariant mass of the three-neutron system. Left: Experimental data points. The dashed line indicates the kinematical limit of three unbound neutrons. The solid lines are cubic spline fits that are used to approximate the contribution from unbound neutrons in the kinematically forbidden region. The dotted curve represents a 4-body phase space distribution. See text for details. Right: Difference of experimental data and the fitted contribution of unbound neutrons

- TRIUMF
- E(π)<120 MeV
- CHAOS spect. Angle integrated
- No evidence found

History of unbound ^{3}Li(3p) search by ^{3}He(p,n)^{3}Li

VOLUME 23, NUMBER 20 PHYSICAL REVIEW LETTERS 17 NOVEMBER 1969

EVIDENCE FOR BROAD RESONANCES IN THE THREE-NUCLEON SYSTEM

L. E. Williams,* C. J. Batty, B. E. Bonner, and C. Tschalär
Rutherford High Energy Laboratory, Chilton, Didcot, England

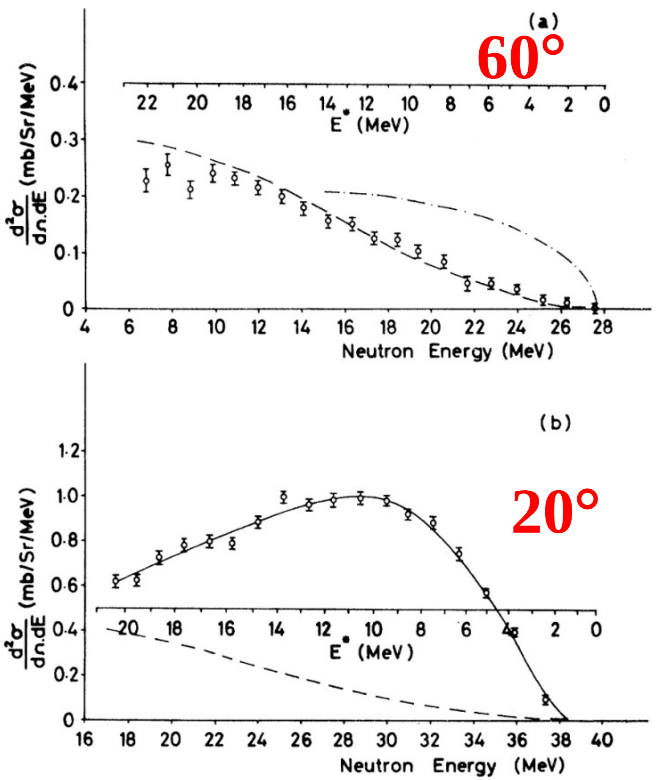


FIG. 1. Neutron spectra observed for the reaction ^{3}He(p,n)3p. The incident energy was 48.8 MeV and the neutron angles were (a) 60°, (b) 20°. The dashed curve is the calculated four-body phase-space distribution normalized to the spectrum measured in (a). The dash-dot curve gives the results of a three-body phase-space calculation.

- Rutherford HEL
- N-TOF
- E=50 MeV (low)
- Large θ
- Evidence **Yes**

  E_r=9 MeV, Γ=11 MeV

Review on $^3n/^3Li(3p)$ studies

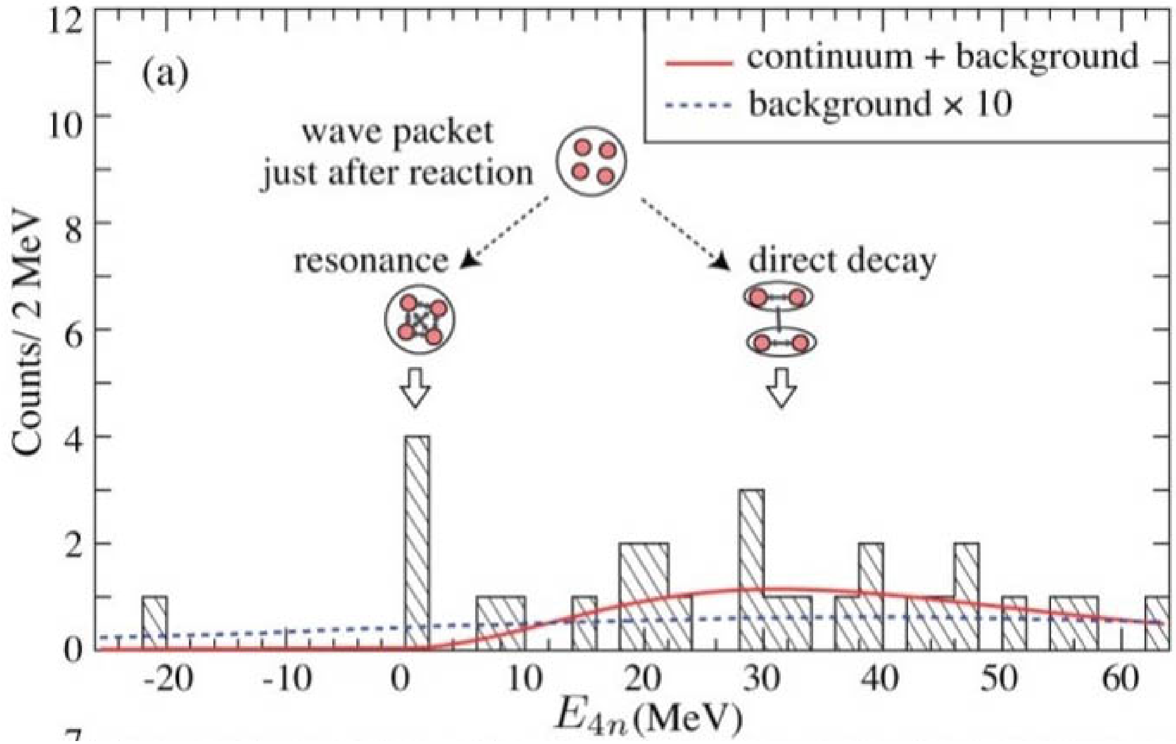
1. Works done mostly in the last century
2. No bound state found
3. Unbound (contradicting results)
4. No clear evidence of resonance
5. Experiments suffer from:
   - Small bombarding-energy
     →complex reaction mechanism
   - Large scattering angle
     →large momentum transfer
     q>180 MeV/c for (π-,π+)

Recent new development

1. Tetra-neutron observed
2. Suggestion of $^{3}Li(3p)$ resonance
3. Theoretical prediction

Observation of Tetraneutron

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



- Why ^{4}n was successfully observed ? or
- What is different from preceding researches ?

⇒ Exothermic charge-exchange reaction at θ=0.

Observation of Tri-proton ^{3}Li(3p) resonance

PHYSICAL REVIEW C **77**, 054611 (2008)

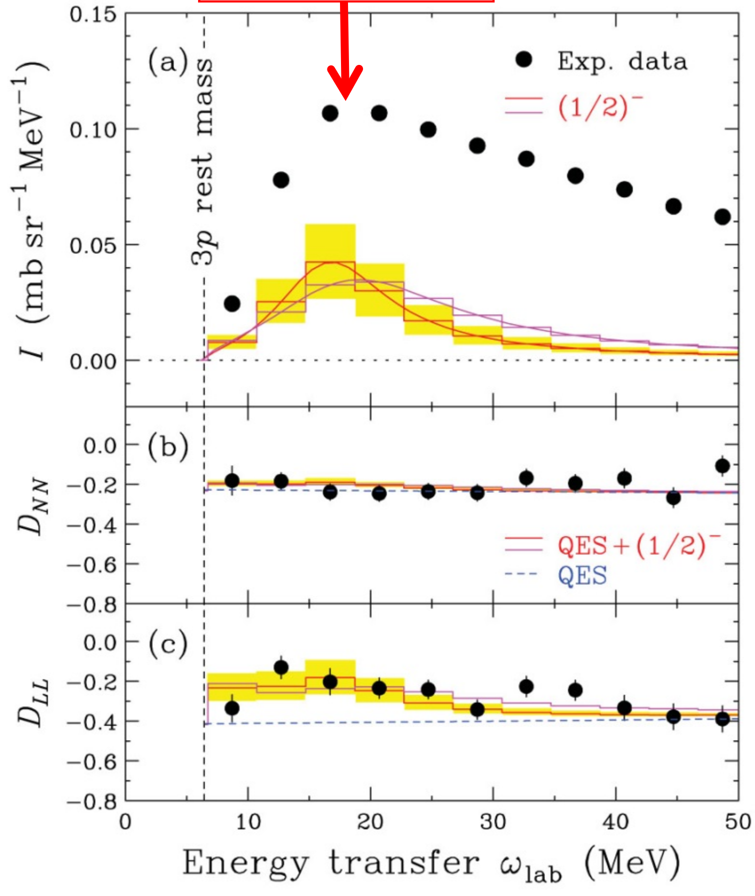
Complete set of polarization transfer coefficients for the ^{3}He(p, n) reaction at 346 MeV and 0 degrees

T. Wakasa,[1,*] E. Ihara,[1] M. Dozono,[1] K. Hatanaka,[2] T. Imamura,[1] M. Kato,[2] S. Kuroita,[1] H. Matsubara,[2] T. Noro,[1] H. Okamura,[2] K. Sagara,[1] Y. Sakemi,[3] K. Sekiguchi,[4] K. Suda,[2] T. Sueta,[1] Y. Tameshige,[2] A. Tamii,[2] H. Tanabe,[1] and Y. Yamada[1]

- ^{3}He(p,n)^{3}Li at 345 MeV
- θ=0 degrees
- Polarization transfer(PT) D_{LL} & D_{NN}

^{3}Li(3p) quasi-resonance state
- Ex=9±1 MeV
- Γ=10.5±1 MeV

q~30 MeV/c



- Candidate of 3p resonance deduced by PT
- Result similar to Williams (PRL 23(1969))

⇒ But still marginal

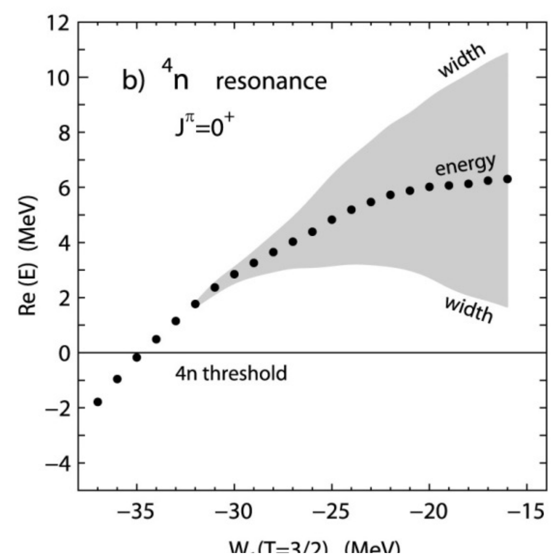
Hiyama-san's prediction

Hiyama, *et al.*, Phys. Rev. C 93, 044004 (2016).

- **Solve 4 body eq. (Faddeev-Yakubovski eq.)**
- **2NF ; reproduce various data of stable nuclei**
- **3NF ; T=1/2, -2.04 MeV**
  T=3/2, free parameter

- **Require unrealistically strong T=3/2 3NF to reproduce experimental result.**
- **W(T=3/2) ~17 ×W(T=1/2) !!**

- **For 3n resonance:**
  with W(T=3/2) ~17 ×W(T=1/2)
  E_R~4 MeV, Γ~4 MeV
  $J^\pi=1/2^-$ and/or $3/2^-$



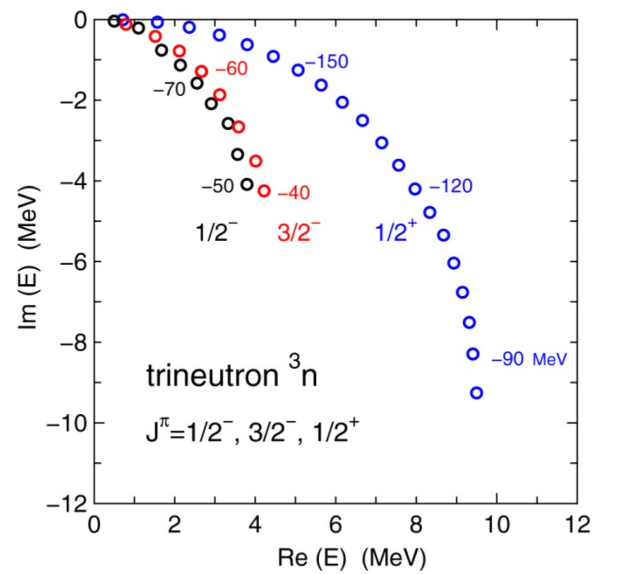


FIG. 8. Trineutron ^3n resonance trajectories for $J = 3/2^-, 1/2^-$, and $1/2^+$ states. The circles correspond to resonance positions for $W_1(T = 3/2)$ from −75 to −40 MeV for $J = 3/2^-$, from −90 to −50 MeV for $J = 1/2^-$, and from −180 to −85 MeV for $J = 1/2^+$ in steps of 5 MeV.

Gandolfi, Schwenk *et al.*'s prediction

arXiv 1612.01502

Is a trineutron resonance lower in energy than a tetraneutron resonance?

S. Gandolfi,[1,*] H.-W. Hammer,[2,3,†] P. Klos,[2,3,‡] J. E. Lynn,[2,3,§] and A. Schwenk[2,3,4,¶]

Very exotic & challenging prediction !

$$H = -\sum_i \frac{\hbar^2}{2m}\nabla_i^2 + \sum_i V_{WS}(r_i) + \sum_{i<j} V_{ij} + \sum_{i<j<k} V_{ijk}$$

- χEFT
- N2LO (2NF+3NF)
- AFDMC method
- Extrapolated to V_0=0

3n : E_R~1.1 MeV, Γ=? MeV, J^π=?
4n : E_R~2.1 MeV, Γ=? MeV, J^π=0^+?

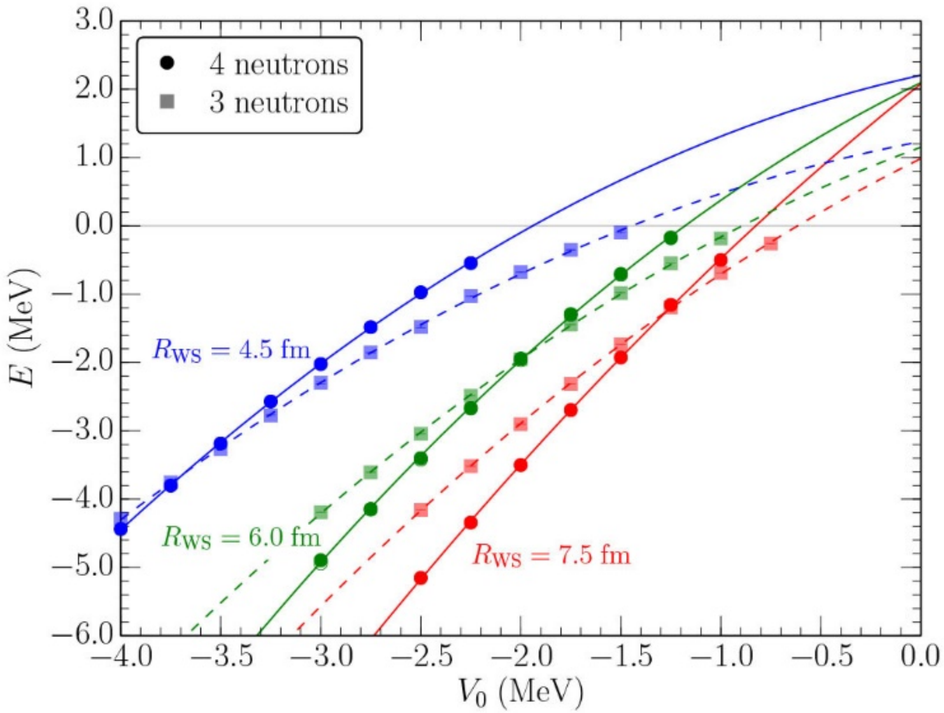


FIG. 1. The energy of three (squares) and four (circles) neutrons in external Woods-Saxon potentials for varying radius R_{WS} as a function of the well depth V_0. The blue/upper lines correspond to R_{WS} = 4.5 fm, the green/middle lines to R_{WS} = 6 fm, and the red/lower lines to R_{WS} = 7.5 fm. In each case, a quadratic fit to the AFDMC results was obtained and used to extrapolate to the zero-well-depth limit.

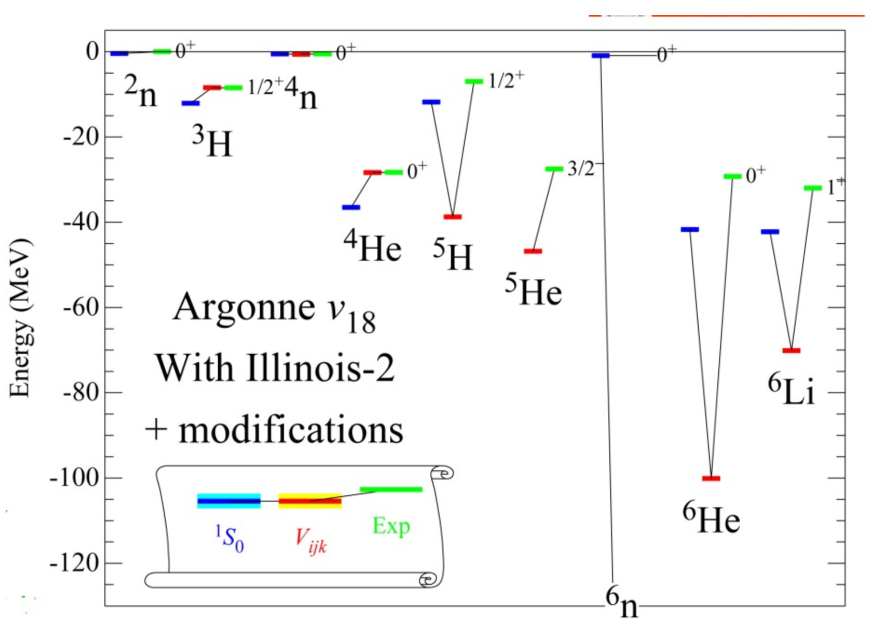
Revisit of theoretical wisdom

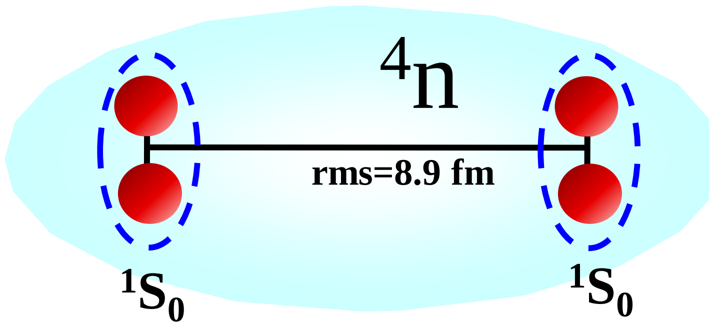
Steven Pieper's prediction

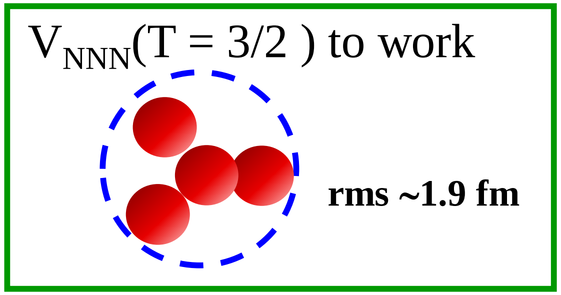
- S.C. Pieper, Phys. Rev. Lett. 90, 252501 (2003)

> - *A bound ^4n is incompatible with our understanding of nuclear forces.*
> - V_{NN} acts pairwise; pairs typically very far apart. rms radius = 8.9 fm
> - ^4n looks like two well separated ^2n (dimer-dimer coupling)
> - V_{NNN} requires triples to be close together. rms radius = 1.9 fm
> - Then $V_{NNN}(T = 3/2)$ should work

⇒same conclusion by Hiyama-san







How to create the 'close together' condition?

It may be worthwhile to attack tri-neutron search again

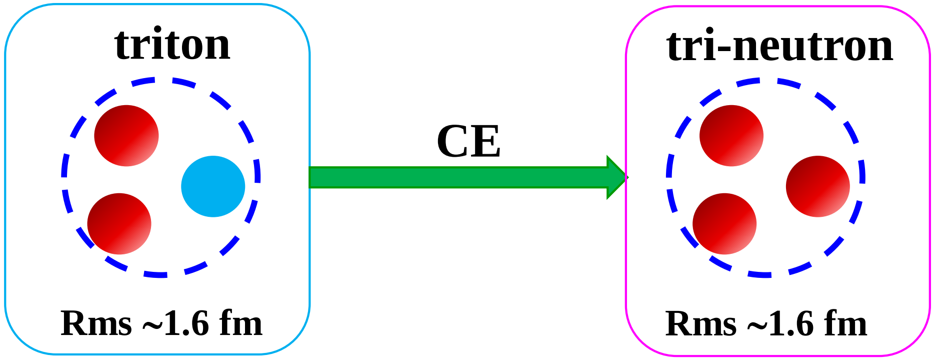
by the

Exothermic Charge-Exchange reaction

My very biased view (1)

For success of tri-neutron state observation (same as the tetra-neutron search)

- **Realize 'close together (CT)' condition**
  ⇒utilize the charge-exchange (CE) reaction



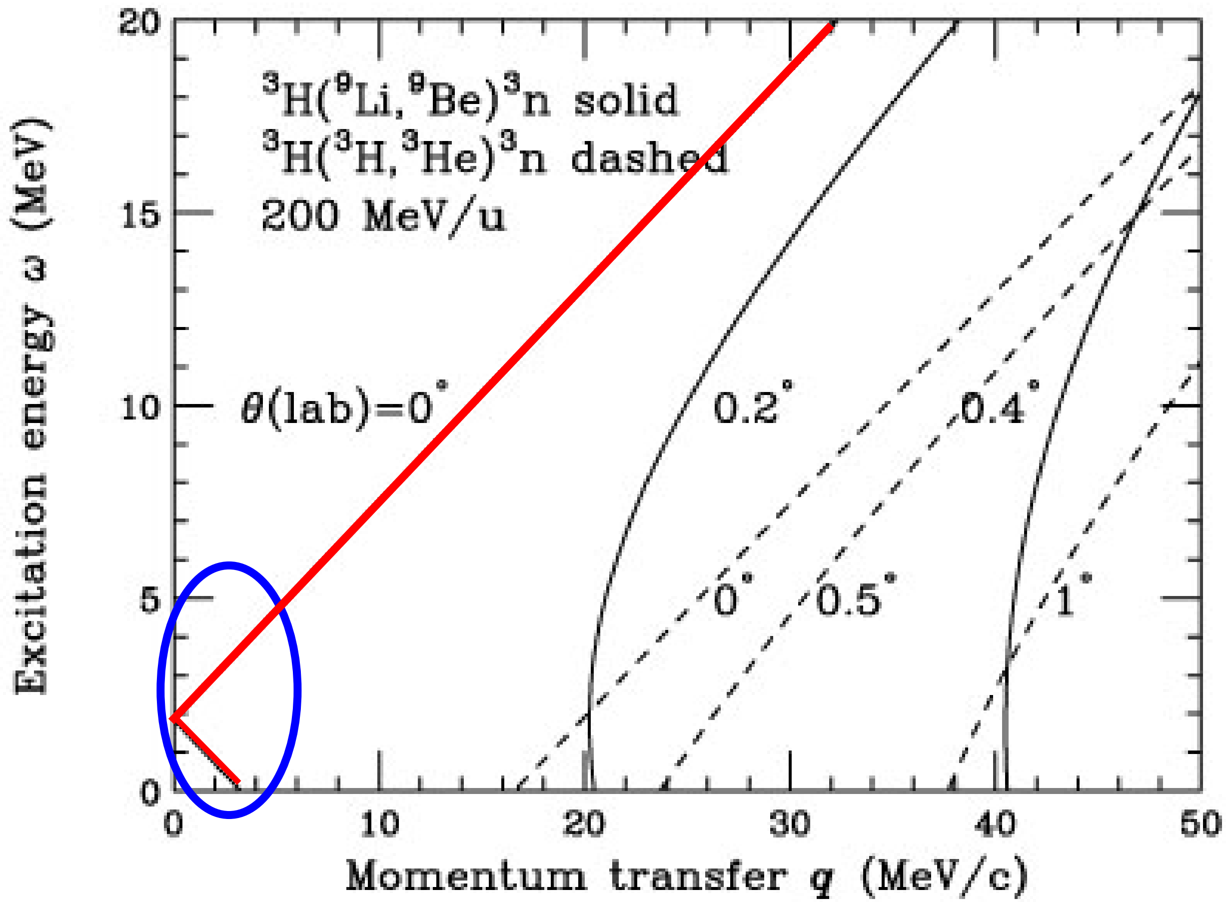
Keeps the size!

⇒Satisfy CT condition

My very biased view (2)

- **Create ‘at rest (AR)’ =‘Recoilless’ condition in lab. to help 3NF to operate ⇒utilize the exothermic CE reaction to achieve q=0**

My choice : (^{9}Li,^{9}Be) reaction △*m*=+13.6 MeV



***q*: momentum transfer in lab. system**

ω: excitation energy of ^{3}n

How the exo. CE reaction chosen?

Charge-exchange(CE) (a,b) reaction

- (a,b) must be in isobar relation
- (a,b) should be (n,p)/β+ type
- 'b' should not have an excited state

- Exothermic $m_a - m_b > +10$ MeV
  - $m(^3H) - m(3n)$=--10 MeV

Choice

- $^3H(^9Li,^9Be)^3n$ 1st choice
  - $m_a - m_b = +13.6$ MeV
  - Q=+4.4 MeV

- $^3H(^3H,^3He)^3n$ 2nd choice
  - Q=–9.2 MeV

Here, only SCE reaction considered.

Particle mass	Spin-parity	M-A (MeV)	Excited state
p	$1/2^+$	7.28	No
n	$1/2^+$	8.07	No
^3n	$(1/2^-)$?	24.21	
^{3}H	$1/2^+$	14.95	No
^{3}He	$1/2^+$	14.93	No
^{3}Li	$1/2^-$	21.84	
^{6}He	0^+	17.60	No
^{6}Li	1^+	14.09	Few
^{7}Li	$3/2^-$	14.91	Few
^{7}Be	$3/2^-$	15.58	Few
^{8}He	0^+	31.61	No
^{8}Li	2^+	20.9	Few
^{8}Be	0^+	4.9	'No' $\to 2\alpha$
^{8}B	2^+	22.92	Few
^{9}Li	$3/2^-$	24.95	Few
^{9}Be	$3/2^-$	11.35	No
^{9}B	$3/2^-$	12.41	Not stable
^{9}C	$3/2^-$	28.91	No
^{10}Be	0^+	12.61	Few
^{10}B	3^+	12.05	Few
^{10}C	0^+	15.70	Few
^{11}Li	$3/2^-$	40.80	No
^{11}Be	$1/2^+$	20.17	$1/2^-$(0.32 MeV)
^{11}B	$3/2^-$	8.67	Many
^{11}C	$3/2^-$	10.65	Many

Candidate of Exothermic CE reaction to satisfy CT & AR conditions:

^{3}H(^{9}Li,^{9}Be)3n reaction

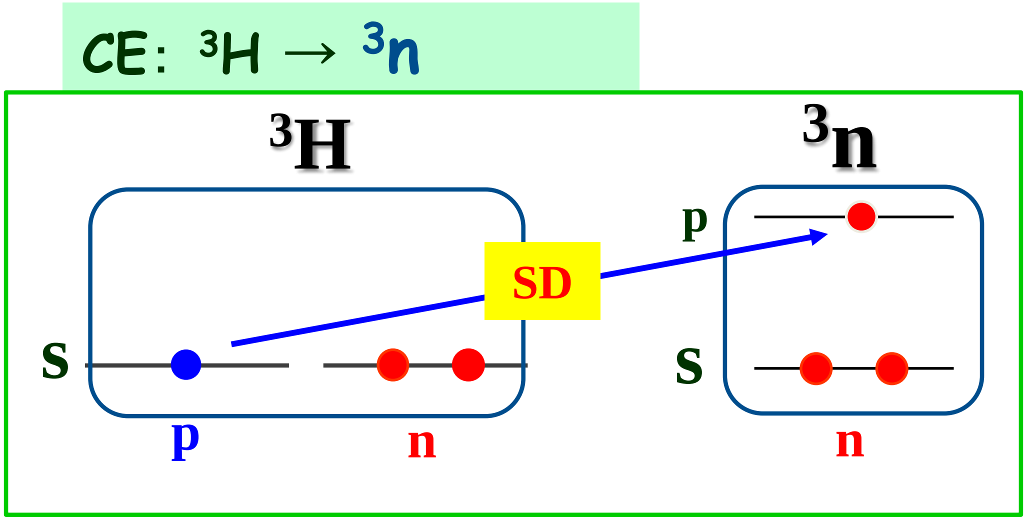
$\triangle m(m_{9Li}-m_{9Be}) = +13.6$ MeV

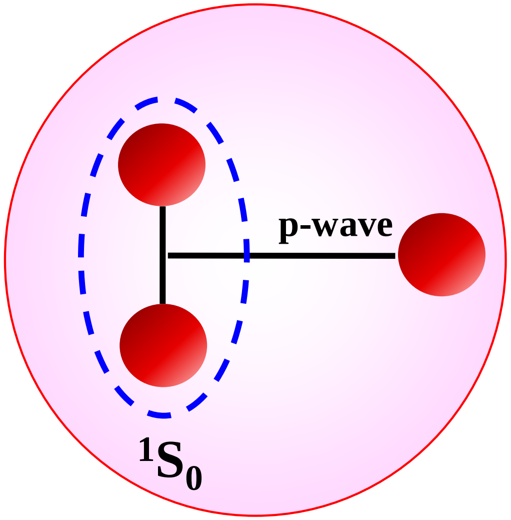
Q = + 4.4 MeV

$\theta = 0°$ (q~0)

Requires unstable ^{9}Li beam & tritium target

Transition and structure of ^3n





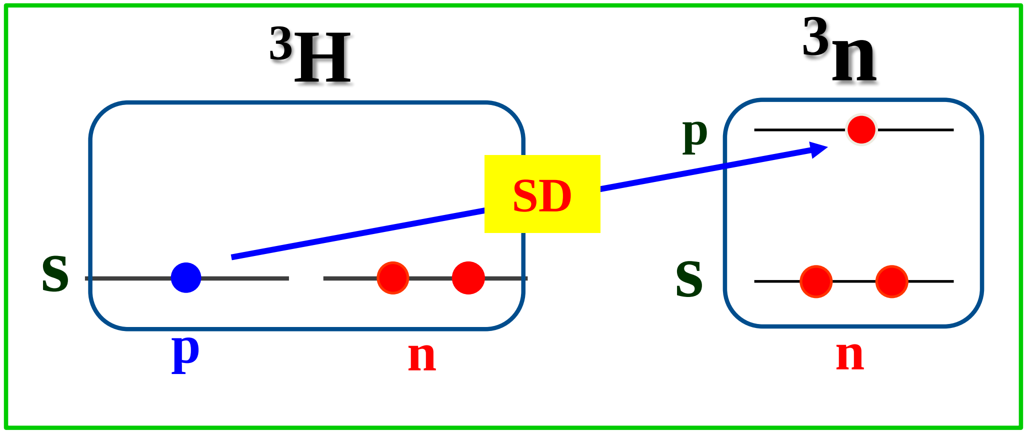
$J^{\pi}(^3n)$: $3/2^-$ or $1/2^-$ or …

Wakasa assigned as $1/2^-$

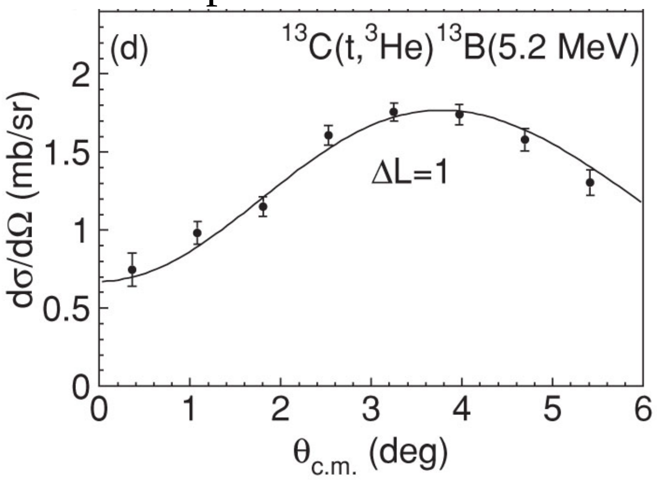
- Transition: $^3H(1/2+) \rightarrow {}^3n(1/2\text{- or }3/2\text{-})$
  ⇒spin-dipole type $\Delta L=1$

Angular momentum transfer

- $^3H/^3He(1/2+) \rightarrow {}^3n(1/2-$ or $3/2-)$: $\Delta L=1$



Example of SD



Max at around qR~2 → q=finite !

q (fm^{-1})	realization	$<\phi(^3n(q))\|\Phi(3n)>$	^3n obs. possibility
~ 0	recoil-less	large ?	small but finite ?
~ 0.5	$\ell_{tr} = 1$	small ?	broken up ?

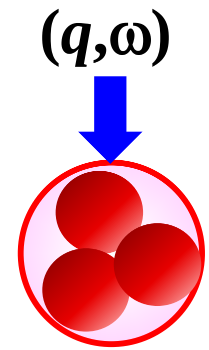
NOT compatible !

My biased choice is the recoil-less condition.
I need a distortion by an imaginary OP.

Largest issue is BG yield around ^3n resonance region.

3n "resonance" and QFS background

- Hiyama-san's prediction → Peak ω~ 4 MeV, Γ ~ ±4 MeV

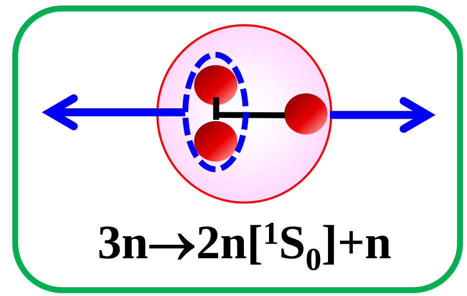


- QFS background: Shimoura-Ichimura analytic expression

$$\frac{d\sigma}{d\Omega}(\omega) \propto \left|F^{proj}(q_{cm})\right|^2 \cdot \left|\mathrm{v}(q_{cm})\right|^2 \cdot P(\omega, q_{cm})_{\mathrm{3body/2body}}$$

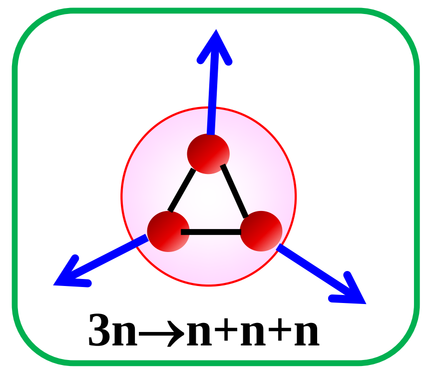
➤ **Two-body decay**

$$P(\omega, q_{cm})_{\mathrm{2body}} = \frac{2}{\sqrt{\pi}} \frac{1}{\varepsilon_a} (q_{cm} a)^2 \left(\frac{\omega - \omega_{\mathrm{bnd}}}{\varepsilon_a}\right)^{\frac{3}{2}} \exp\left(-\frac{\omega - \omega_{\mathrm{bnd}}}{\varepsilon_a}\right)$$



➤ **Three-body decay**

$$P(\omega, q_{cm})_{\mathrm{3body}} = \frac{1}{36} \frac{1}{\varepsilon_a} (q_{cm} a)^2 \left(\frac{\omega}{\varepsilon_a}\right)^3 \exp\left(-\frac{\omega}{\varepsilon_a}\right)$$



$$\rho_{3n}(r) \propto \exp\left[-3\left(\frac{r}{\mathrm{a}}\right)^2\right] \qquad \varepsilon_a = \frac{\hbar^2}{m_N a^2}$$

$a(^3\mathrm{H}) = 2.21\ \mathrm{fm}$

3n "resonance" and QFS background

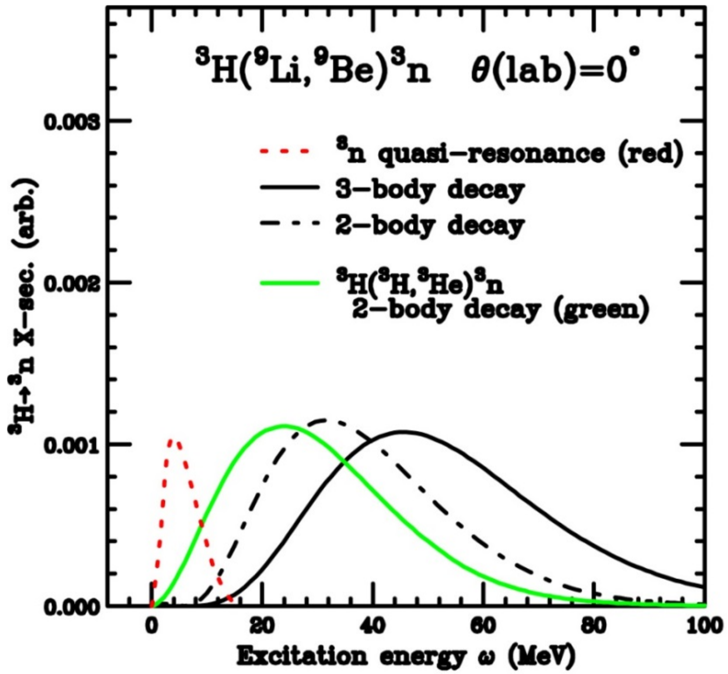
- QFS background: Ichimura-san's analytic expression

$$\frac{d\sigma}{d\Omega}(\omega) \propto \left|F^{proj}(q_{cm})\right|^2 \cdot \left|v(q_{cm})\right|^2 \cdot P(\omega, q_{cm})_{3body/2body}$$

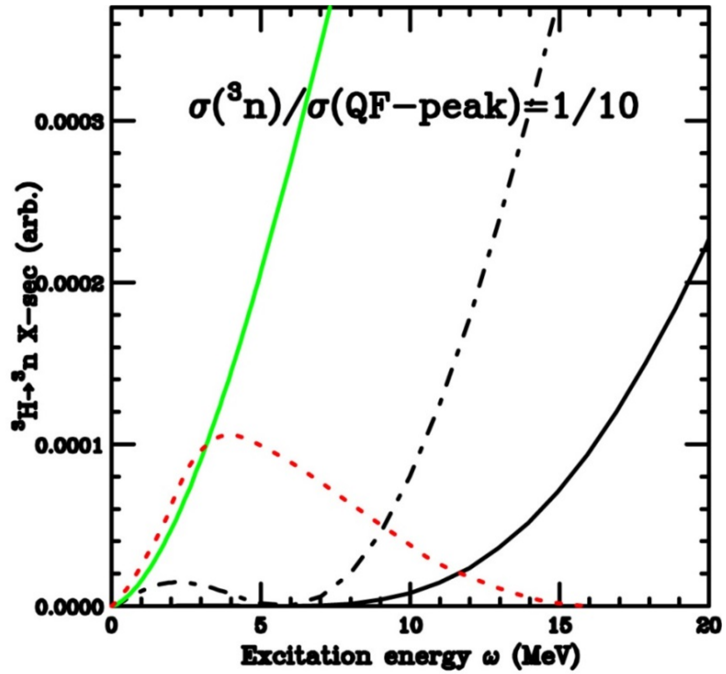
↳ =1 (assumed)

↳ Love-Franey |t(qcm)| matrix

S/N=1/1



S/N=1/10



Shows excellent S/N for the exothermic CE at 0°.
If the BG is due to 2-body decay, $^3H(^3H,^3He)^3n$ may be difficult.

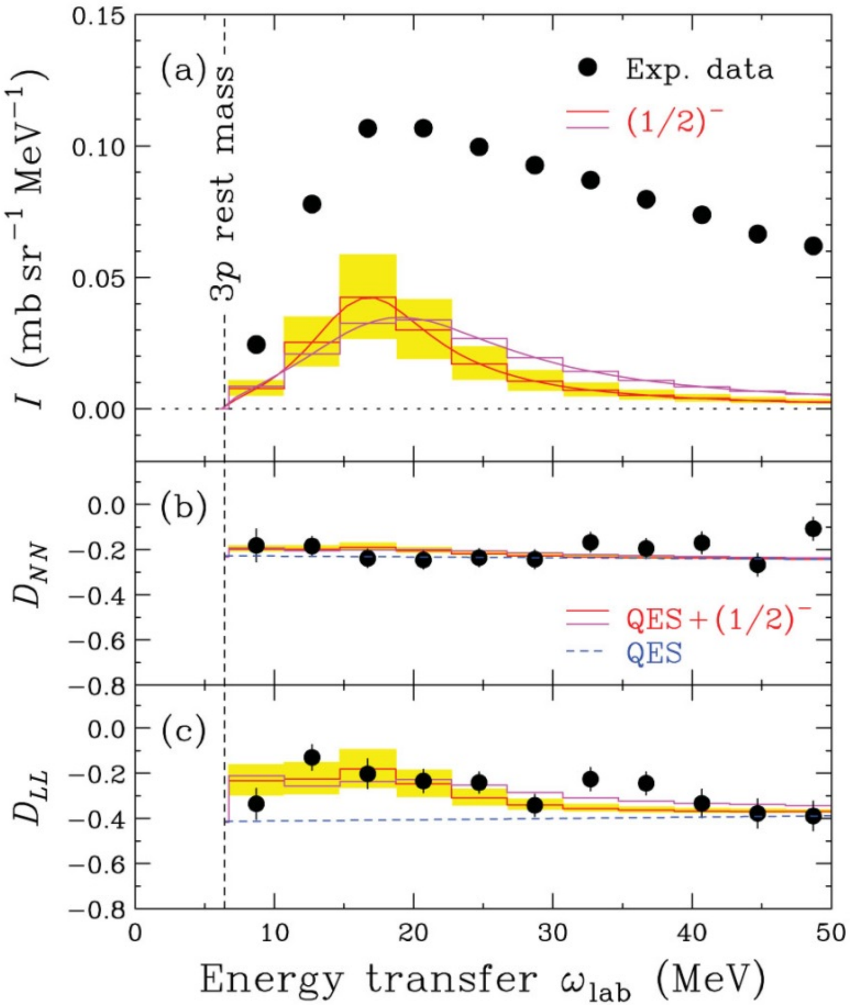
Comparison to ^{3}Li (3p) data

PHYSICAL REVIEW C **77**, 054611 (2008)

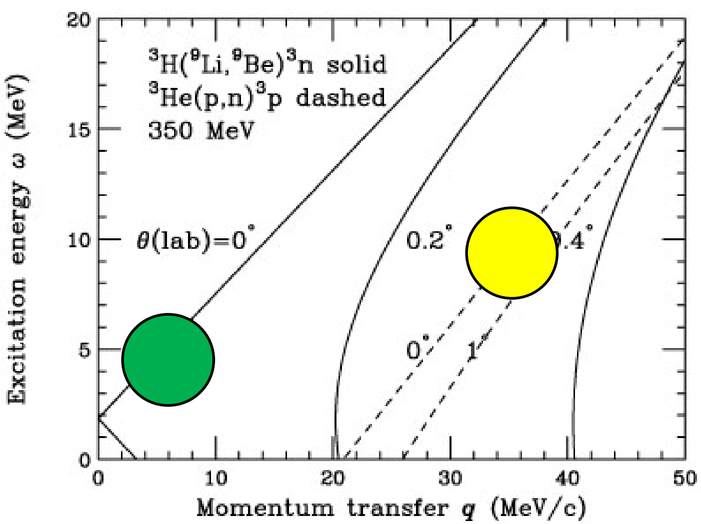
Complete set of polarization transfer coefficients for the ^{3}He(p, n) reaction at 346 MeV and 0 degrees

T. Wakasa,[1,*] E. Ihara,[1] M. Dozono,[1] K. Hatanaka,[2] T. Imamura,[1] M. Kato,[2] S. Kuroita,[1] H. Matsubara,[2] T. Noro,[1] H. Okamura,[2] K. Sagara,[1] Y. Sakemi,[3] K. Sekiguchi,[4] K. Suda,[2] T. Sueta,[1] Y. Tameshige,[2] A. Tamii,[2] H. Tanabe,[1] and Y. Yamada[1]

3Li(3p) "resonance" data by Wakasa et al.



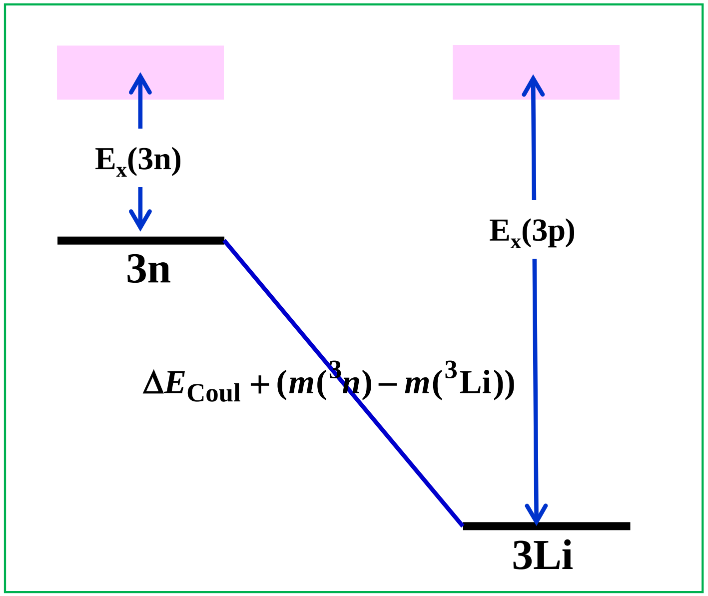
^{3}Li(3p) quasi-resonance state
- Ex=9±1 MeV
- Γ=10.5±1 MeV



q-transfer:
^{3}Li → ~35 MeV/c
3n → ~5 MeV/c

Isobaric analog relation

$$E_{\rm Coul} = \frac{3}{5}\frac{Z^2e^2}{R}$$
$$= \frac{3}{5}\times\frac{198}{137}\frac{Z^2e^2}{R} = 0.87\frac{Z^2}{R} = 0.87\frac{9}{2}$$
$$= 3.9\ \text{MeV}$$



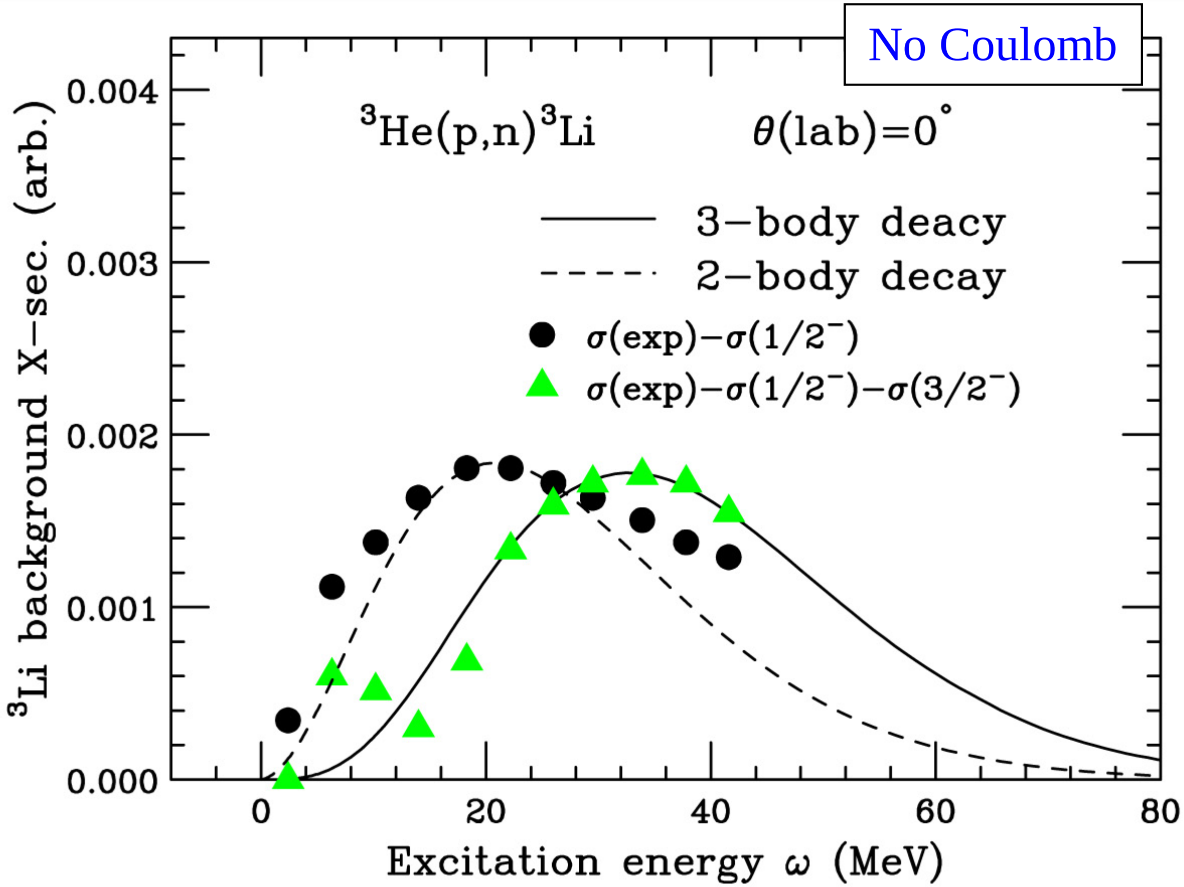
$$E_x(^3{\rm Li}) = E_x(^3n) + \Delta E_{\rm Coul} + (m(^3n) - m(^3{\rm Li})) = 4 + 3.9 + 2.4 = 10.3\ \ \text{MeV}$$

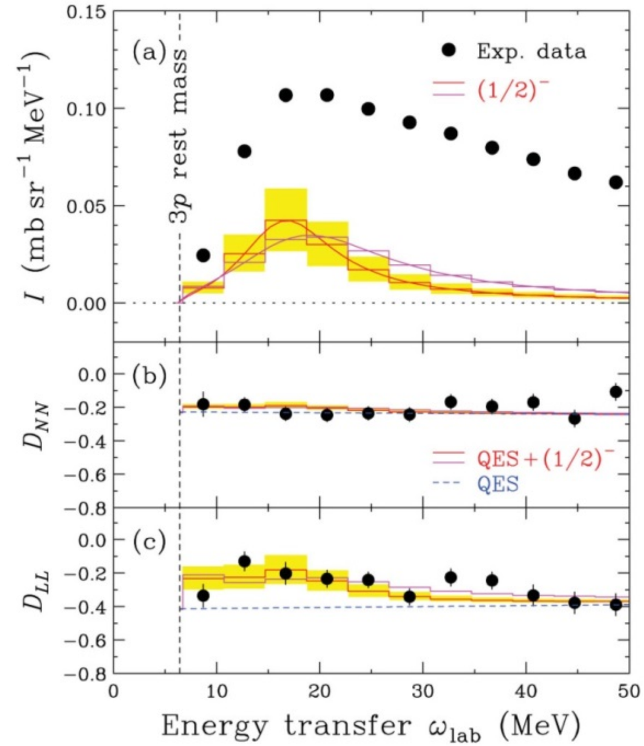
↑ Hiyama's prediction

Wakasa : Ex=9±1 MeV

→ **Comparable to Hiyama-san's prediction.**

QFS background (dubious discussion)





→ Backbround can be understood by the models.
But 2-body or 3-body or both?

Feasibility of experiment

1. Tritium target
2. Yield of $^{3}H(^{9}Li,^{9}Be)^{3}n$
3. Setup at SHARAQ
4. Cocktail beam exp.

Tritium Target for Muon Catalyzed Fusion (μCF)

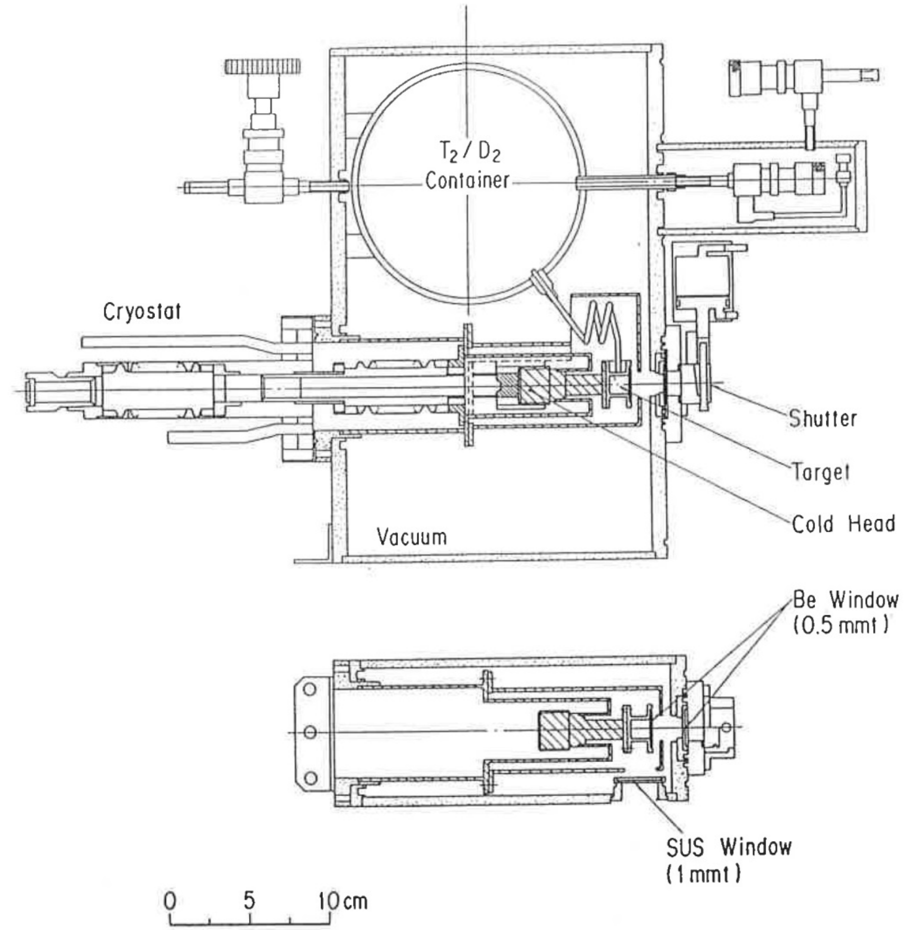
- Constructed for μCF
- 800 Ci (24 TBq)
- 1 cm^3 liquid
- Used at KEK

- Difficulty to acquire a permission of 24 TBq tritium in RIKEN

Muon Catalyzed Fusion 5/6(1990/91)387–394 387

DOUBLY-SEALED D–T TARGET SYSTEM FOR μCF EXPERIMENT AT UT-MSL/KEK

T. MATSUZAKI[1,2], K. ISHIDA[2], K. NAGAMINE[1,2], S. SAKAMOTO[1], E. TORIKAI[3], H. KUDO[4], M. TANASE[4], M. KATO[4] and H. UMEZAWA[4]



3n "resonance" yield of $^{3}H(^{9}Li,^{9}Be)^{3}n$

- $d\sigma/d\Omega$=4 mb/sr (T(^{9}Li)=200 MeV/A assumed)
- N=2.5×10^{21} atoms/cm^{2} (liq. ^{3}H :1mm thick)
- I=10^{7} (max of RIBF regulation)
- $\Delta\Omega$=0.04 msr ($\theta\leq0.2°$ assumed)
- ε=1 (assumed)

$$Y = \frac{d\sigma}{d\Omega}\cdot N\cdot I\cdot \Delta\Omega\cdot \varepsilon$$

$$= 4\times10^{-27}\cdot 2.5\times10^{21}\cdot 10^{7}\cdot 0.04\times10^{-3}\cdot 1$$

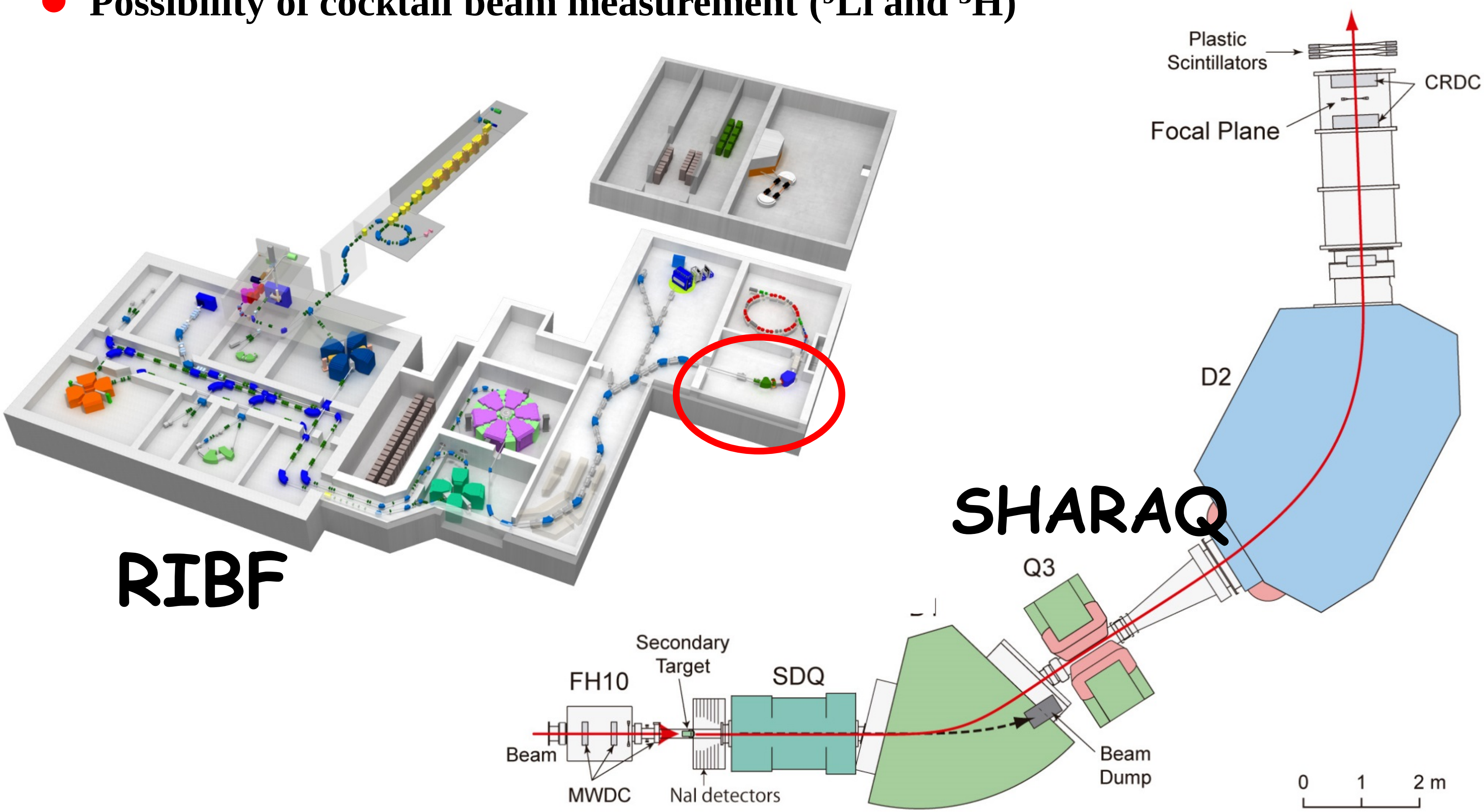
$$= 0.4\times10^{-2}. \qquad \text{(c/s)}$$

→ ~350 counts / days. Feasible! And challenging ….

Experimental setup for $^{3}H(^{9}Li,^{9}Be)^{3}n$

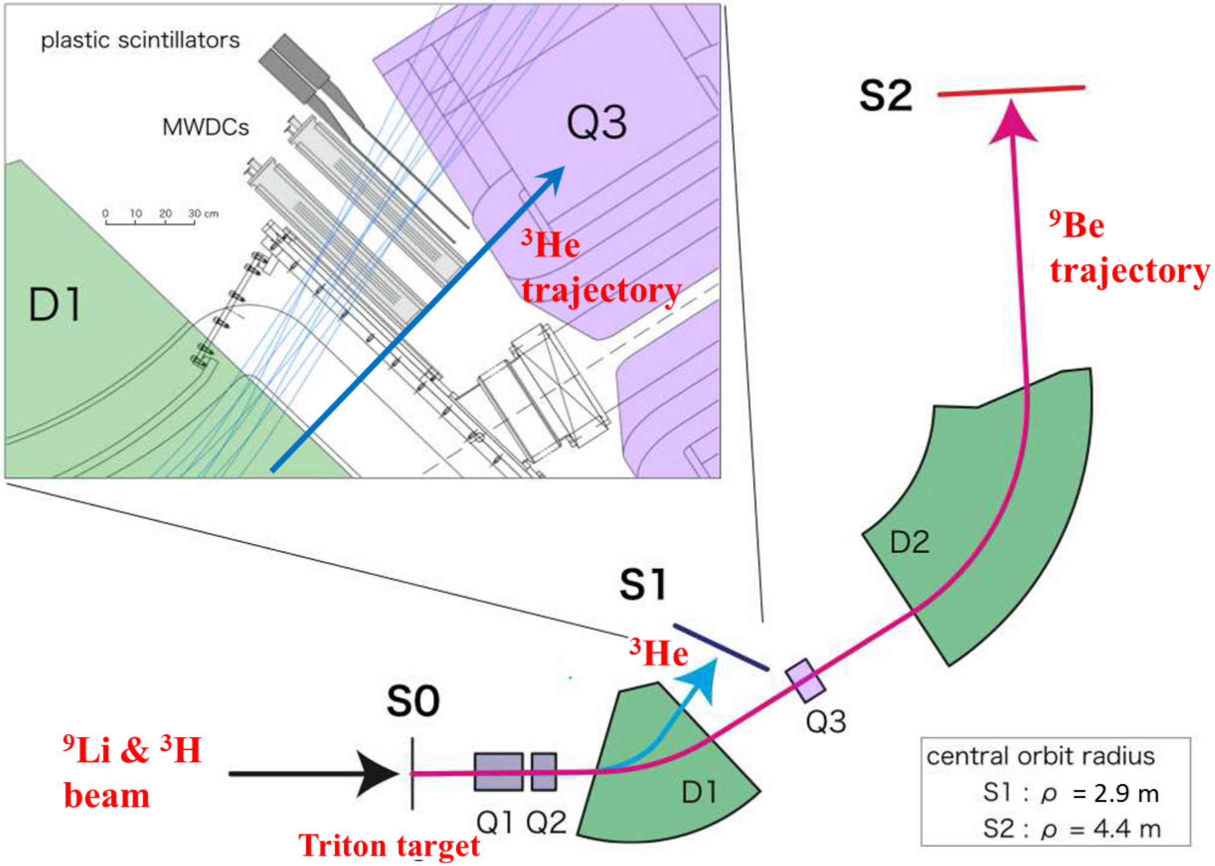
- **Similar to tetraneutron (^{4}n) measurement**
  →Dispersion matching BT & SHARAQ spectrometer

- **Possibility of cocktail beam measurement (^{9}Li and ^{3}H)**



Cocktail beam measurement with SHARAQ

- ^{9}Li beam is always contaminated with ^{3}H. (same A/Z value) →always annoying.
- Simultaneous measurement possible !
  - $^{3}H(^{9}Li,^{9}Be)^{3}n$ at S2
  - $^{3}H(^{3}H,^{3}He)^{3}n$ at S1



Conclusion

- Key to success to observe tri-neutron resonance (my biased view)
  - ✓ Achieve 3n to be close together (<2 fm), 3NF to work
    →charge exchange reaction, keep initial target size
  - ✓ Achieve c.m. of 3n at rest in lab-system, minimize disturbance
    →exothermic reaction
- The best exothermic CE reaction may be $^{3}H(^{9}Li,^{9}Be)^{3}n$
  - ✓ 350 counts / days
  - ✓ if tritium target becomes available. Challenging !
- Cocktail beam measurement could be possible with SHARAQ
  - ✓ $^{3}H(t,^{3}He)^{3}n$ @S1 and $^{3}H(^{9}Li,^{9}Be)^{3}n$@S2

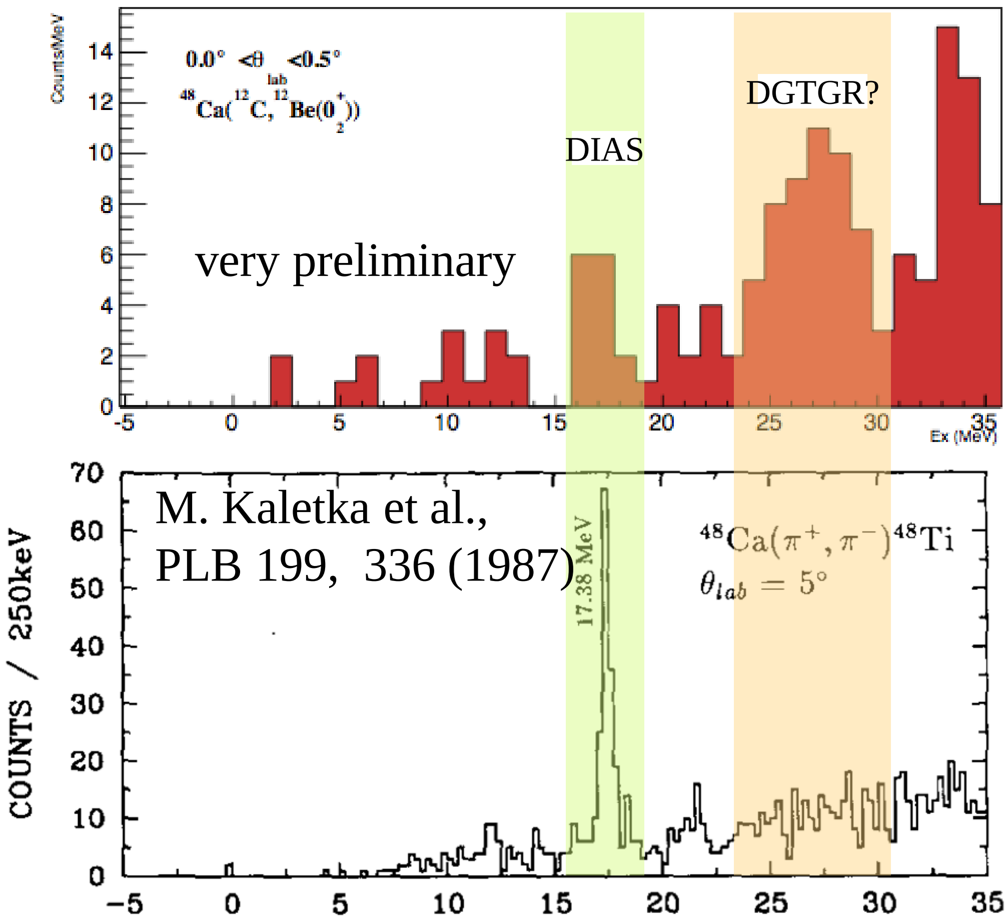
- Home work to theorists:
  - ✓ Construct dynamical (time-dependent) reaction model incorporated with initial condition (3n size, rms=2 fm) with realistic T=3/2 3NF.
    ⇒Time evolution of wave-packet (not necessarily energy eigen state).
  - ✓ Realistic estimate of tri-neutron resonance cross section vs. BG

Double GTGR by HI double CH-EX reaction

- **HI double CH-EX reaction**

→ ^{48}Ca(^{12}C,^{12}Be(0_2^+)) ^{48}Ti Reaction

→ proposed by Motonobu Takaki

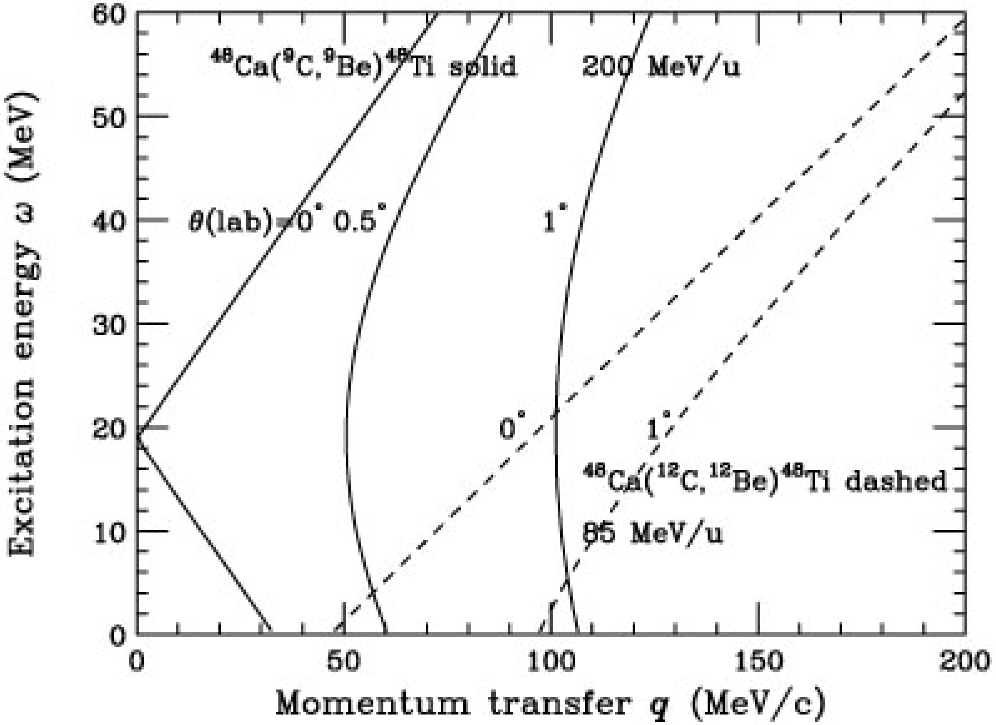


- DIAS (+DGT) ?
- DGT J=0 ? or 2?
- IAS⊗GT ?

How to extract absolute strength is a big challenge.

Best DCE reaction for double GTGR study

$^{48}Ca(^{9}C,^{9}Be)\,^{48}Ti$ Reaction



$(^{9}C,^{9}Be)$ is the best DCE reaction probe !

Cross section of 3n

Let me try to use Wakasa-san's result to guess the production cross section of ^3n.

In terms of DWBA the cross section may be estimated

$$\frac{d\sigma}{d\Omega} = \left(\frac{\mu}{2\pi\hbar^2}\right)^2 |\mathrm{T}|^2,$$

where μ is the reduced mass and T is the T-matrix.

The $\mu = \frac{m_1 m_2}{m_1+m_2}$ value for the $^3\mathrm{H}(^9\mathrm{Li},^9\mathrm{Be})^3n$ reaction is quite different from that of the $^3\mathrm{He}(p,n)^3\mathrm{Li}$ reaction.

$$\left(\frac{\mu(\mathrm{LiBe})}{\mu(\mathrm{pn})}\right)^2 = \left(\frac{\frac{9}{4}}{\frac{3}{4}}\right)^2 = 9 \quad (\sim \mathcal{O}(10^1)).$$

It is an order of magnitude larger.

Now the T-matrix in very crude approximation might be

$$\mathrm{T}_{\mathrm{LiBe}}(\vec{q}) \propto \int dq' d^3\vec{R}\, \mathrm{D}_{\mathrm{LiBe}}(q',\vec{q}\cdot\vec{R}) \cdot V(q') \cdot \rho_{\mathrm{Li}\to\mathrm{Be}}(q') \cdot \rho_{^3\mathrm{H}\to{}^3n}(q')$$

$$\mathrm{T}_{\mathrm{pn}}(\vec{q}) \propto \int dq' d^3\vec{R}\, \mathrm{D}_{\mathrm{pn}}(q',\vec{q}\cdot\vec{R}) \cdot V(q') \cdot \rho_{\mathrm{p}\to\mathrm{n}}(q') \cdot \rho_{^3\mathrm{He}\to{}^3p}(q')$$

$$\left(\frac{\mathrm{D}_{\mathrm{LiBe}}}{\mathrm{D}_{\mathrm{pn}}}\right)^2 =? \quad (\sim \mathcal{O}'(10^{-1})).$$

Here, without any scientific ground, I assumed the reduction by distortion of the LiBe system is an order of magnitude smaller $\sim \mathcal{O}(10^{-1})$ (maybe much more reduced).

Thus the cross section ratio might be approximated as

$$\frac{d\sigma(\mathrm{LiBe})}{d\sigma(\mathrm{pn})} \sim \mathcal{O}(10^1) \times \mathcal{O}'(10^{-1}) \sim 1.$$

- **~1 mb/sr ?**