CENuM-RULiC Joint Workshop on
Extreme Nuclear States and Reactions

November 1, 2019

Search for tetra- and tri-neutron resonance states

~ Three-nucleon force study with a personal recollection ~

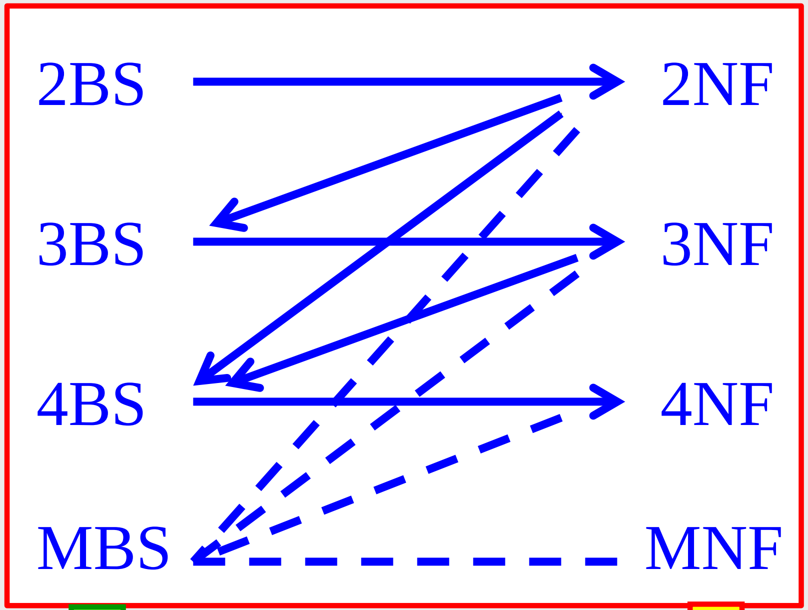
Hideyuku Sakai

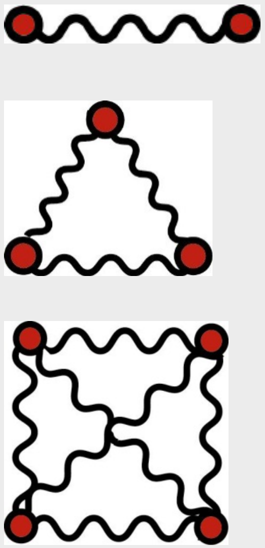
RIKEN Nishina Center

Contents

Three-body force
in
Nuclear system

How to identify 3NF?





- V(2NF) > V(3NF) > V(4NF) > ….
- 3NF is easily masked by strong 2NF effects
- 2NF must be known precisely prior to study 3NF

Requires QM Schrodinger equation

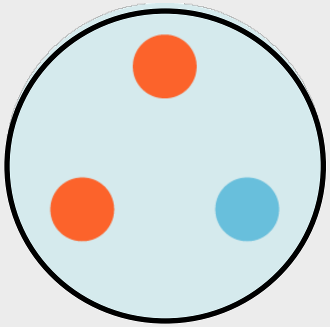
- **2BS: Schrodinger eq.**
- **3BS: Faddeev eq.**
- **4BS: Faddeev- Yakubovski eq.**

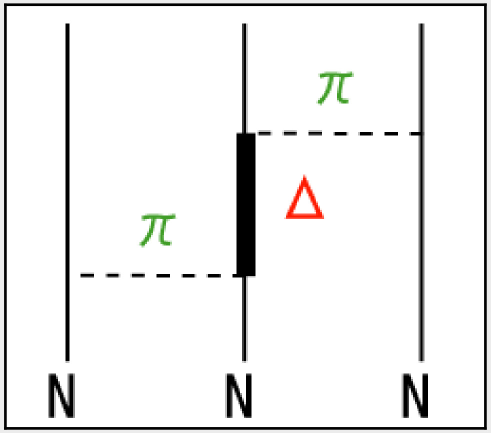
First modern three-nucleon force (3NF)

● **Fujita•Miyazawa type 3NF**

(Prog. Theor. Phys. 17(1957)360.)

2π exchange 3NF





π+N→Δ→π+N'

Δ : excited state of N

- **FM were too early to verify their 3NF, experimentally.**
  - **Correct QM Schrodinger eq. for 3BS (Faddeev eq. 1961)**
  - **2NF was not yet established (established around 1990.)**

Note: To solve Faddeev eq. super CPU is needed (be available at late 1980)

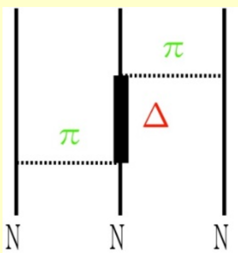
Various 3NFs (operator form)

$$V_{3NF}^{(j)} = \frac{g^2}{4m_N^2} \frac{\vec{\sigma}_i \cdot q}{q^2 + m_\pi^2} \frac{\vec{\sigma}_k \cdot q'}{q'^2 + m_\pi^2} F_{\pi NN}^2(q^2)\, F_{\pi NN}^2(q'^2) \times \left\{ \xi^{\alpha\beta} \left[a + b\, q \cdot q' + c\left(q^2 + q'^2\right) \right] - d\left(\tau_j^\gamma \epsilon^{\alpha\beta\gamma} \vec{\sigma}_j \cdot q \times q' \right) \right\} \tau_i^\alpha \tau_k^\beta$$

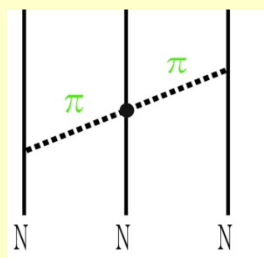
$$F_{\pi NN}(q^2) = \frac{\Lambda^2 - m_\pi^2}{\Lambda^2 + q^2}.$$

3NF model	a	b	c	d
FM	0.0	-1.15	0.0	-0.29
TM	1.13	-2.62	1.05	-0.60
Urbana IX	0.0	-1.20	0.0	-0.30
Brazil	1.05	-2.29	1.05	-0.77
Texas	1.87	-3.82	0.0	-1.12
Ruhr	0.51	-1.82	0.0	-0.48
TM'	-0.87	-2.62	0.0	-0.60

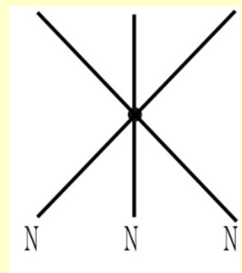
b, d p-wave



a s-wave

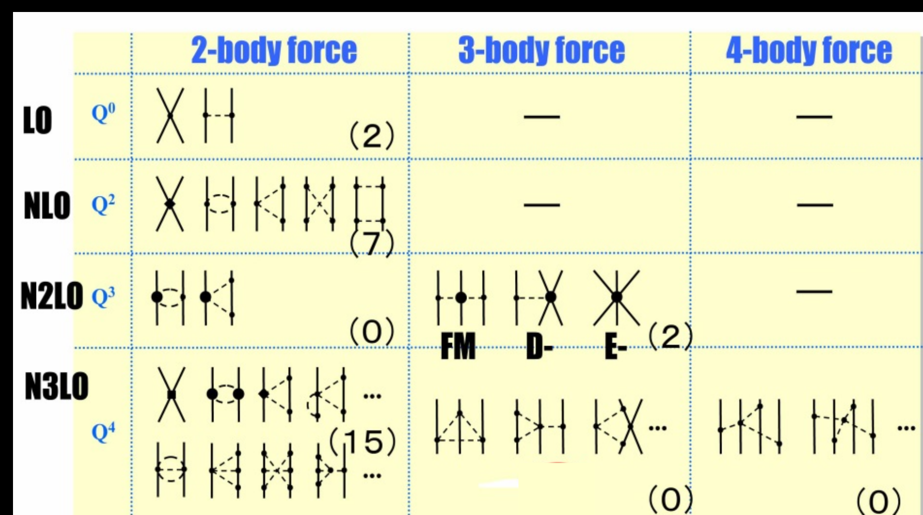


c



● Chiral EFT (modern force)

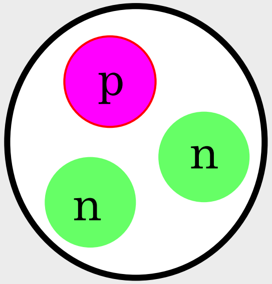
- ➢ (may be) Connected to QCD
- ➢ Interactions: π, N, contact-term
- ➢ 2NF,3NF: extracted naturally on the same bases.



Looking for 3NF

Looking for 3NF

-- Binding energy of ^{3}H (simplest 3 nucleon system)--



$$BE(^3H)=[M_p+2M_n-M(^3H)]c^2=\Delta Mc^2$$
$$= 8.48 \text{ MeV}$$

2N potential	w/o 3NF (MeV)	with 3NF (MeV)
CDBONN	8.013	8.48
Nijmegen I	7.741	8.48
Njimegen II	7.659	8.48
Nijmegen 93	7.668	8.48
AV-18	7.628	8.48
experiment		8.48

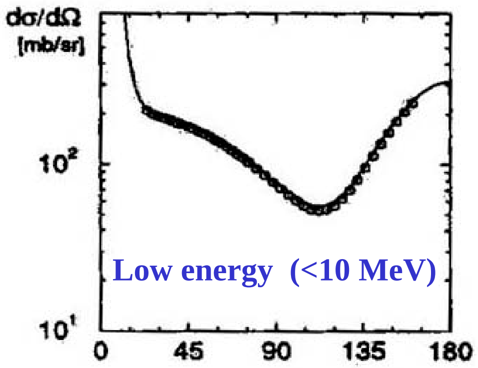
2NF : various modern forces
3NF : Fujita-Miyazawa

One parameter exists.
Λ : π-N form factor adjusted

Once Λ fixed, parameter free Faddeev calc.

Looking for 3NF in pd scattering

●Precise *pd* scattering

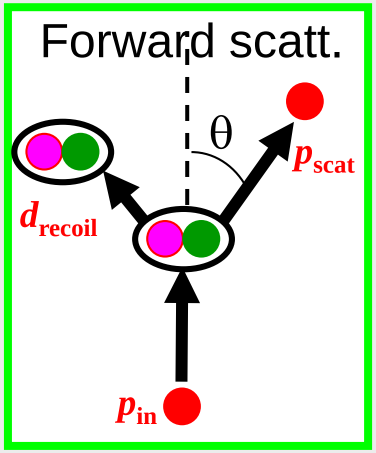


Faddeev cal.

Excellent fit!

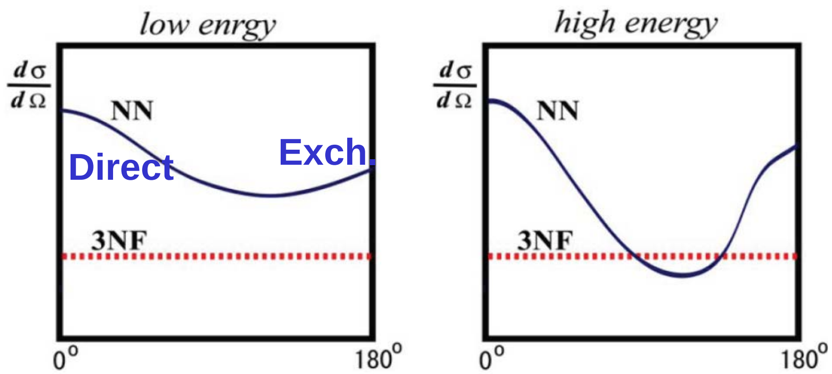
No 3NF effect visible!

（No need of experiment！）



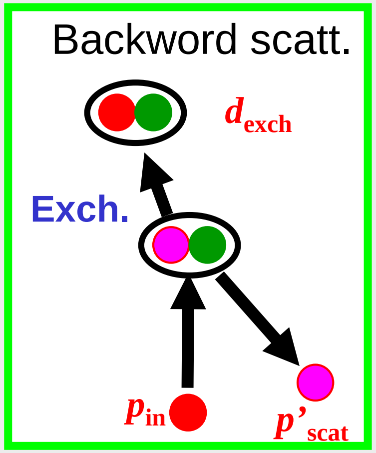
●Prediction of H.Witała. PRL 81(1998) 1183.

→ ***pd*** **scatt. at intermediate energy (≥100 MeV)**



Measure Xsec *dσ/dΩ* at minimum.

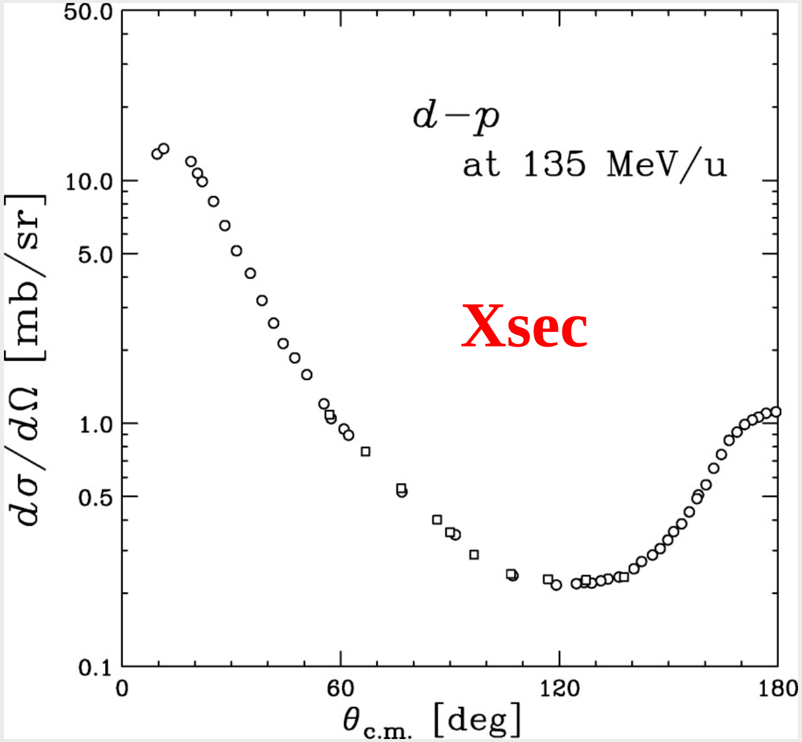
→ require high precision data

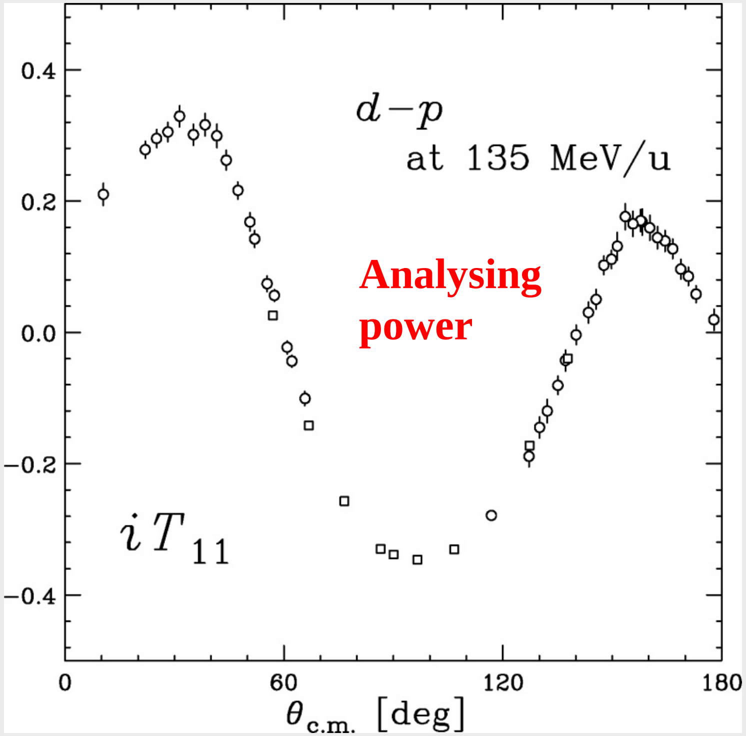


p_{in} picks-up n_{targ} to form d_{exch}.

Results for p+d scattering at 135 MeV

135 MeV (a half of light velocity)





Sakamoto et al., PLB367(1996)60.

Sakai et al., PRL 84(2000)5288.

Sekiguchi et al., PR C65(2002)034003.

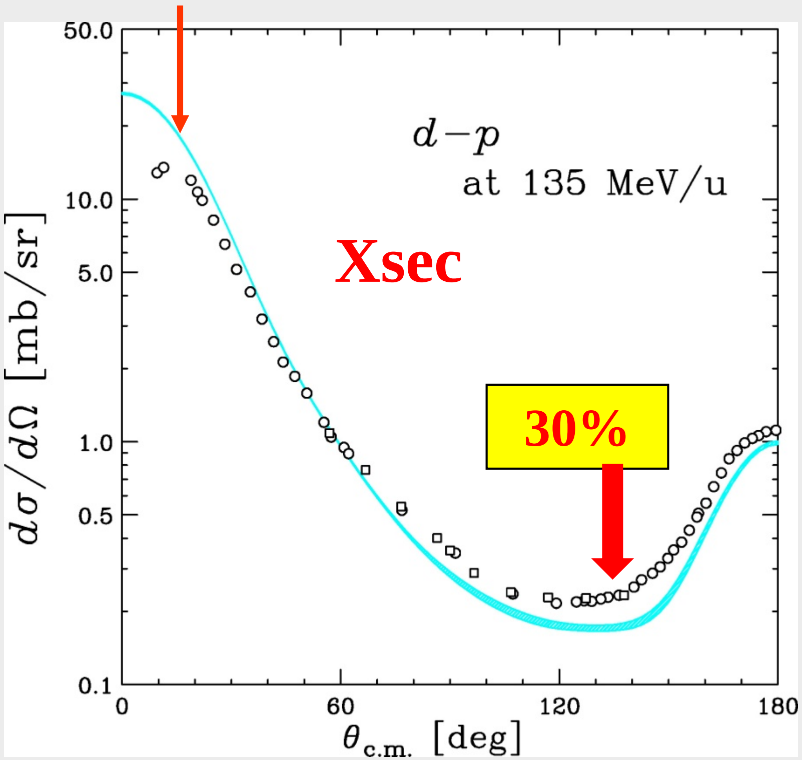
Results with 2NF only Faddeev cal.

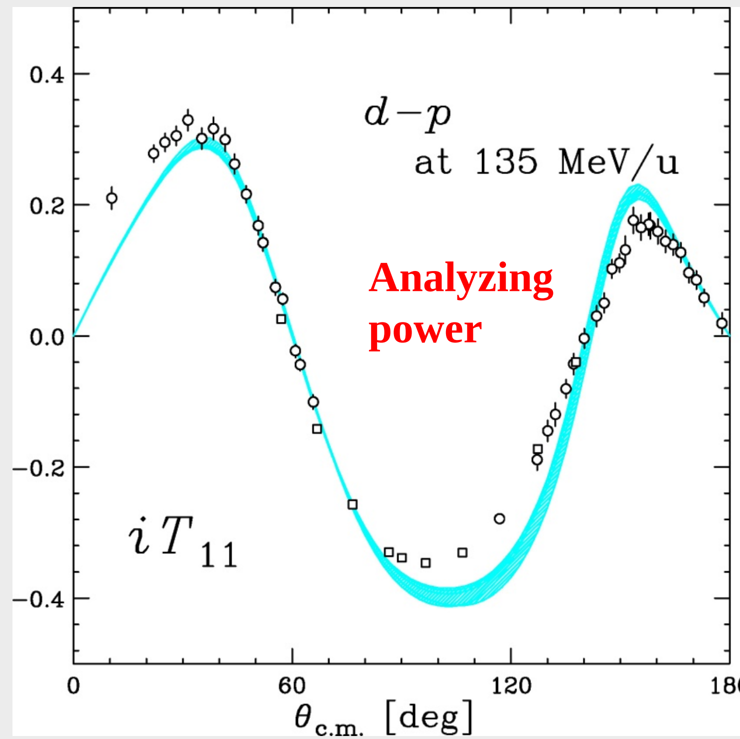
No free parameter calculations

Bochum-Cracow-KIT Gr. calc.

2NF only

Coulomb





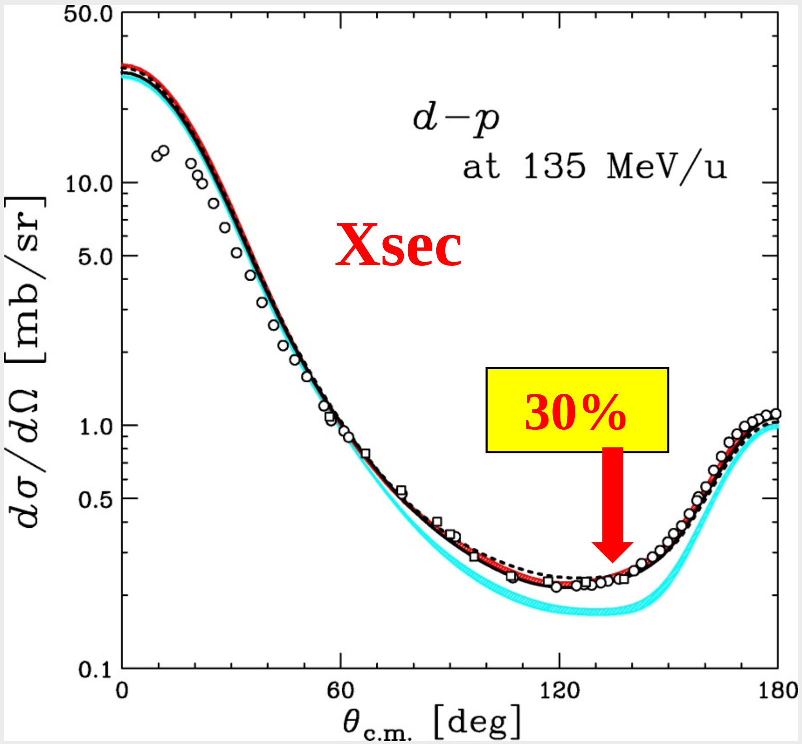
Results with 2NF + 3NF

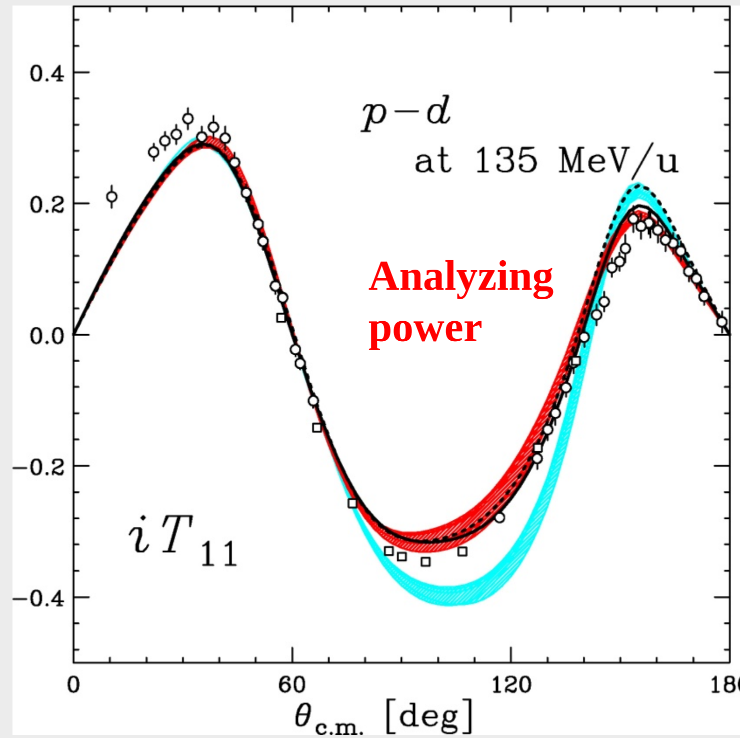
No free parameter calculations

Bochum-Cracow-KIT Gr. calc.

2NF only

2NF + 3NF



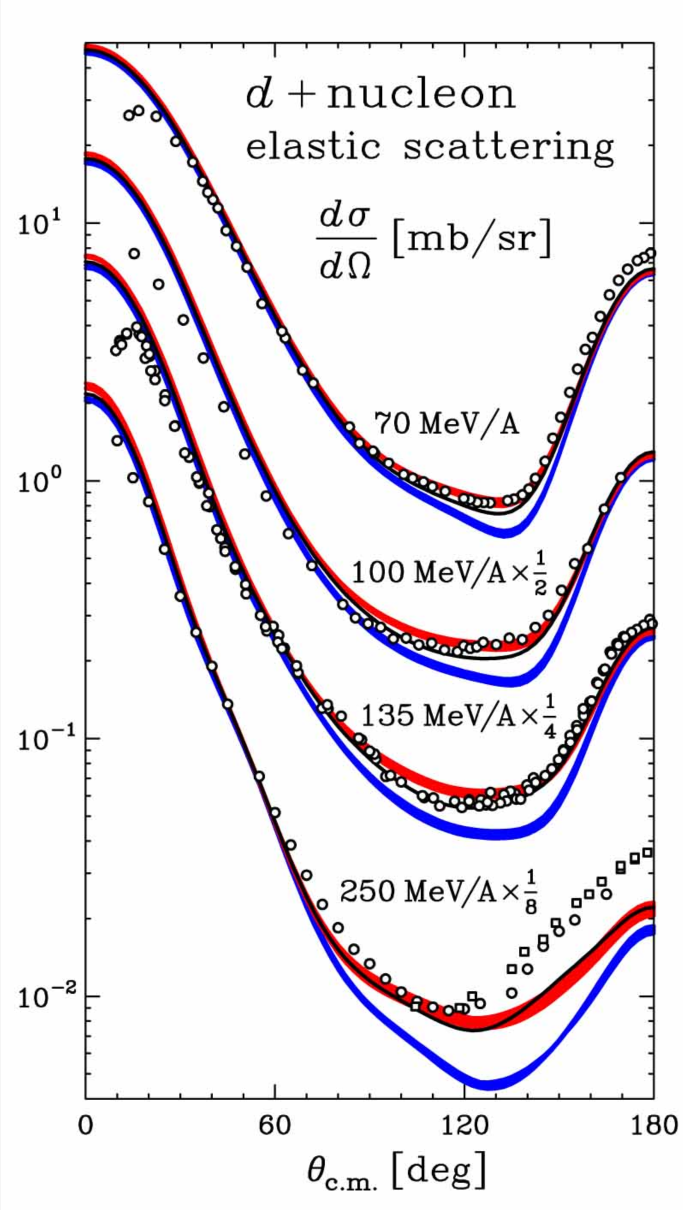


Calculations reproduce beautifully data.

⇒ Effects of 3NF confirmed !

Sensitive only to T=1/2 3NF.

Systematic study



Our pd data available for 70-320 MeV

Contact: Kimiko Sekiguchi, Tohoku Univ.

Sekiguchi et al.

PRC **65**, 034003 (2002)
PRL **95**, 162301 (2005)
PRC **79**, 054008 (2009)
PRC **83**, 061001 (2011)
PRC **89**, 064007 (2014)
PRC **96**, 064001 (2017)

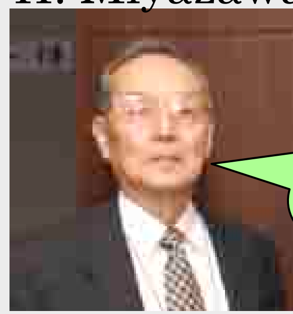
- **Discrepancy increases at backward angles**
- **Some important ingredient is still missing**

Anecdote

We established 3NF effects in pd scattering around 2,000.

In 2007 we held a symposium FM50 to commemorate Fujita-Miyazawa 3NF theory at University of Tokyo.

H. Miyazawa

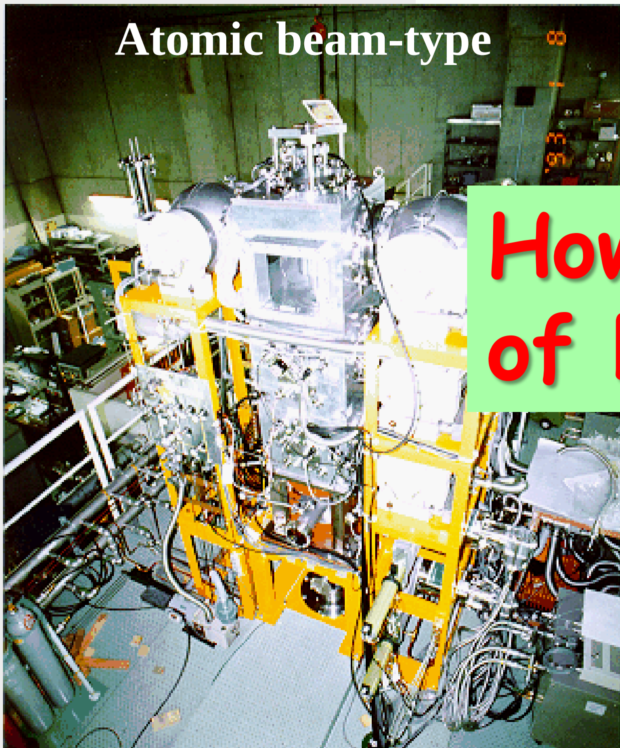


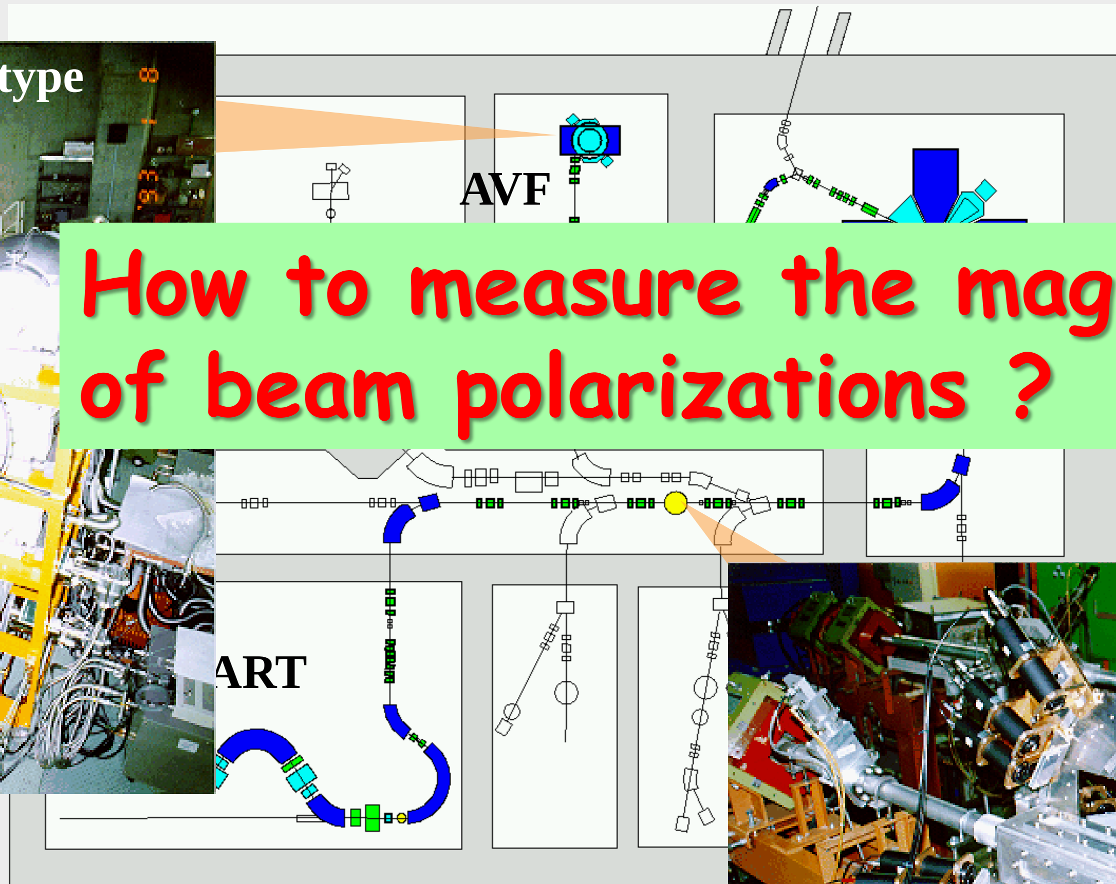
I never thought our theory(FM) could be tested by experiment.

- It took 50 years!
  Needed time for Faddeev theory and 2NF.
- Next challenge : T=3/2 3NF and 4NF?

How I was involved in few-body physics

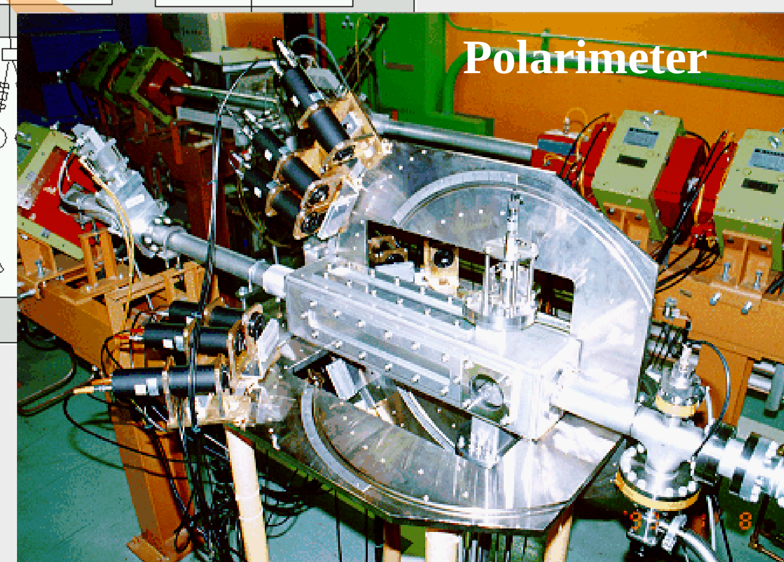
- Started with a construction of polarized ion source (1992 ~1994)





K = 540 MeV

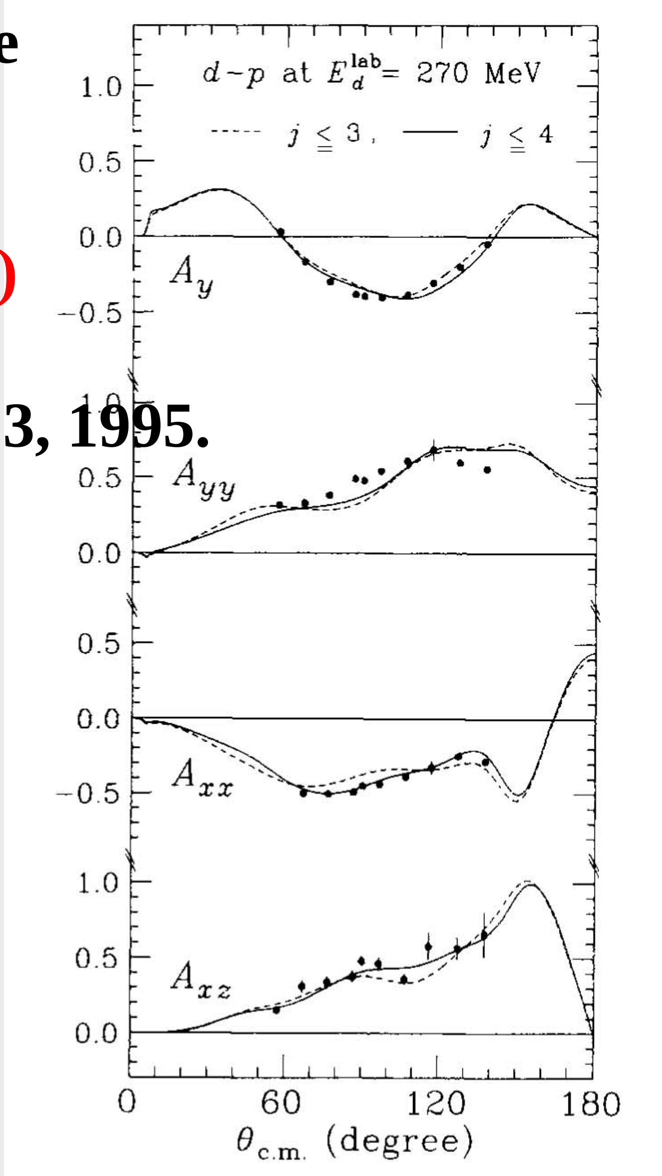
How to measure the magnitudes of beam polarizations ?



- Adoped d_{pol} + p scattering for a beam polarimetry

- Complete polarization observables (Ay, Ayy, Axx, Axz) successfully measured for the first time at intermediate energy.
  (I was very proud of this and did not pay strong attention to X-sec.)

- And submitted to Phys. Lett. on June 13, 1995.



PHYSICS LETTERS B

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SAITAMA 351-01
Japan

Rejected !

Groninge... 12 J... 19..

Re.: PLB/RH... 742

Sincerely yours,

Rolf H. Siemssen

c.c.: Dr. H. Sakai (KVI)

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Re: PLB/RHS 742

Measurement of the vector and tensor analyzing powers for the d-p elastic scattering at E_d = 270 MeV
N. Sakamoto *et al.*

This paper presents new data on vector- and tensor analyzing powers in d-p scattering at 270 MeV. The data are compared to Faddeev calculations. While good agreement between data and calculations is found for the analyzing powers, systematic discrepancies occur in the cross section.

The paper has a number of shortcomings that make it unsuitable for publication in Phys. Lett.:

- The polarization of the beam is measured only *before* acceleration in the cyclotron. No evidence is presented that the cyclotron would not lead to partial depolarization.
- The cross section measurements, with estimated 10 — 20% systematical errors and fluctuations larger than the error bars (fig.2) are hardly "state of the art".
- Interpretation of the data in terms of the asymptotic S/D-state ratio is inappropriate given the high momentum transfers involved. S/D-state ratios should be determined

- The cross section measurements, with estimated 10 — 20% systematical errors and fluctuations larger than the error bars (fig.2) are hardly "state of the art".

Concerning the presentation of the results, the details of table 1 are of little interest to the reader. The details of the separable expansion (table 2) would better be left to a paper by Koike *et al* who do the calculation. (The statement on the use of a nondescript workstation used for the calculations is not helpful either).

For the reasons listed above I cannot recommend publication in Phys. Lett. B. Major reworking would be needed to make the paper acceptable.

After getting better X-sec data, revised paper was resubmitted.

ELSEVIER

18 January 1996

Physics Letters B 367 (1996) 60–64

PHYSICS LETTERS B

Measurement of the vector and tensor analyzing powers for the d-p elastic scattering at $E_d = 270$ MeV

N. Sakamoto[a], H. Okamura[a], T. Uesaka[a], S. Ishida[a,1], H. Otsu[a], T. Wakasa[a], Y. Satou[a], T. Niizeki[b], K. Katoh[b], T. Yamashita[b], K. Hatanaka[c], Y. Koike[d], H. Sakai[a]

[a] *Department of Physics, University of Tokyo, Bunkyo-ku, Tokyo 113, Japan*
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[c] *Research Center for Nuclear Physics, Osaka University, Ibaraki, Osaka 567, Japan*
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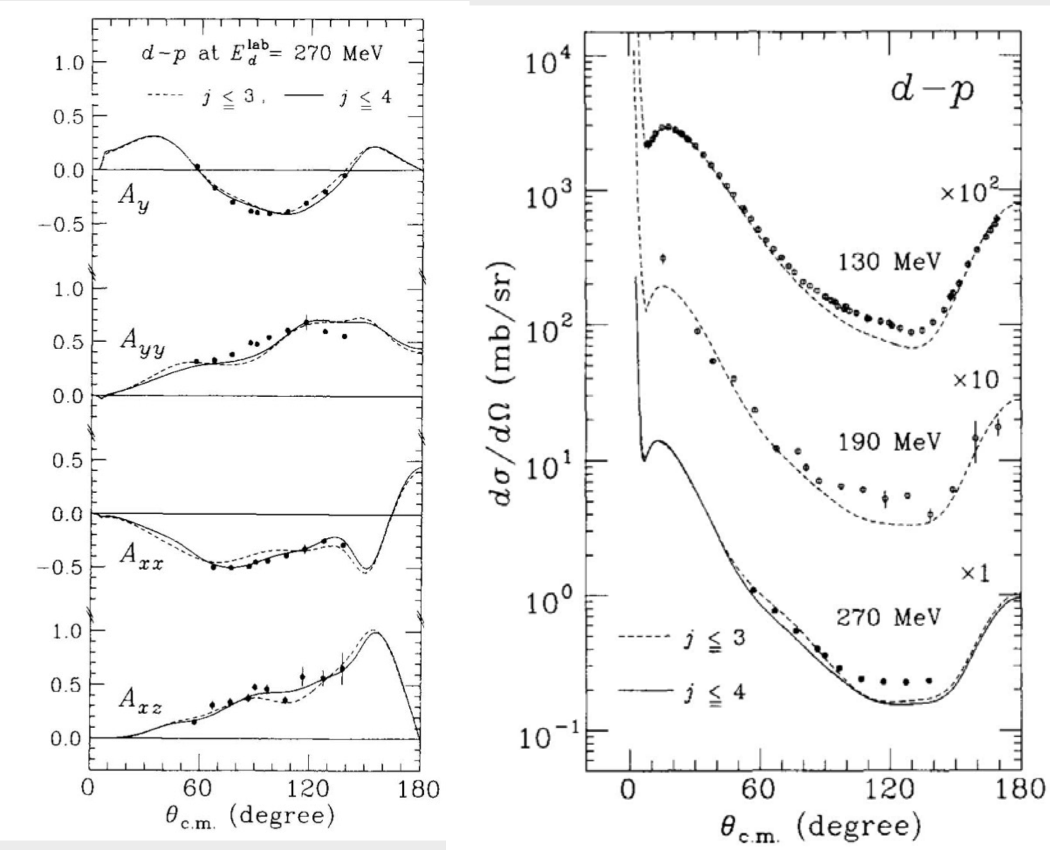
Received 13 June 1995; revised manuscript received 18 October 1995
Editor: R.H. Siemssen

Abstract

The differential cross sections and the vector and tensor analyzing powers A_y, A_{yy}, A_{xx}, and A_{xz} for the d-p elastic scattering were measured at $E_d^{\rm lab} = 270$ MeV over the c.m. angular range from 57° to 138°. The data are compared with a Faddeev calculation. A good description is obtained for all components of the analyzing powers, while a discrepancy of about 30% is found in the cross section around $\theta_{\rm c.m.} = 120°$.

Sakamoto paper, PL B367(1996)60



- **Koike,s calc.**
  - **Faddeev calc.**
  - **With Coulomb**
  - **Separable potential**
  - **No 3NF**

- **A_y,A_{xx},A_{yy},A_{xz} reproduced well for measured angular range**

My surmise at that time

Without deteriorating good fits to all Aij, 30% diff. in X-sec cannot be recovered.

After this measurement, the rigorous Faddeev calc. appeared and I was seriously involved in FB physics.

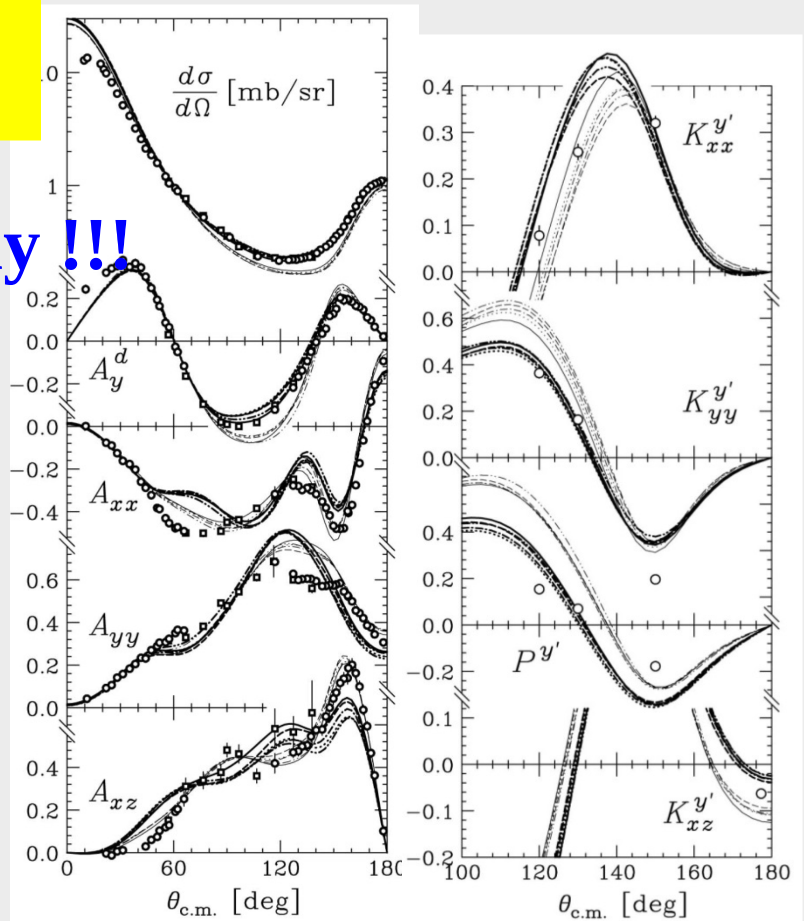
3NF is included in the title in the PRL

VOLUME 84, NUMBER 23 PHYSICAL REVIEW LETTERS 5 JUNE 2000

Precise Measurement of *dp* Elastic Scattering at 270 MeV and Three-Nucleon Force Effects

H. Sakai,[1,5,*] K. Sekiguchi,[1] H. Witała,[2] W. Glöckle,[3] M. Hatano,[1] H. Kamada,[3] H. Kato,[1] Y. Maeda,[1]
Y. Satou,[5] K. Suda,[4] A. Tamii,[1] T. Uesaka,[4]

State-of-the-art $d\sigma/d\Omega$,
A_y,A_{xx},A_{yy},A_{xz},P_y,$K_{xx}^{y'}$,$K_{yy}^{y'}$,$K_{xz}^{y'}$
Now everywhere 3NF !



Research develops unexpectedly !!!

Serendipity ?

Right time by lucky

- NN-int. established
- NN+3NF Faddeev calc. available
- PIS: dedicated only for deuteron
- Polarimetry by *dp* scattering
- etc.

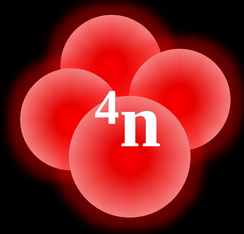
So far T=1/2 3NF

Next challenge: T=3/2

Requires n-n-n/p-p-p system

Tetraneutron with SHARAQ

Multi-neutron system to study T=3/2 3NF

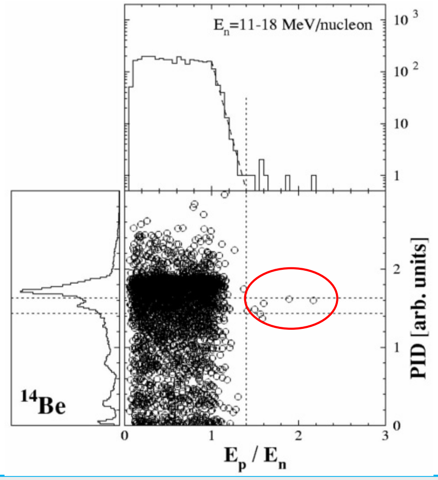


Spokesperson: K. Kisamori, S. Shimoura

K. Kisamori et al., PRL116, 052501 (2016)

Tetraneutron (^{4}n) prior to our experiment

- **Marques *et al.*, PRC65(02)044006**
  - **Neutron cluster search**
    ^{14}Be $\rightarrow$ ^{10}Be + ^{4}n
  - **Hint of bound tetraneutron !**



PHYSICAL REVIEW C **72**, 034003 (2005)

Is a physically observable tetraneutron resonance compatible with realistic nuclear interactions?

Rimantas Lazauskas*

DPTA/Service de Physique Nucléaire, CEA/DAM Ile de France, BP 12, F-916

Jaume Carbonell†

Laboratoire de Physique Subatomique et de Cosmologie, 53, avenue des Martyrs, F-38026 Grenoble Cedex, France‡

(Received 22 April 2005; published 20 September 2005)

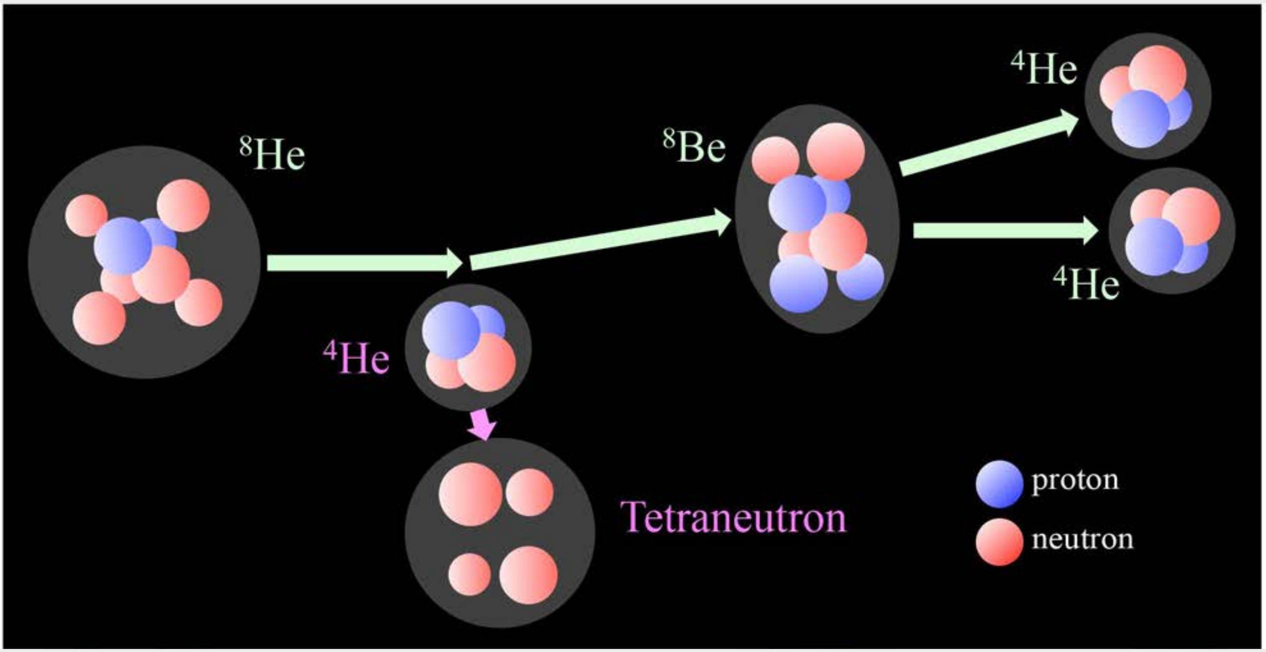
4NF introduced to artificially bind tetraneutron !

The possible existence of four-neutron resonances close to the physical energy region is explored. Faddeev-Yakubovsky equations have been solved in configuration space using realistic nucleon-nucleon interaction models. Complex scaling and analytical continuation in the coupling constant methods were used to follow the resonance pole trajectories, which emerge out of artificially bound tetraneutron states. The final pole positions for four-neutron states lie in the third energy quadrant with negative real energy parts and should thus not be physically observable.

Exothermic DCHEX reaction to create ^4n

$^4He(^8He,^8Be)^4n$ reaction

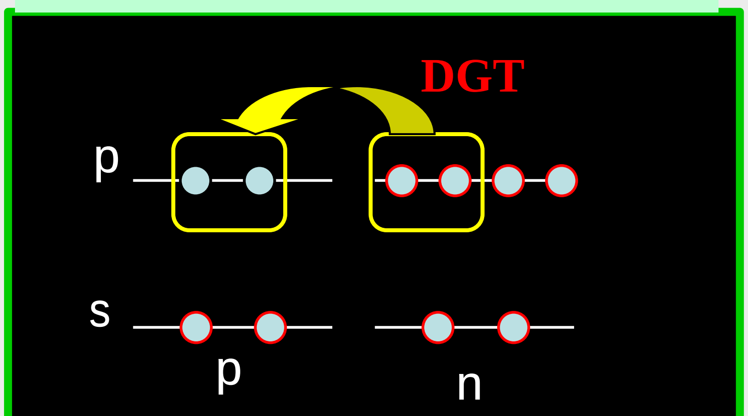
$^8Be \rightarrow 2\alpha$ observed



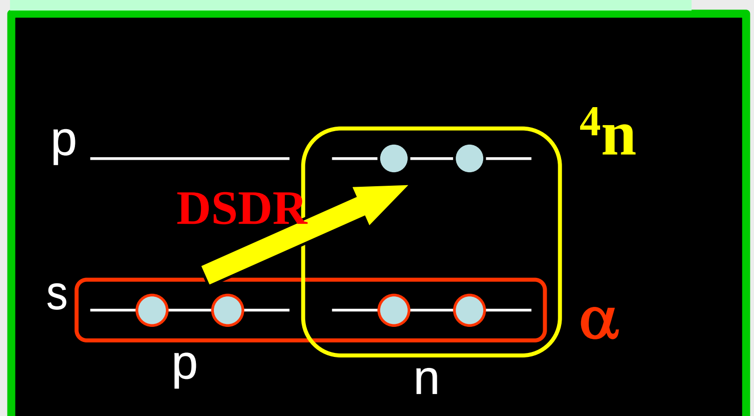
Merits

- $\Delta m(^8He)=+32MeV$
- Q=–3MeV
- **Recoil-less**
  (q=15MeV/c)

Projectile side : $^8He \rightarrow {}^8Be$

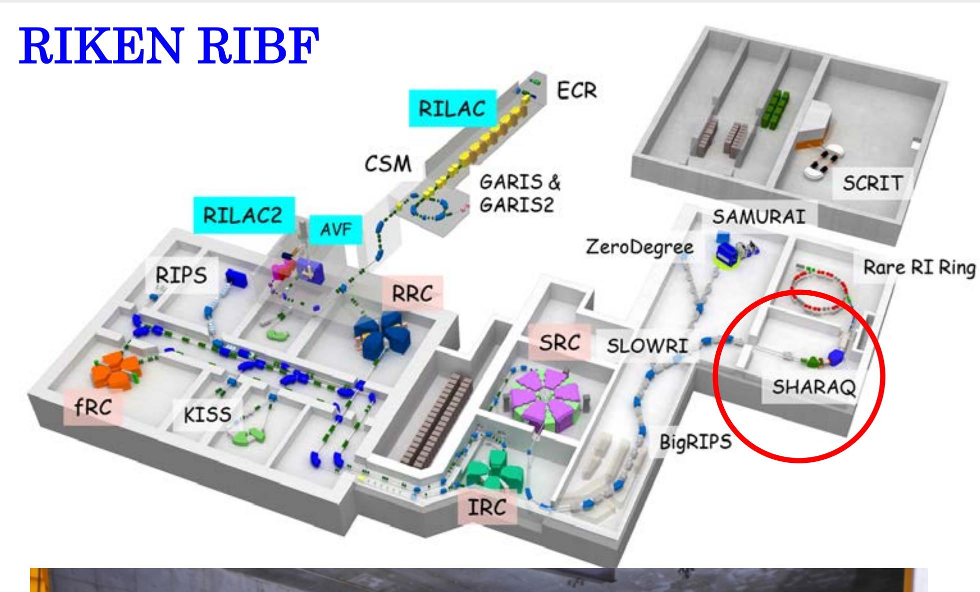


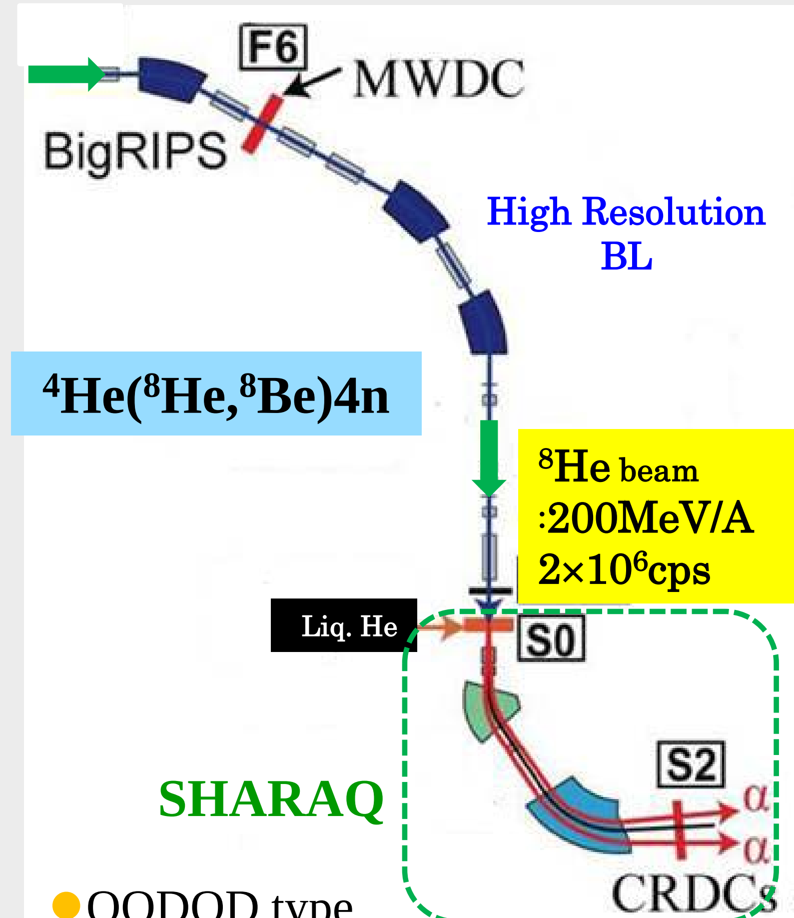
Target side : $^4He(\alpha) \rightarrow {}^4n$



Measurement of ^{4}n at rest with SHARQ

- ^{8}Be : 2α measured at SHARAQ magnetic spectrometer
- SHARAQ :constructed under ICHOR Project (Spokesperson H. Sakai)

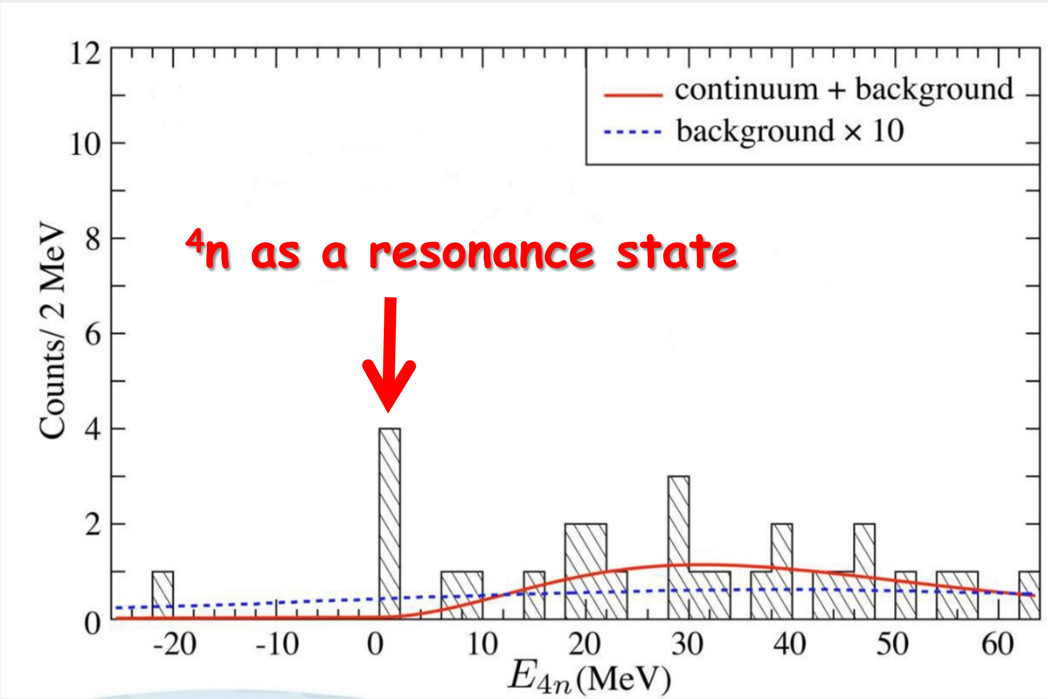




- QQDQD type
- Bρ=6.4 Tm
- ΔE/E=0.02% (dispersion matching)
- ΔΩ:10mrad × 30mrad

Result of $^4He(^8He,^8Be)4n$

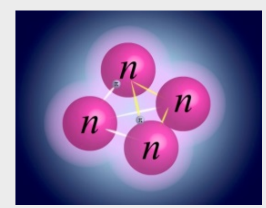
K. Kisamori, Shimoura, Sakai *et al*., Phys. Rev. Lett. 116, 052501 (2016).

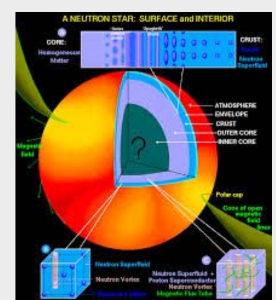


- 4 counts (resonance!)
- E_R=0.83 ± 0.65(stat.) ± 1.25(sys.) MeV
- $\Gamma \leq$ 2.6 MeV(FWHM)
- σ = 3.8 $^{+2.9}_{-1.8}$ nb
- significance = 4.9σ

Recoilless exothermic CHEX reaction!

T=3/2 3NF must play an important role.
→ also important for multineutron system
as well as neutron stars.

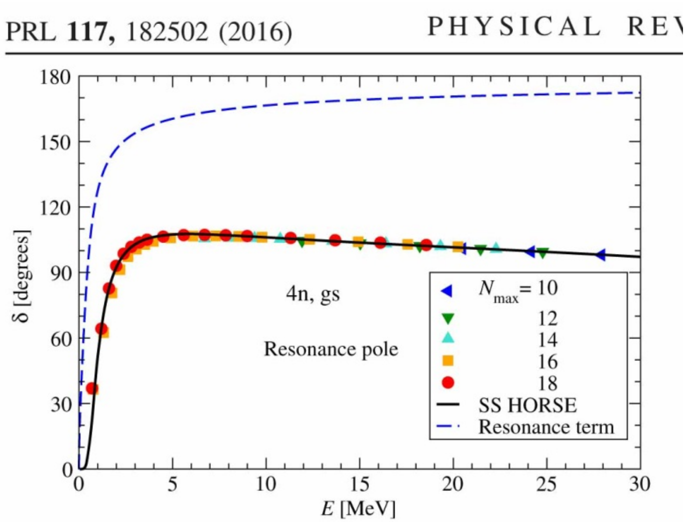




Recent theoretical works on ^{4}n (yes)

- **A.M. Shirokov et al., PRL 117(2016)182502**

NCSM calculation with DISP16 interaction: No 3NF! Non-local

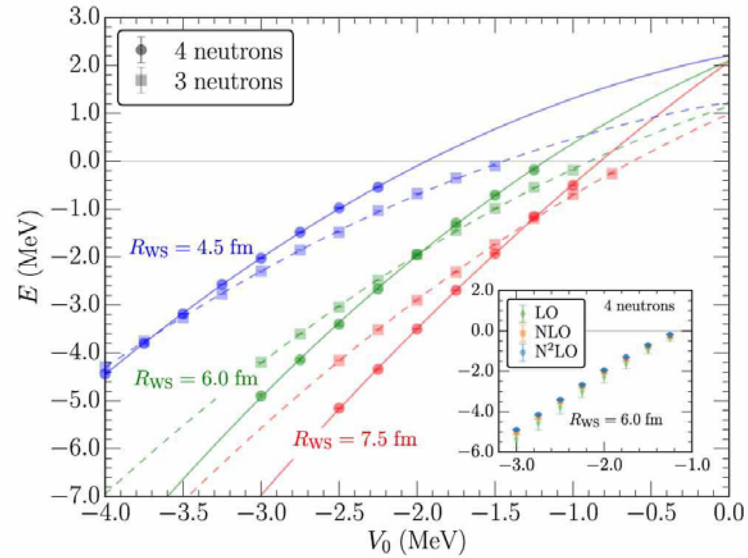


4-body phase shift (HH coordinate) shows resonance around E_r=0.8 MeV with Γ=1.4 MeV.

- **S. Gandolfi et al., PRL 118(2017)232501**

***Ab initio* calc. with 2N+3N in chiral EFT**

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



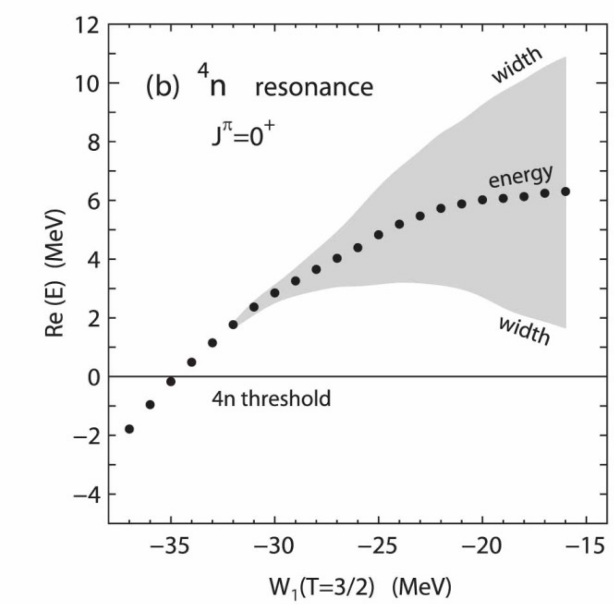
E_R=1.84 MeV with Γ=0.28 MeV.
$E_R(^3n) < E_R(^4n)$
Trineutron resonance at 1 MeV!

Recent theoretical works on ^{4}n (No)

- E.Hiyama et al., PRC 93(2016)044004
  - ➢ Solve Faddeev-Yakubovsky (FY) equations
  - ➢ Complex scaling method to get E_r and Γ

3NF

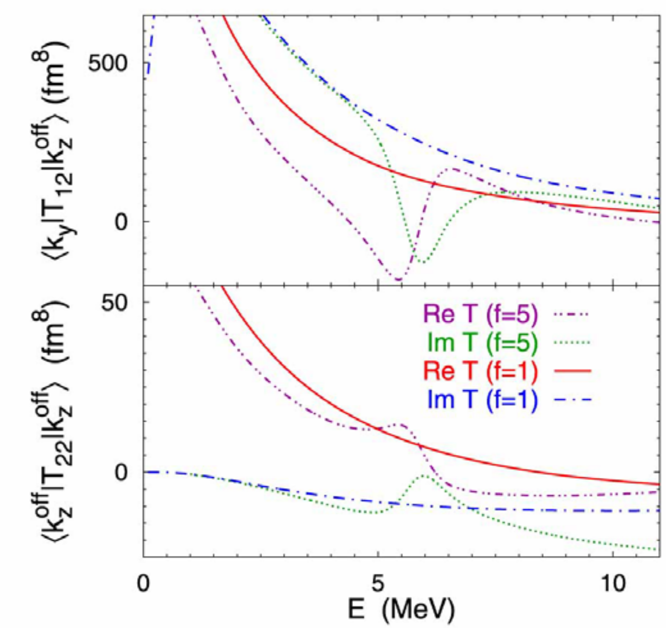
$$V_{ijk}^{3N} = \sum_{T=1/2}^{3/2} \sum_{n=1}^{2} W_n(T) e^{-(r_{ij}^2+r_{jk}^2+r_{ki}^2)/b_n^2} \mathcal{P}_{ijk}(T),$$



Too strong attraction is necessary for ^{4}n resonance, which makes ^{4}H bound!

- A. Deltuva, PLB 782(2018)238
  - ➢ Exact continuum eq. for trans. ope.
  - ➢ AGS equation (momentum space)

No 3NF!



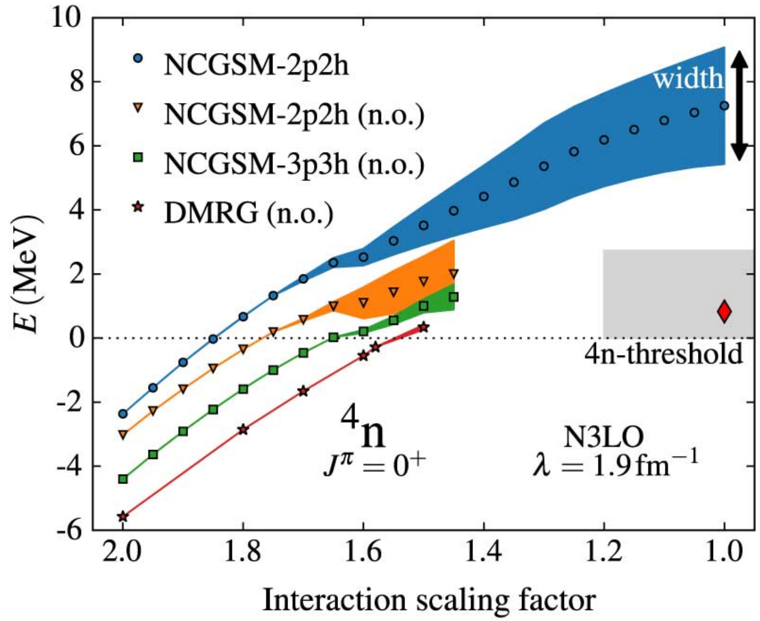
To produce a resonance, 5 times more attraction is necessary.

Recent theoretical works on ^{4}n (Yes/No)

- **K. Fossez, PRL 119(2017)032501**

No Core Gamow SM+density reno. G
2 neutrons in the continuum

No 3NF.

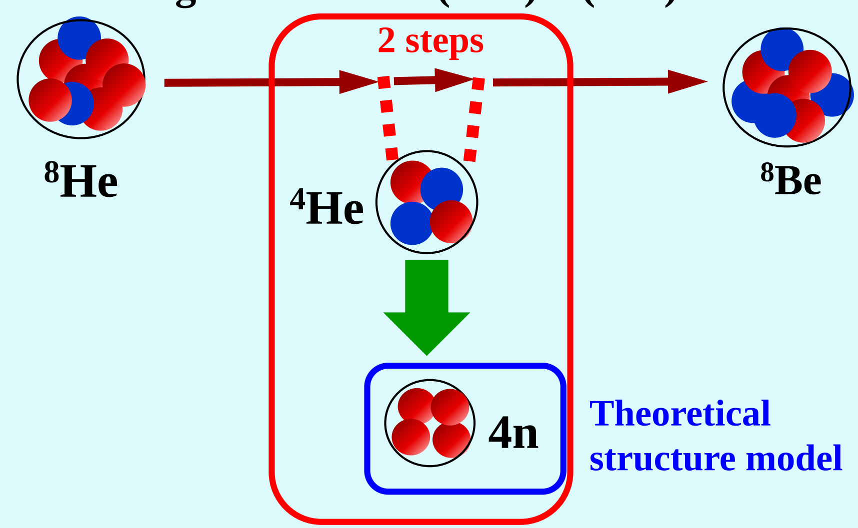


E_r may be compatible with exp. but
Γ_r must be larger than 3.7 MeV.

We confirm the existence of a pole of the scattering matrix associated with the spin and parity $J^\pi = 0^+$ in this system as shown in previous studies; however, the proper inclusion of the couplings to the continuum shows that this pole must be a feature in scattering experiments and not a genuine nuclear state. Physically this can be interpreted as a reaction process involving four neutrons, which is too short to form a nucleus.

Our measurement

- **Missing mass : Ex=E(8He)-E(8Be)**



- **Reaction dynamics should be included.**
- **4n created with ^{4}He (<R> ~1.9 fm)**

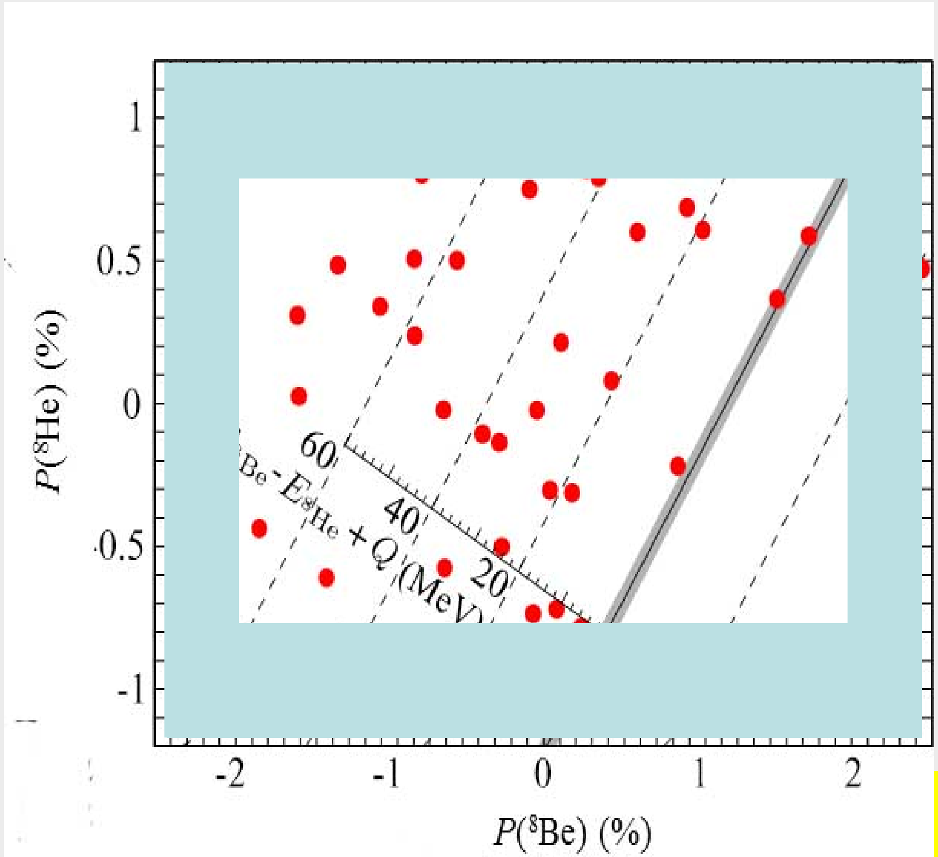
-- New measurement --

Spokesperson: S. Masuoka, S. Shimoura

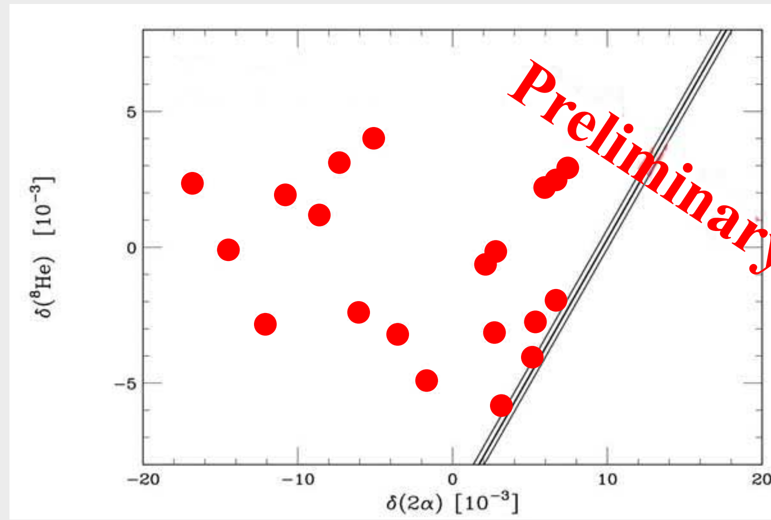
Measurement was carried out in June 2016 to get more statistics

New measurement (still preliminary)

Kisamori et al. PRL



New data



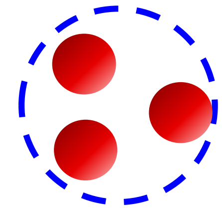
- 4 counts around E_x=1 MeV
- Similar feature observed

Why we could observe ^{4}n resonance
My preconceived idea

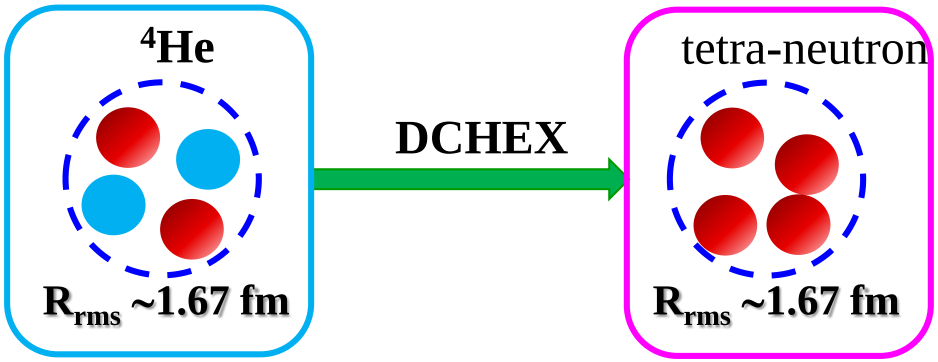
Maximize T=3/2 3NF effects !!!

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

V_{NNN}(T = 3/2) will work when 3n are in R_{rms} < 1.9 fm.



- **Exothermic DCHEX is essential**



Keep the size!
(initial wave-packet size)

- **Merit of exothermic DCHEX reaction:**

1. **Keep size of 4n in 1.7 fm ⇒T=3/2 3NF works !**
2. **Recoil-less (q~0) ⇒ cm of 4 neutrons is at rest**

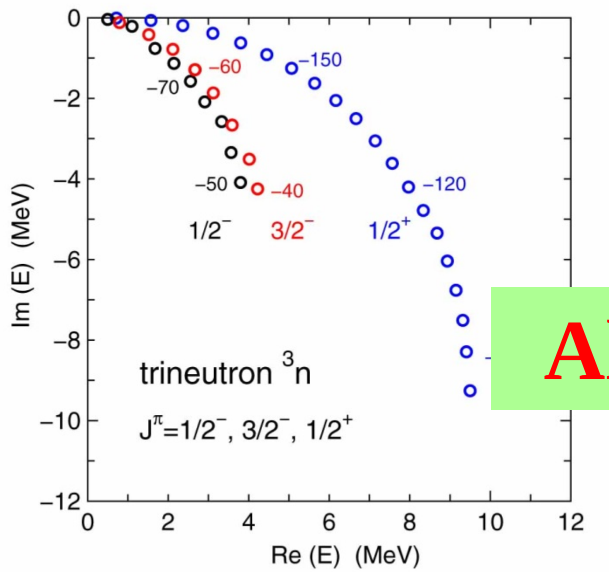
Results of ^{1}H(^{8}He,pα)4n are eagerly awaited.
(Single-step knockout reaction. Huge X-sec.)

Search for tri-neutron (^{3}n) resonace to study T=3/2 3NF

Recent theoretical works on ^{3}n after ^{4}n

- **E.Hiyama et al., PRC 93(2016)044004**

➢ **Solve Faddeev-Yakubovsky equations**
➢ **Complex scaling method to get E_r and Γ**



Stronger T=3/2 3NF attraction is necessary for ^{3}n resonance.

E_R~4 MeV, Γ~4 MeV
J^π=1/2$^-$ and/or 3/2$^-$

- **A. Deltuva, PRC 97(2018)034001**

AGS equation (momentum space)

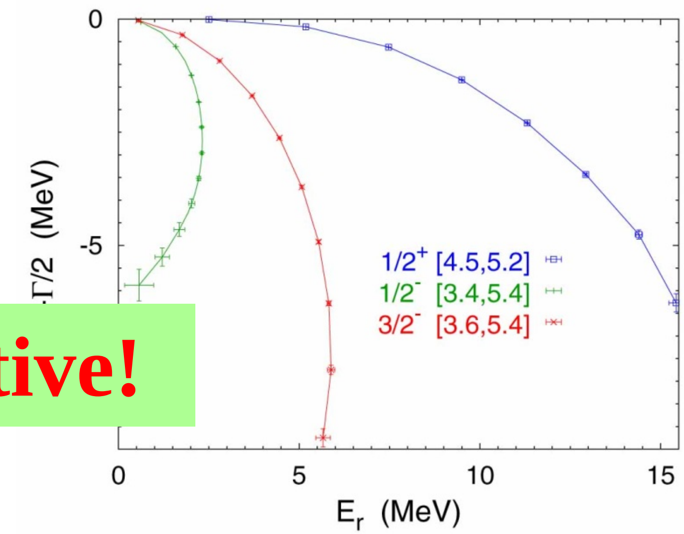


FIG. 6. Three-neutron $J^\Pi = \frac{1}{2}^+, \frac{1}{2}^-$, and $\frac{3}{2}^-$ resonance trajectories obtained with the attractive $^3P_1$ potential as described in the text. Results are based on the SRG model while the enhancement factor f is varied in the given interval with the step of 0.1 (0.2) for positive (negative) parity states.

All negative!

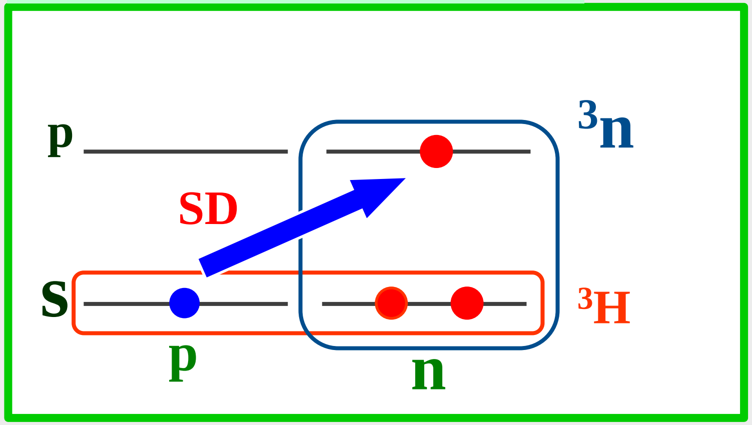
Non-existence of 3n resonance

Tri-neutron search by CHEX reaction

For tri-neutron search (same as the tetra-neutron search)

- Create 3n system **at rest** by **exothermic CHEX reaction**
- Best choice is ^{3}H(^{9}Li, ^{9}Be)3n. Q=+4.4 MeV
- Recoilless condition (q=0) can be achieved.
- Alternative might be ^{3}H(t, ^{3}He)3n. Q=–6.9 MeV (not exothermic)
- In any case, ^{3}H Target needed

Single CE : ^{3}H → ^{3}n



- SD: σ(ΔL=1)~finite angle
- → large q transfer (~100 MeV/c))
- →give up recoilless condition

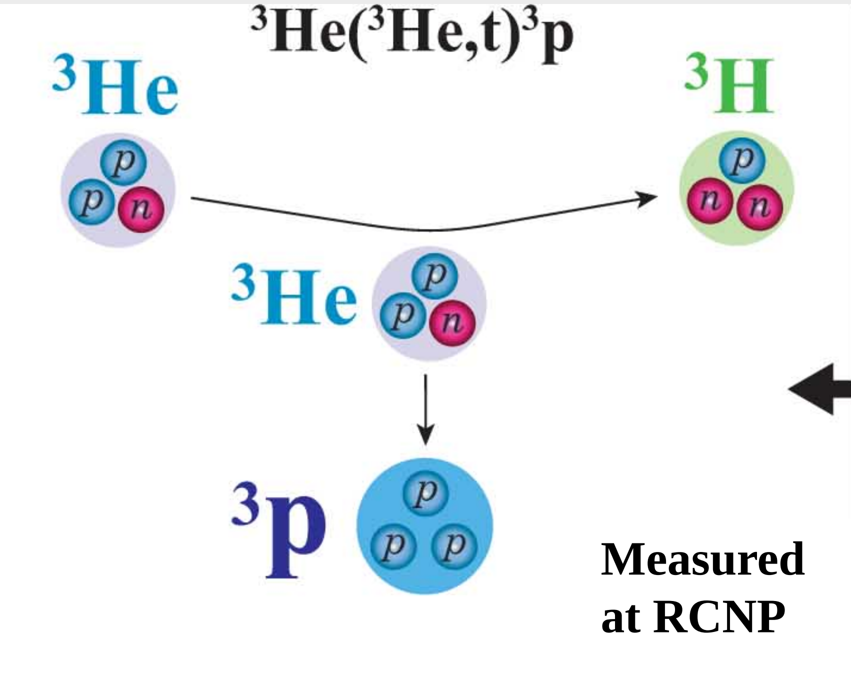
Large opportunity of observing 3n resonance .
(It depends on S/N(QFS)).

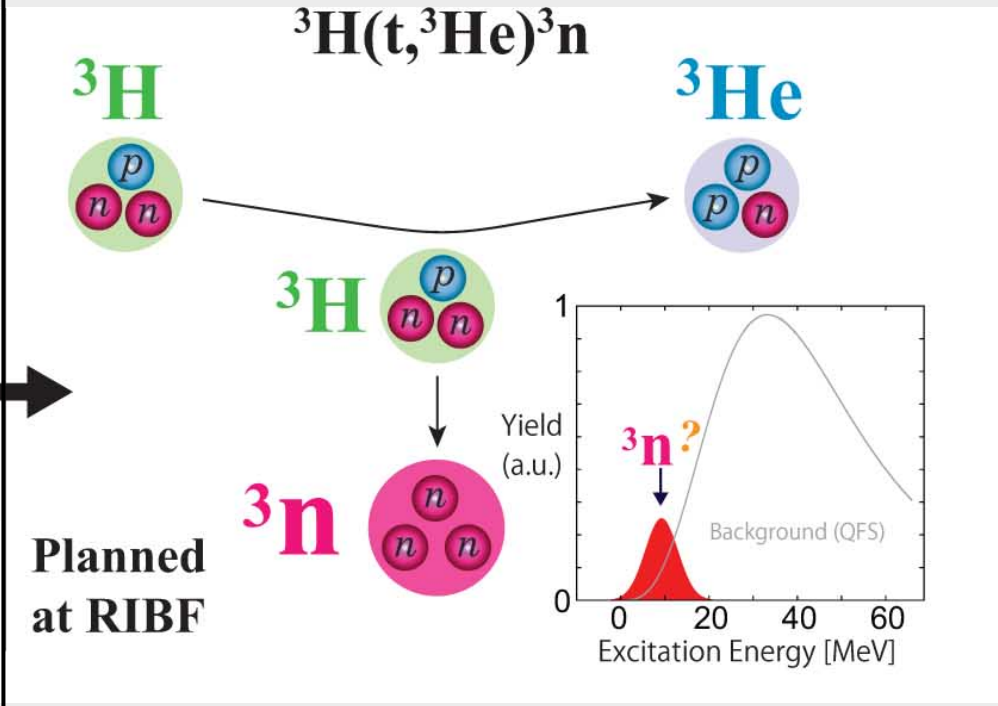
Considering isospin symmetry,
^{3}He(^{3}He,t)3p is very interesting (3p ↔ 3n).

Study of three-nucleon resonance states via ^{3}He(^{3}He,*t*)3p and ^{3}H(*t*,^{3}He)3n

Spokesperson: K. Miki, D. Sakai

^{3}p (new) and ^{3}n (plan) measurements



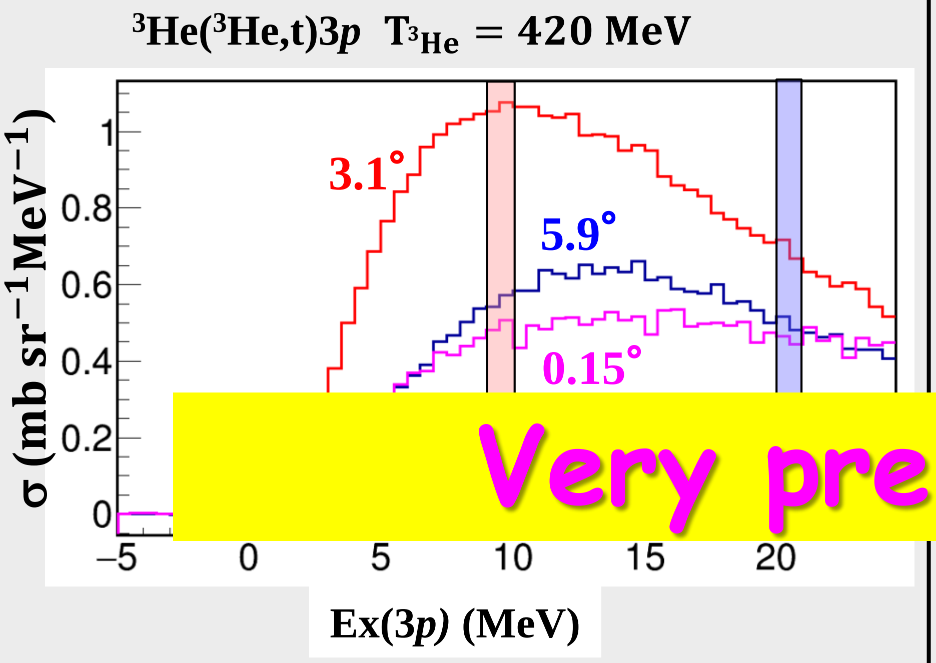


- E502 exp. Done.
- GRAIDEN at RCNP
- E(3He)=140 MeV/u
- ΔE~0.4 MeV
- Ex=0 – 25 MeV
- θ(lab)=0 – 6 degrees

- Proposal accepted (NP1712-SHARAQ11)
- SHARAQ at RIBF
- E(*t*)~140 MeV/u
- Tritium target, in preparation

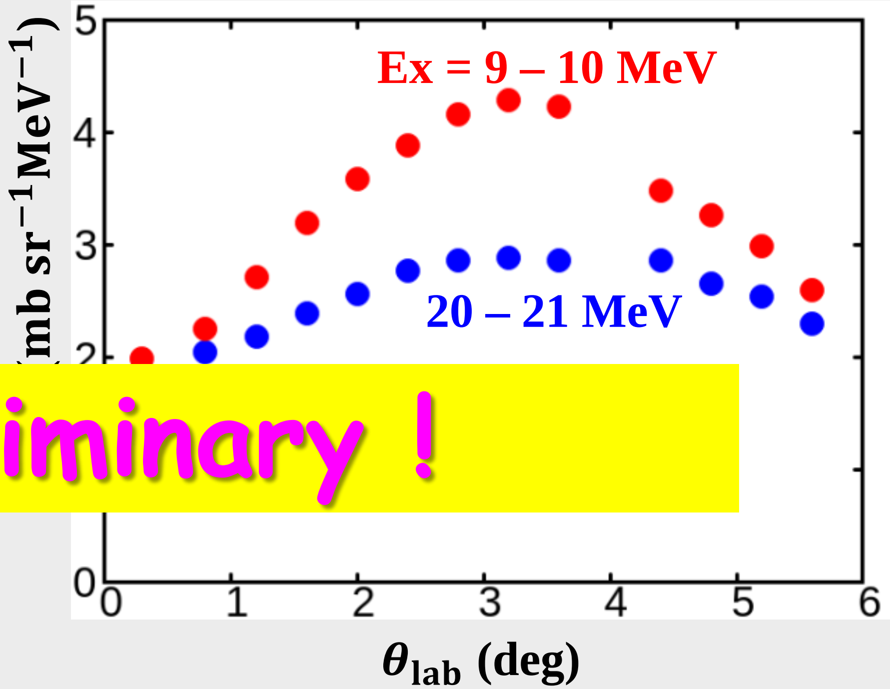
$^3He(^3He,t)3p$ measurement (preliminary)

- **Excitation-energy functions**



- No sharp peak
- Broad peak at Ex~10 MeV

- **Angular distributions**



Very preliminary !

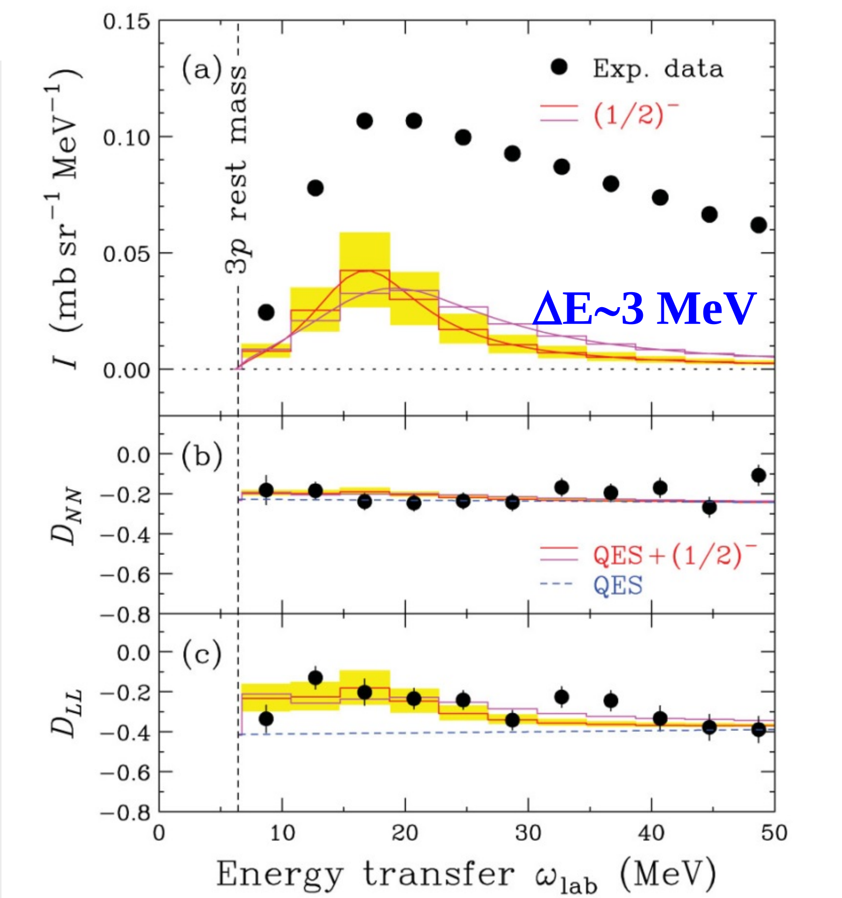
- σ(θ) peaks at ~3°, expected for L=1.
- QFS background?

^{3}He(p,n)3p vs. ^{3}He(^{3}He,t)3p at 0°

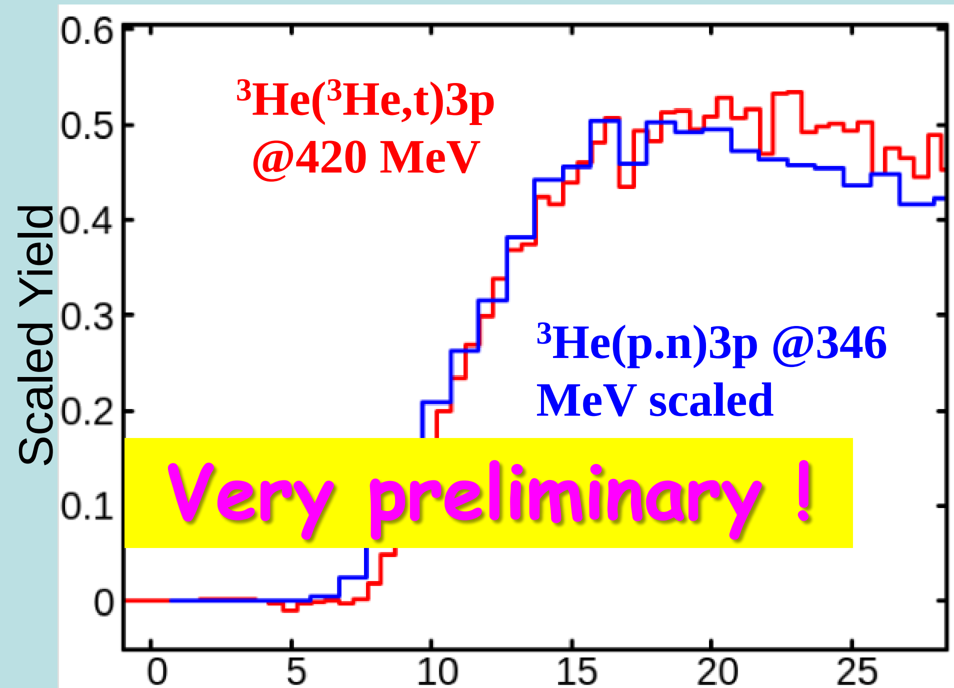
PHYSICAL REVIEW C **77**, 054611 (2008)

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]



Comparison at 0°



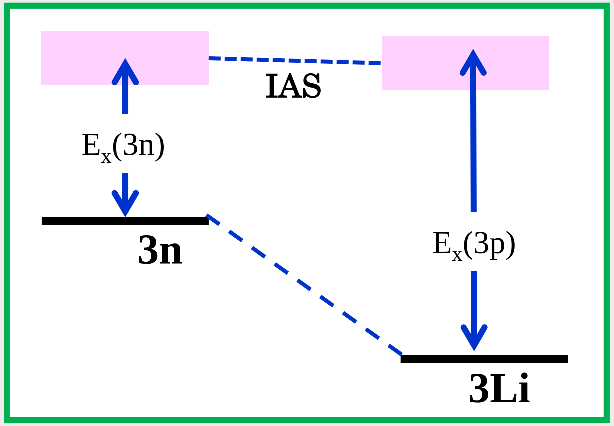
Amazing agreement!

Isospin symmetry and 3n resonance energy

- **Wakasa derived**

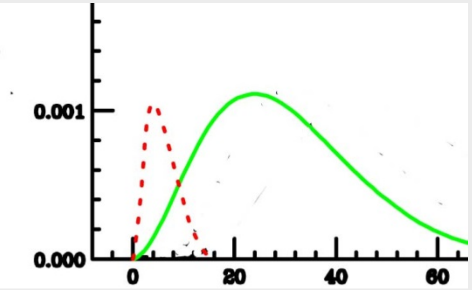
$E_r(^3Li) = 9\pm1$ MeV
$\Gamma_r(^3Li) = 10.5\pm1$ MeV

$J^\pi(3p) = 1/2^-$ suggested



$$E_x(^3n) = E_x(^3p) - \left[\Delta\varepsilon_{Coul} + \left(m(^3n) - m(^3p)\right)\right]$$
$$= 9 - 3.4 - 2{,}4 \sim \mathbf{3\ MeV}$$

- **Tetraneutron resonance may exist at Ex ~ 3 MeV !**
- **Width Γ and S/N ?**



Please look forward to 3H(t,3He)3n measurement.
Stay tuned.

4NF

How about four nucleon force (4NF) ?

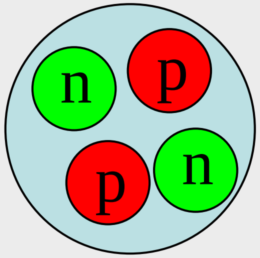
- **Binding energy ^{4}He [MeV]**

Potential	w/o 3NF	With 3NF
CDBONN	26.26	28.40
Nijmegen I	24.98	28.60
Njimegen II	24.56	28.56
AV-18	24.25	28.36
Exp. value		28.30

6 pairs : 2NF

4 pairs : 3NF

1 pair : 4NF



Reproduced only with 3NF

→ 4NF : very small, if exists at all.

- **χEFT prediction**

J.L. Friar : FBS Suppl. 99(2018)1

$$\langle V_{NN} \rangle \sim 20\,\mathrm{MeV/pair}\,,$$

$$\langle V_{3Nf} \rangle \sim 1\,\mathrm{MeV/triplet}\,,$$

$$\langle V_{4Nf} \rangle \lesssim 0.1\,\mathrm{MeV/quartet}\,.$$

Summary

- **Three nucleon force (3NF)**
  - Proton + deuteron scattering ⇒ 30% discrepancy in X-sec.
  - Clear signature of 3NF (sensitive to T=1/2)
- **Tetraneutron (4n) search**
  - Exothermic DCHEX. ^{4}He(^{8}He,^{8}Be)4n
  - 4 counts at Ex~1 MeV; resonance?
  - New meas. ; still in analysis
- **Trineutron (3n) search**
  - 3n measurement with ^{3}H(t,^{3}He)3n is in plan. Tritium target?
  - 3p data is taken with ^{3}He(^{3}He,t)3p.
  - Predicts E_r(3n)~3 MeV
- **Next target : T=3/2 3NF, 4NF or …**

Tritium beam
@ ISOL +SCL3+KOBRA

~my small suggestion~
Could be totally nonsense

18.5 MeV tritium beam@SCL3 A/q=3

- Open up unique facility in the world
  - Few-body physics
  - Nuclear spectroscopy, (t,p)/(t,3He)/etc.
    (astrophysics? (α,p)~(t,γ))
- How to produce tritium beam
  - ISOL (possible ?)
  - Better to construct a dedicated small target system
    - p(70MeV)+ 4He/7Li→ t+etc.
      (only light particles, n,p,d,t,α are produced)
    - etc.
- Many Difficulties
  - Radiation safety
  - etc.

Thank you !　　　감사 !

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성과가 매우 오르는 것을
간절히기도합니다