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

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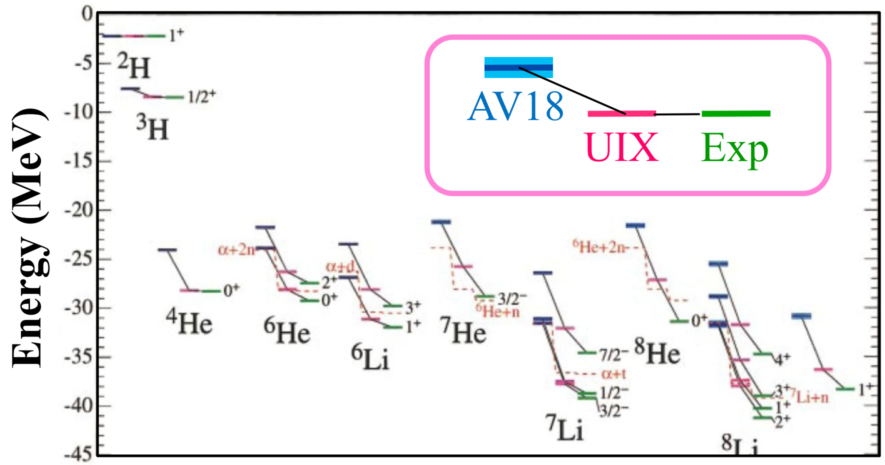
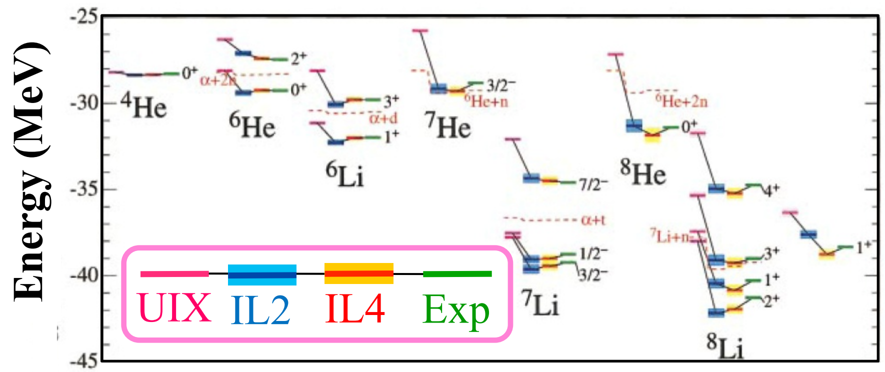
(RCNP-E300 collaboration)

A≧4 Systems and T=3/2 3NF

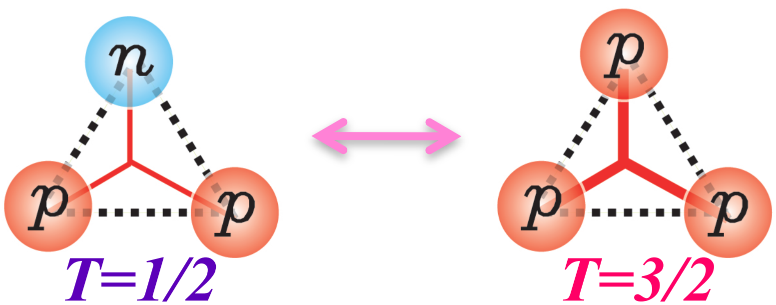
S.C.Pieper et al. PRC 64(2001)014001.

- Binding energy for A≧4
  - Two nucleon force only
    - Significant under-binding
  - With UIX three nucleon force
    - Close to experimental values
    - Still under-binding
- Isospin-dependent three nucleon force
  - Illinois three-nucleon forces (IL2/4)
    - To describe neutron-rich system
      - Repulsive in T=1/2
      - Attractive in T=3/2





Experimental information on A=3&T=3/2 systems are important



T=3/2 Three Nucleon Forces and Resonances

- Recent Faddeev calculations for T=3/2 three nucleon system (3n)

  A.Hemmdan, W.Glockle, and H.Kamada PRC 66, 054001 (2002).

  - Only two-nucleon forces are considered
    - $J^{\pi}=3/2^{-}$ -12.13 -*i*37.96
    - $J^{\pi}=3/2^{+}$ -10.30 -*i*33.20
    - $J^{\pi}=1/2^{-}$ -20.38 -*i*45.27
    - $J^{\pi}=1/2^{+}$ -14.29 -*i*48.34

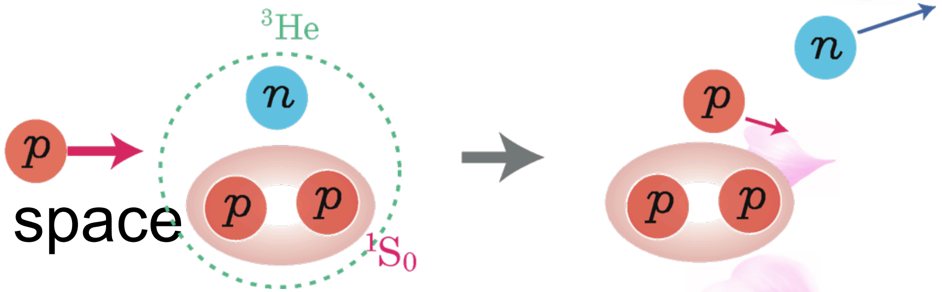
    Far away from the positive real-energy axis

  - "NO" three nucleon resonances
    - Existence of T=3/2 three nucleon resonances
      ⇒ Existence of T=3/2 three nucleon forces
    - Information on T=3/2 three nucleon resonances (Position and width)
      ⇒ Information on T=3/2 three nucleon forces

Previous Study of 3*p* Resonances and 2*p* correlation effects

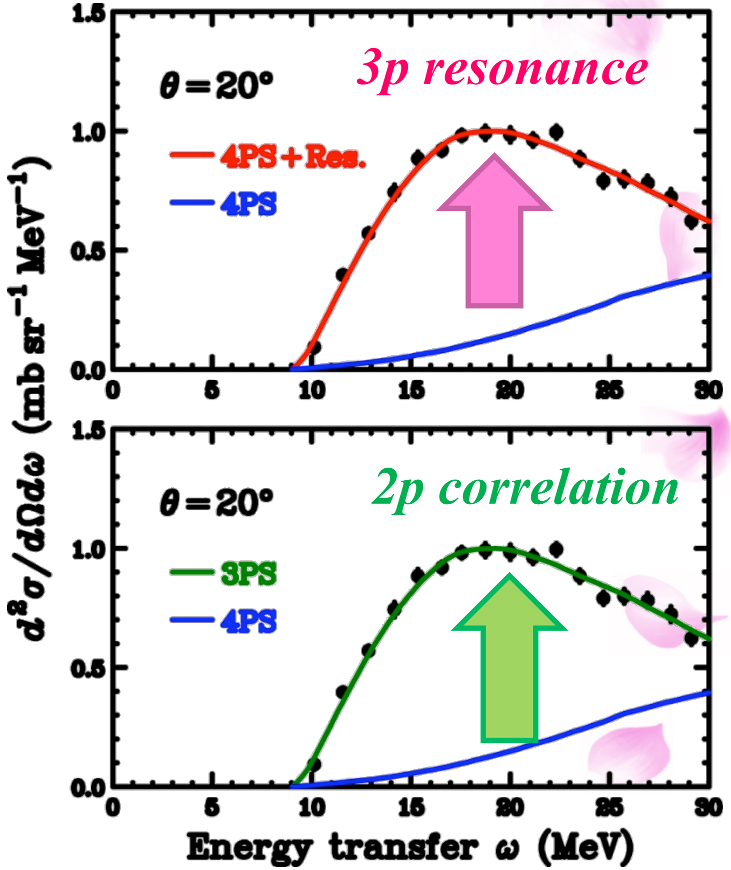
L.E.Williams et al.,PRL 23(1969)1181.
M.Palarczyk et al.,PRC 58(1998)645.

- Production of 3p (T=3/2)
  - ^{3}He(p,n)3p at 48.8 MeV
- Comparison with 4-body phase space calc. would be inappropriate
  - 2-protons in ^{3}He form $^1S_0$ state
    - Strongly correlated
    - Act as 1-body ^{2}He



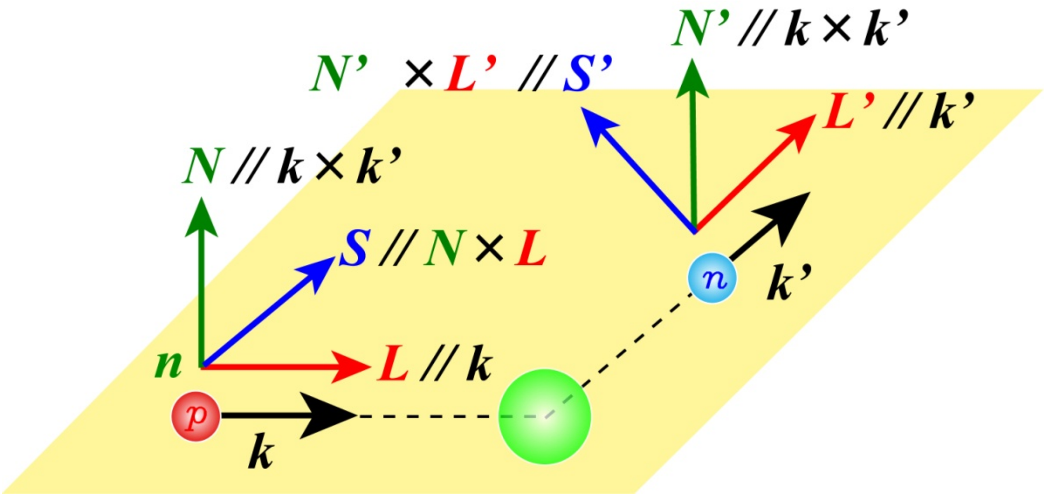
3-body phase space calc. would be appropriate

Excess from 4-body phase space
⇒2p correlation effects
(NOT 3p resonance)

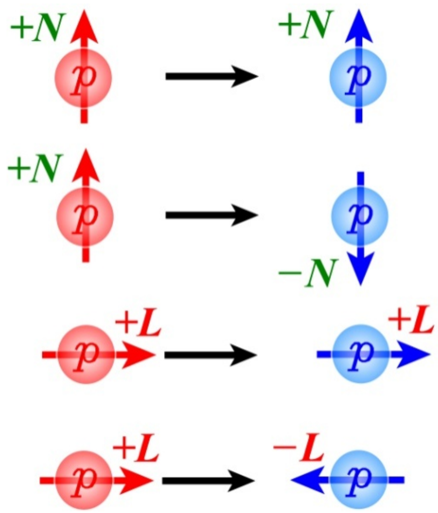


Coordinate System and Polarization Observables

- Coordinate system
  - Longitudinal (k-direction)
  - Normal (to reaction plane)
  - Sideways
- At 0 degrees
  - L = L’
  - N = N’ = S = S’
  - Only L and N are meaningful



- Spin-flip probability S_{ii} and polarization transfer observables D_{ii}



Normal spin-non-flip prob. : $S_{NN} = 0$

Normal spin-flip prob. : $S_{NN} = 1$

Longitudinal spin-non-flip prob. : $S_{LL} = 0$

Longitudinal spin-flip prob. : $S_{LL} = 1$

✓ $S_{ii} \equiv \frac{1}{2}(1 - D_{ii})$

✓ S_{ii} *depends on reaction*

✓ $S_{LN} = S_{NL} = 0.5$ *from symmetry*

NN Scattering and Polarization Observables

- NN t-matrix (scattering amplitude)
  - Franey-Love notation

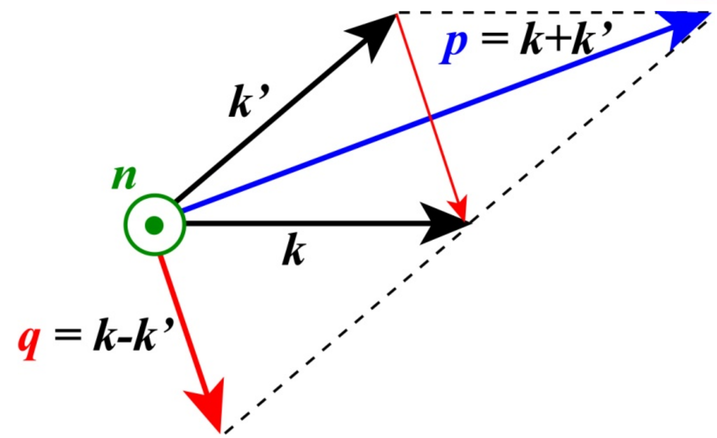
Central Spin-orbit

$$t_{NN}(E,q) = A'P_S + B'P_T + C(\vec{\sigma}_1 + \vec{\sigma}_2)\cdot\hat{n} + E'S_{12}(\hat{q}) + F'S_{12}(\hat{p})$$

Tensor

  - Kerman-McManus-Thaler notation

$$t_{NN}(E,q) = A + B\vec{\sigma}_1\cdot\hat{n}\,\vec{\sigma}_2\cdot\hat{n} + C(\vec{\sigma}_1 + \vec{\sigma}_2)\cdot\hat{n} + E\vec{\sigma}_1\cdot\hat{q}\,\vec{\sigma}_2\cdot\hat{q} + F\vec{\sigma}_1\cdot\hat{p}\,\vec{\sigma}_2\cdot\hat{p}$$



$$S_{12}(\hat{u}) = 3\vec{\sigma}_1\cdot\hat{u}\,\vec{\sigma}_2\cdot\hat{u} - \vec{\sigma}_1\cdot\vec{\sigma}_2$$

- Cross section and polarization observables

$$\frac{d\sigma}{d\Omega}(E,q) = \mathrm{Tr}(t^+t) = 2(A^2 + B^2 + 2C^2 + E^2 + F^2)$$

$$D_{nn}(E,q) = D_{NN}(E,q) = \frac{\mathrm{Tr}(t^+\vec{\sigma}_1\cdot\hat{n}\ t\vec{\sigma}_1\cdot\hat{n})}{\mathrm{Tr}(t^+t)} = \frac{A^2 + B^2 + 2C^2 - E^2 - F^2}{A^2 + B^2 + 2C^2 + E^2 + F^2}$$

$$\vec{\sigma}_1\cdot\hat{i}\,\vec{\sigma}_1\cdot\hat{j} = i\varepsilon_{ijk}\vec{\sigma}_k + \delta_{ij}$$

$$\{i,j,k\} = \{n,p,q\}$$

Scattering t-matrix (amplitude) ⇒ D_{ij} in NN scattering is calculable

Power of Polarization Observables

Filter to Spin-Parity

M.Dozono et al., J.Phys.Soc.Jpn.77(2008)014201

- Resonance has definite spin-parity
  - J^π sensitive probe is useful to identify resonance
  - Polarization observables are powerful
    - Sensitive to spin-parity
- Example for $0^+ \rightarrow J^\pi$ ($\Delta S=1$) transition
  - PWIA with central only

$$D_L = \frac{1}{2}(2S_{NN} - S_{LL}) = \frac{1}{4}(1 - 2D_{NN} + D_{LL})$$

$$D_T = S_{LL} = \frac{1}{2}(1 - D_{LL})$$

Significantly different

J^π	D_L	D_T	D_L/D_T
1^+	0.33	0.67	0.50
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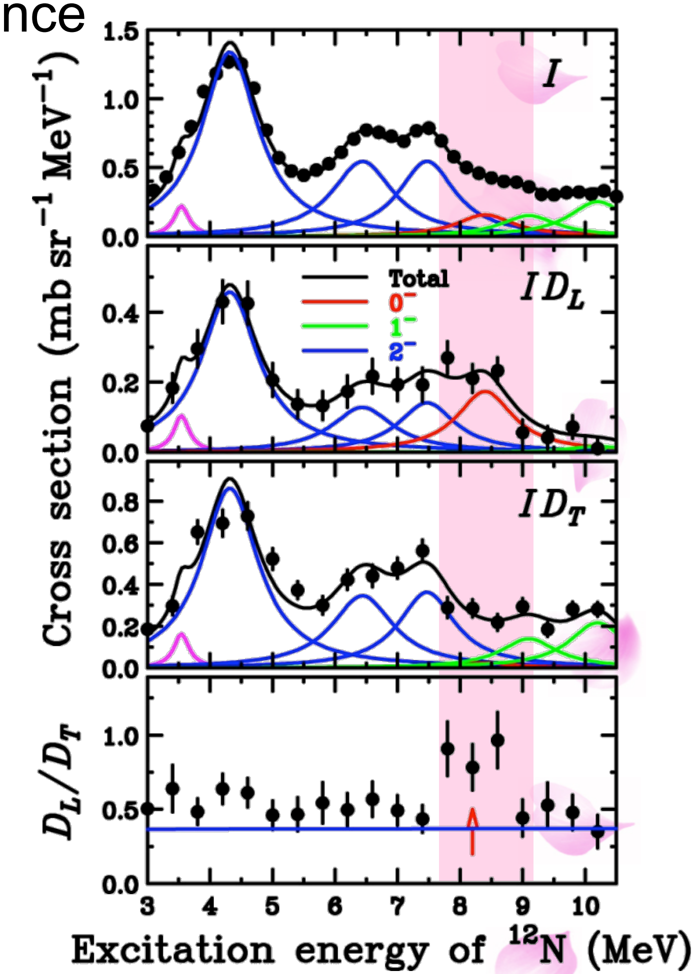
$^{12}C(p,n)^{12}N$ at 296 MeV and 0°



Measure D_{ii} (D_L/D_T) for $^3He(p,n)$ → Identify resonance and its J^π

Experiment

RCNP Ring Cyclotron Facility

60 mm

Cooled Gas

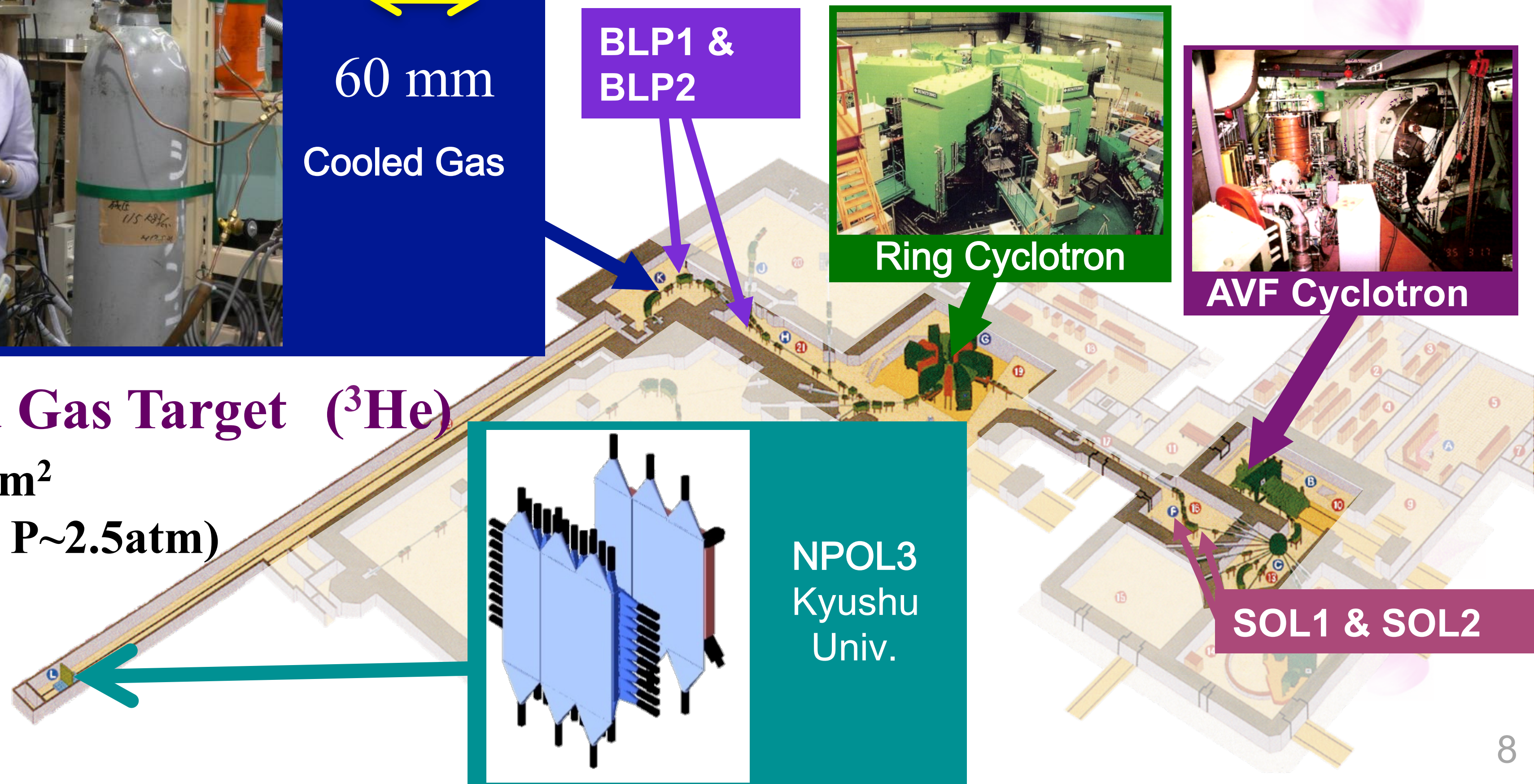
Polarized proton beam

- $T_p = 346$ *MeV*
- $p = 60\%$

Cooled Gas Target (^{3}He)

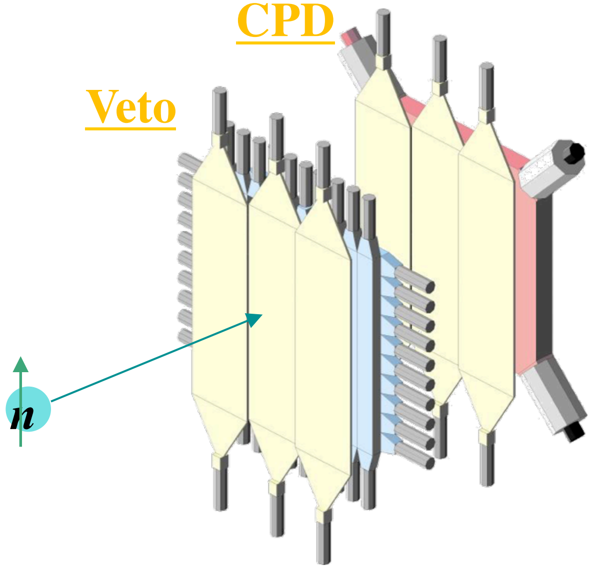
~11mg/cm^2

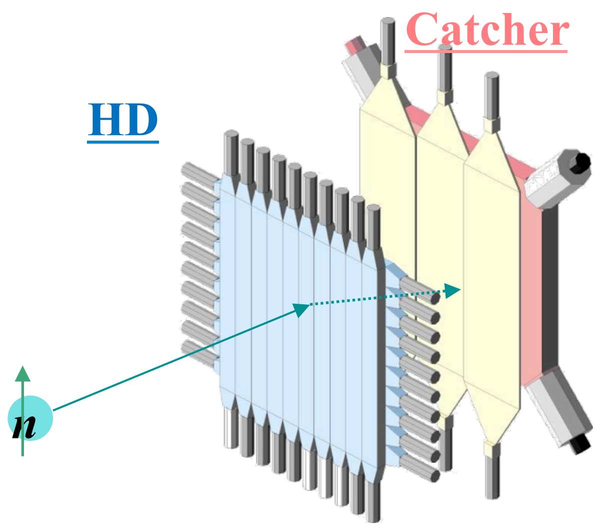
(T~25K, P~2.5atm)



Neutron Detector/Polarimeter NPOL3

T.W., Y.Hagihara et al.,NIM A 547(2005)569.





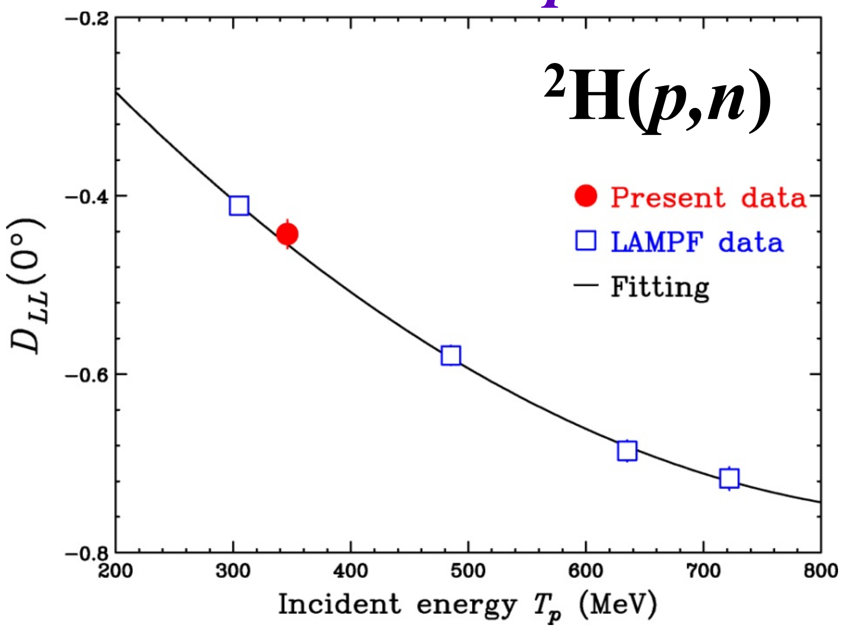
Veto/CPD …. Veto/Identify protons

HD …. Neutron scatterer (analyzer)

Catcher …. Detect recoil protons

Left/Right asymmetry

→ Neutron polarization



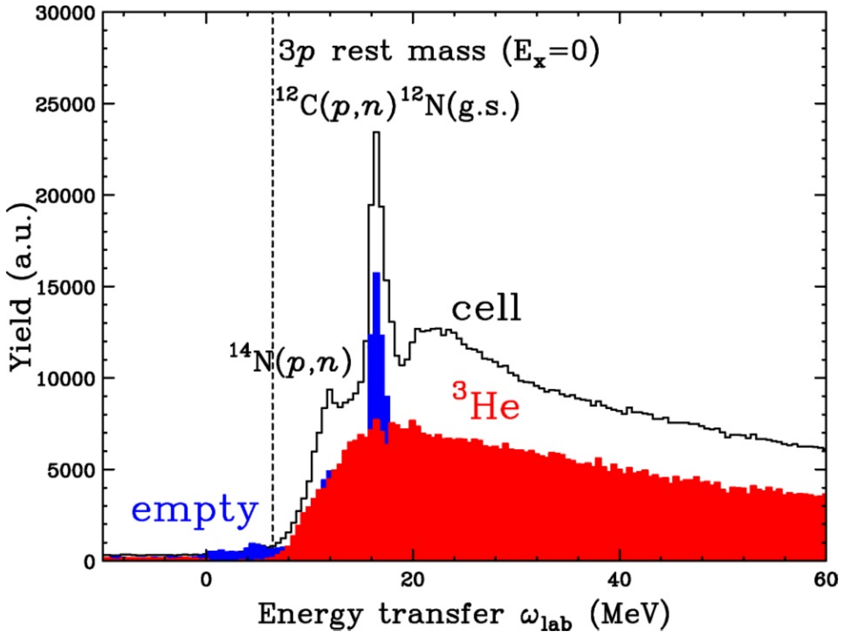
Consistent with previous data ⇒ High reliability

M. W. McNaughton et al., Phys. Rev. C 45 (1992) 2564.

Results

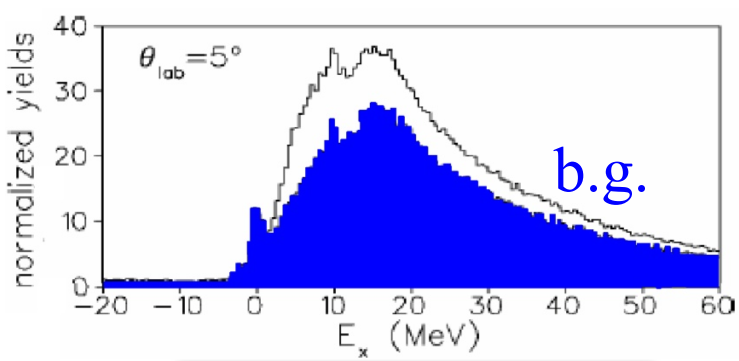
Background Subtraction

- High S/N compared with Indiana data
  - Thanks to relatively thin Alamid window
- B.G. including narrow peaks and broad bump (SDR)
  - Successfully subtracted without adjusting relative normalization
  - *Demonstrating reliability of our data*



Our data

^{3}He(p,n) at 200 MeV at Indiana



Indiana data

Results

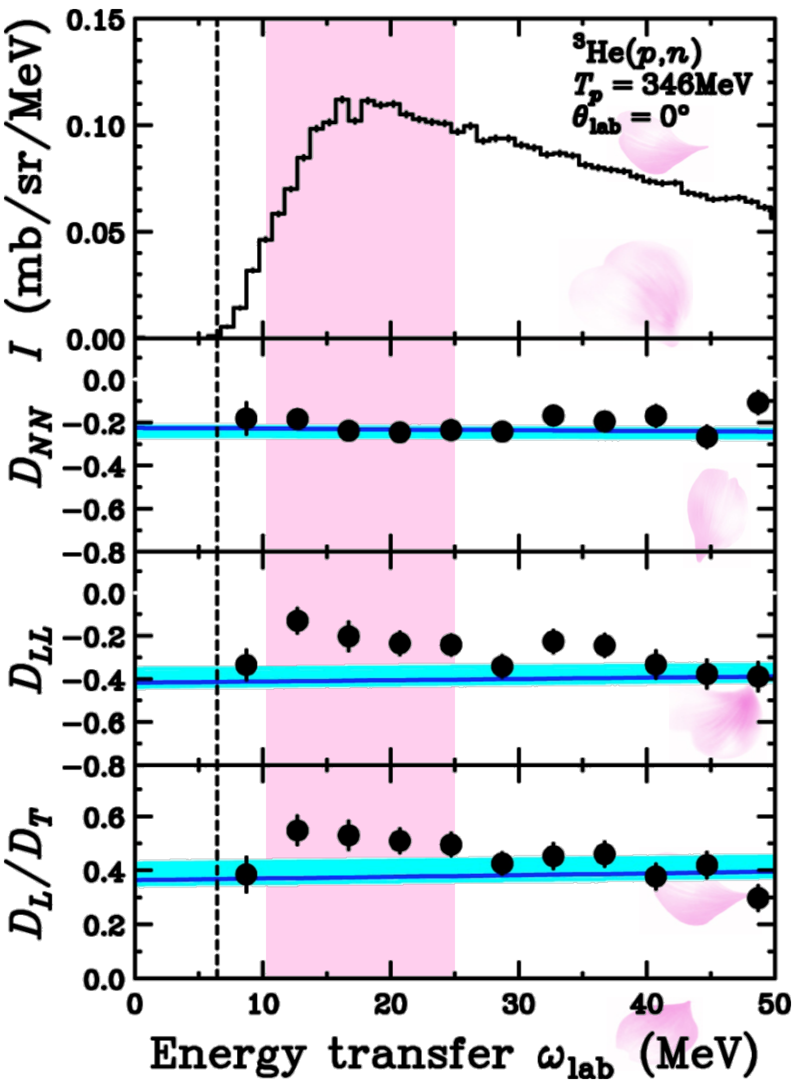
Polarization Observables

- Comparison with QES
  - Free NN values (w/o medium effects)
    - Blue curve
      - Phase-shift solution FA07
    - Cyan band
      - Modern NN potential (AV18, CD-Bonn, Nij93, Paris)
  - Significant deviations in D_{LL} and D_L/D_T

Signature of resonance (?)

- D_L/D_T for resonance
  - QES(B.G.) $D_L/D_T = 0.4$
  - Exp.(B.G. + Res.) $D_L/D_T > 0.5$

Resonance $D_L/D_T > 0.5$
⇒ Determination of J^π

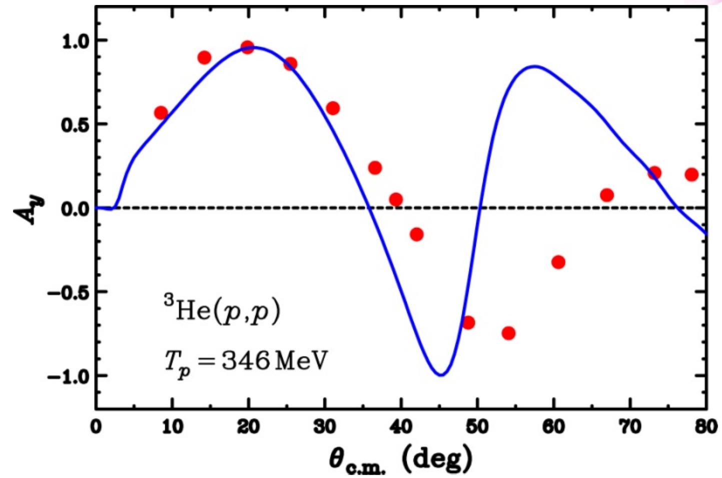


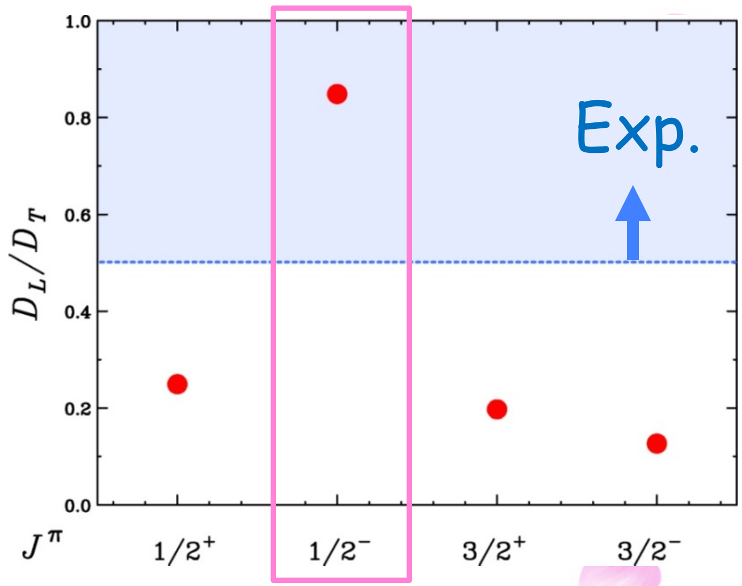
Spin-Parity of Resonance

- DWIA calculations with dw81
  - Optical potential
    - Global potential for ^{4}He
    - Reasonably reproduce our A_y data
  - NN t-matrix
    - Franey and Love at 325 MeV
  - Transition matrix element
    - G-matrix effective interaction for A=3
      - *Hosaka et al., NPA 444, 76 (1985).*
    - 0s-0p-1s0d-0f1p with *OXBASH*

DWIA results are insensitive to params.

Final J^π	$D_{NN}(0°)$	$D_{LL}(0°)$	$D_L(0°)$	$D_T(0°)$
$1/2^+$	−0.19	−0.58	0.20	0.79
$1/2^-$	−0.11	+0.18	0.35	0.41
$3/2^+$	−0.15	−0.65	0.16	0.83
$3/2^-$	+0.16	−0.33	0.09	0.67





Resonance J^π=1/2$^-$

Energy and Width of Resonances

- Assumption
  - "Incoherent" sum of Res. (1/2⁻) and QES

Resonance QES

$$\sigma^{\exp}(0°) = \sigma^{1/2^-}(0°) + \sigma^{\rm QES}(0°)$$

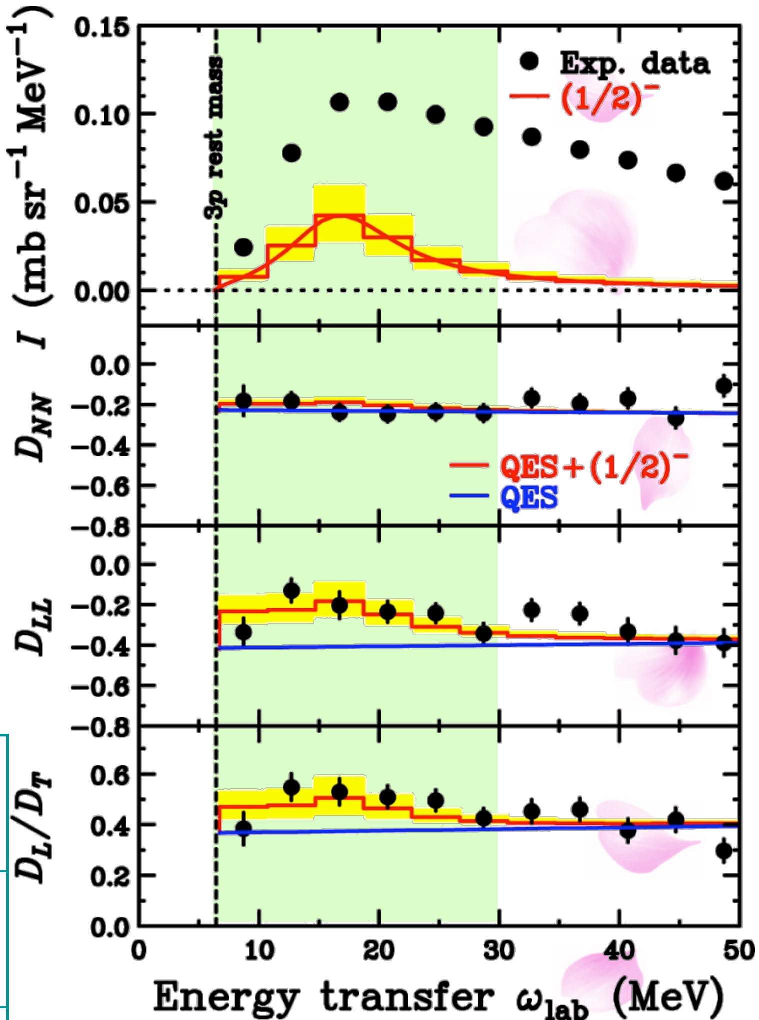
$$\sigma^{\exp}(0°)D_{NN}^{\exp}(0°) = \sigma^{1/2^-}(0°)D_{NN}^{1/2^-}(0°) + \sigma^{\rm QES}(0°)D_{NN}^{\rm QES}(0°)$$

$$\sigma^{\exp}(0°)D_{LL}^{\exp}(0°) = \sigma^{1/2^-}(0°)D_{LL}^{1/2^-}(0°) + \sigma^{\rm QES}(0°)D_{LL}^{\rm QES}(0°)$$

  - Bright-Wigner function (with Phase-space)

$$\sigma^{1/2^-}(0°) = \frac{A}{\pi}\frac{\Gamma/2}{(\omega-\omega_0)^2+(\Gamma/2)^2}$$

Data	Fit range	Central (MeV)	Ex (MeV)	FWHM (MeV)
This work	$\omega_{\rm lab} < 30$MeV	16±1	**10±1**	**11±3**
Williams *et al.* (*I*のみ)			9±1	10.5±1



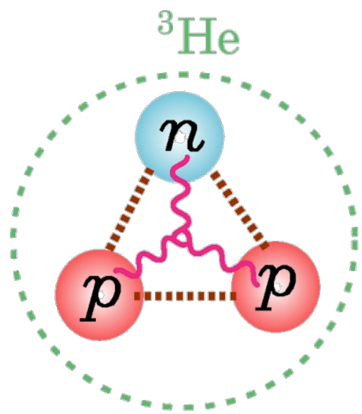
Summary

- First measurement of complete polarization transfer D_{ij} measurements for $^3He(p,n)$ at 0°
  - Clean measurement with high S/N (∼6)
  - Highly precise and reliable data
- Signature of T=3/2 resonance in D_{LL} and D_L/D_T
  - Spin-parity 1/2$^-$
  - Energy $E_x = 10 \pm 1$ MeV
  - Width $\Gamma = 11 \pm 3$ MeV
- Future perspective
  - Detailed theoretical investigations are highly required

MISC

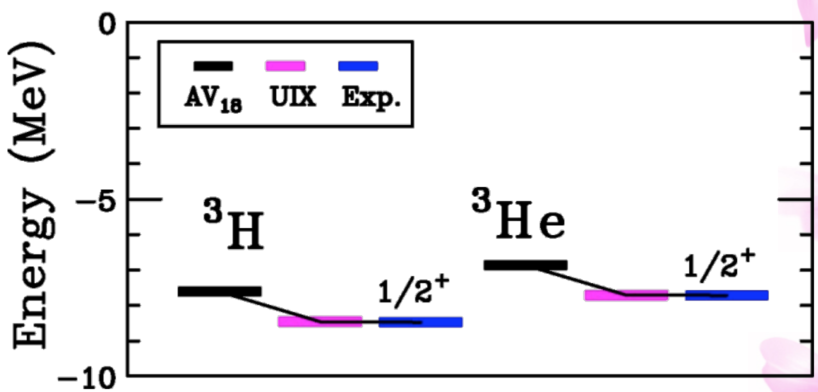
Three Nucleon Forces

- Three Nucleon Systems
  - Isospin T=1/2, 3/2
  - T=1/2 system
    - ^{3}He, ^{3}H, d+p
  - T=3/2 system
    - 3p,3n (No bound state)



- T=1/2 system
  - Scalar observables
    - Binding energy
    - Cross section

  can be reproduced



by introducing three nucleon forces

S.C.Pieper et al.
PRC 64(2001)014001.

How about A≧4 and T=3/2 three nucleon forces

Previous Study of 3*p* Resonances

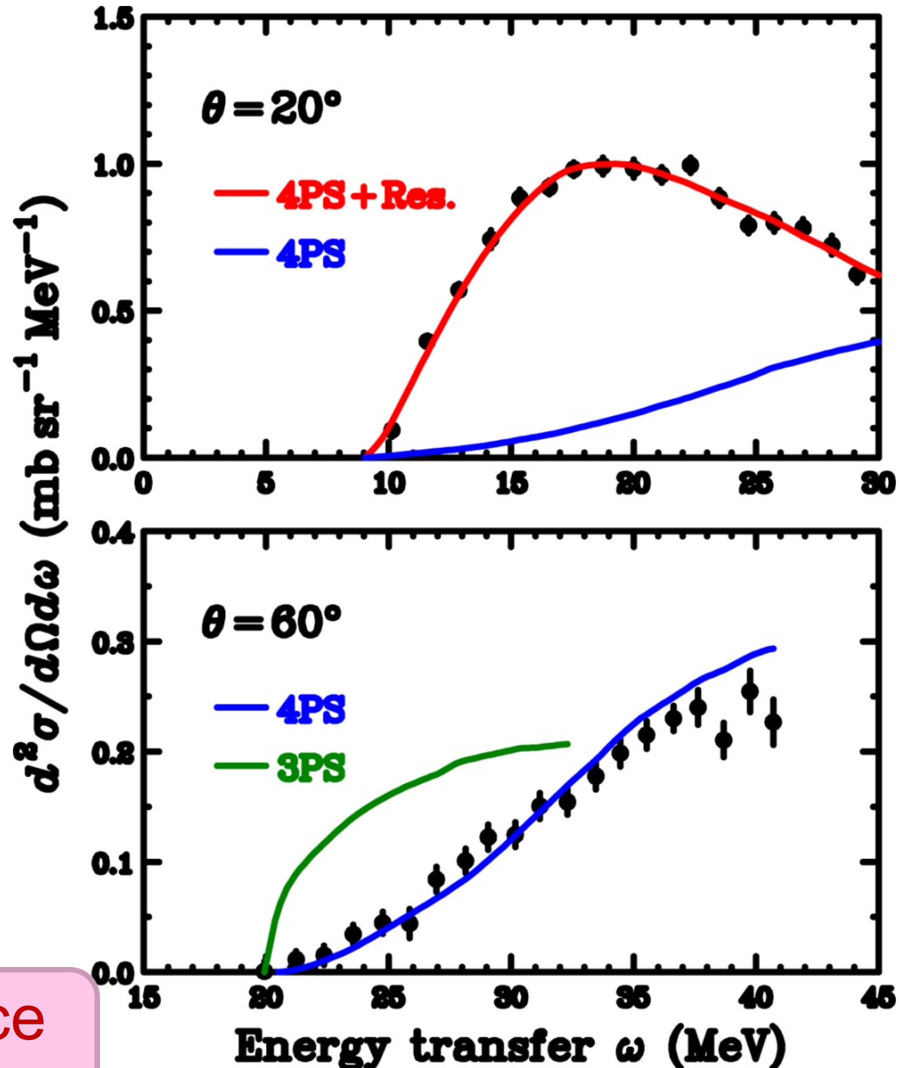
L.E.Williams et al.,PRL 23(1969)1181.

- Production of 3p (T=3/2)
  - ^{3}He(p,n)3p at 48.8 MeV
- At θ=60°(Backward angles)
  - Exp. Data
    = 4-body phase-space calc. (n+3p)
    < 3-body phase-space calc.

Physical B.G. is well described by 4-body phase-space

- At θ=20°(Forward angles)
  - Exp. Data
    > 4-body phase-space calc.

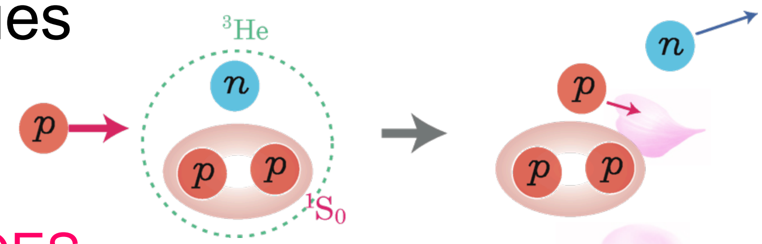
Excess from 4-body phase space
⇒ Contribution from 3p resonance



^{3}He(p,n)3p at Intermediate Energies

G.F.Bertsch and O.Scolten PRC 25(1982)804.

- Physical B.G. at intermediate energies
  - Quasi-elastic scattering (QES)
    - NN scattering in nuclei
  - 3p resonance would be built on top of QES



Quantitative description of QES is important to identify 3p resonance

- Fermi-Gas model for QES

Effective neutron number (<N) *NN cross section*

QES cross section

$$\frac{d^2\sigma}{d\Omega dE} = N_{\mathrm{eff}} \left(\frac{d\sigma}{d\Omega} \right)_{NN} S(q, E)$$

Momentum transfer (q)

Energy transfer (E)

Response function

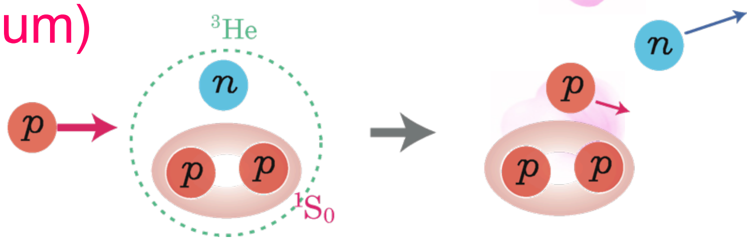
(Imaginary part of Lindhard function)

$$S(q,E) = \begin{cases} \dfrac{3m}{4qk_F^3} 2mE & (|2qk_F| > 2mE + q^2) \\ \dfrac{3m}{4qk_F^3} \left[k_F^2 - \left(\dfrac{1}{2}q^2 - mE \right)^2 / q^2 \right] & (|2qk_F| < 2mE + q^2) \\ 0 & ((q^2/2 - mE)^2 > k_F^2 q^2) \end{cases}$$

Fermi momentum (k_F)

Fermi Gas Response Function

- ^{3}He in Fermi Gas model
  - In momentum space: ^{3}He = $4\pi k_F^3/3$ (Fermi sphere)
  - Neutron momentum $k < k_F$ (Fermi momentum)
- (p,n) scattering on neutron in ^{3}He
  - Target density in $k \sim k+dk = 4\pi k^2 dk$
  - Energy E and momentum q transfer to neutron (n→p)
  - Proton momentum $k' = k'(q, E) > k_F$
    (Outside of Fermi sphere for Pauli exclusion)



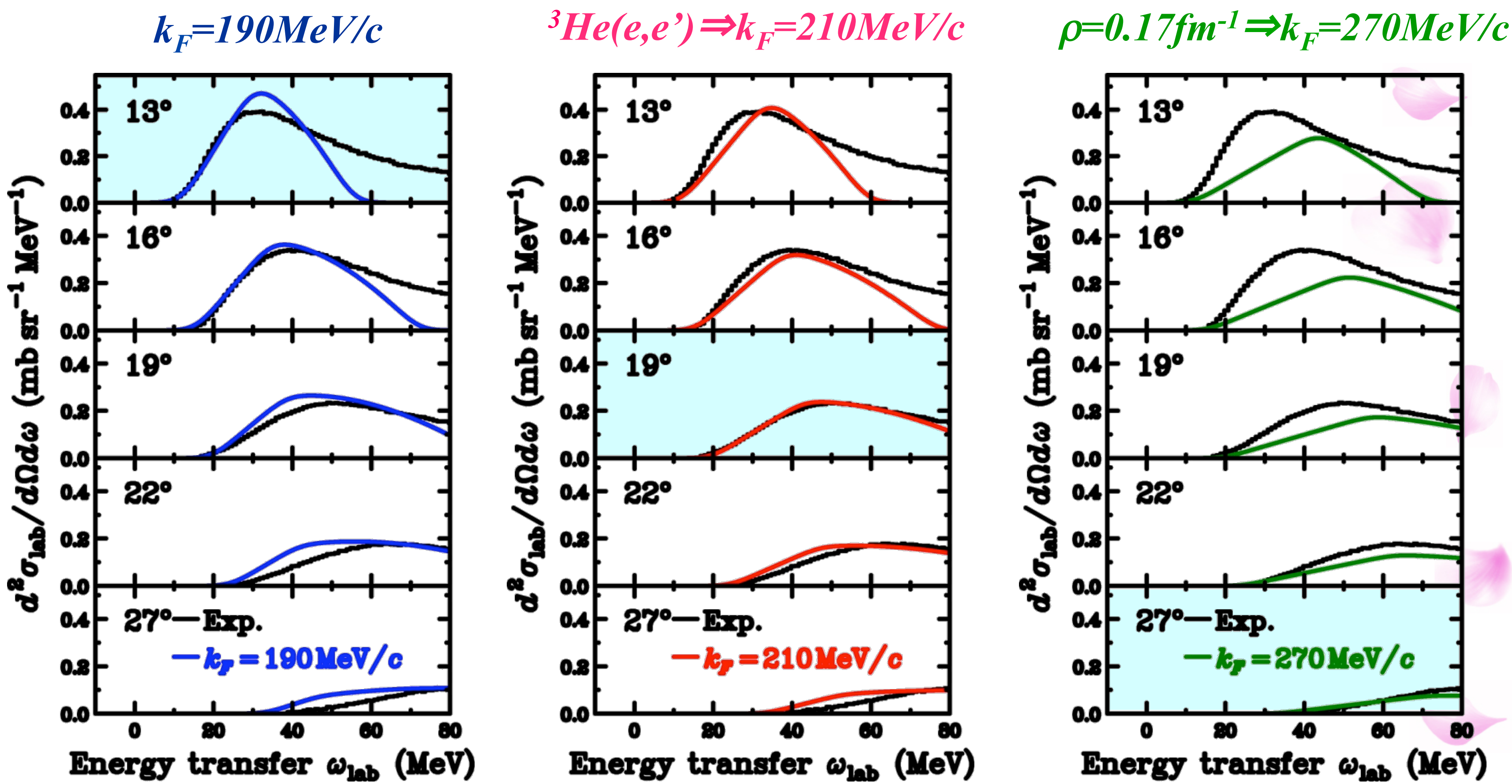
$$S(q,E) = \frac{1}{N}\sum_{k} \langle k | k \rangle \underbrace{\delta\left(\frac{k^2}{2m_N} + E - \frac{k'^2}{2m_N}\right)}_{\text{Energy conservation}}$$

Numerical solution (Imaginary part of Lindhard function)

With condition of
- $k < k_F$
- $k' > k_F$

Comparison with Fermi-Gas Model

$^3He(p,n)$ at 346 MeV (RCNP-E300)



Strong k_F dependence of QES ⇒ Difficult to deduce resonance information

Power of Polarization Observables

Filter to Spin-Parity

M.Dozono et al., J.Phys.Soc.Jpn.77(2008)014201

- Resonance has definite spin-parity
  - J^π sensitive probe is useful to identify resonance
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- Example for $0^+ \rightarrow J^\pi$ (ΔS=1) transition
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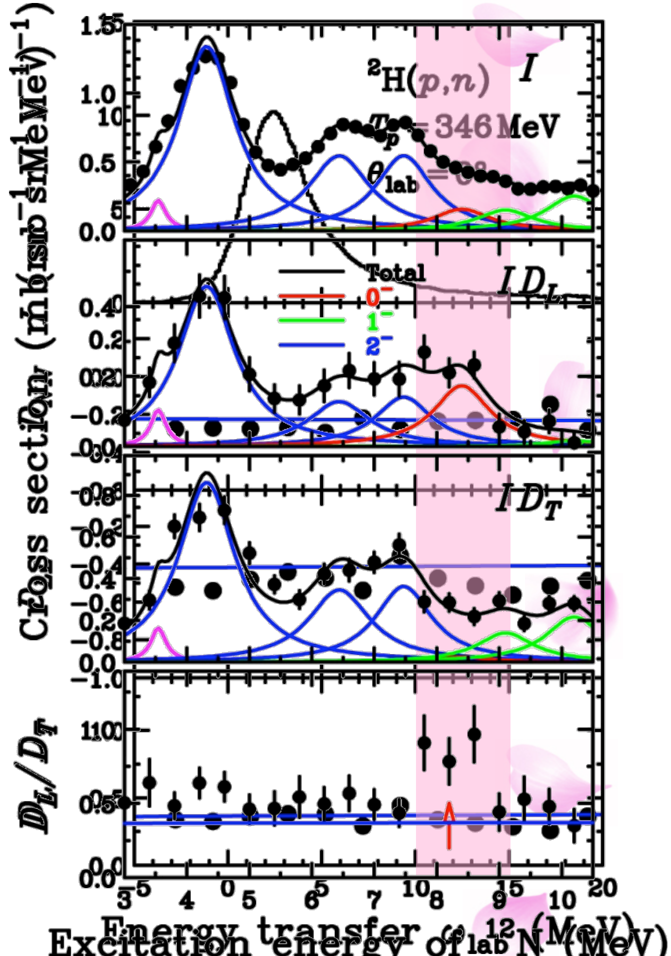
$^{12}C(p,n)^{12}N$ at 296 MeV and 0°



Measure D_{ii} (D_L/D_T) for $^3He(p,n)$ → Identify resonance and its J^π

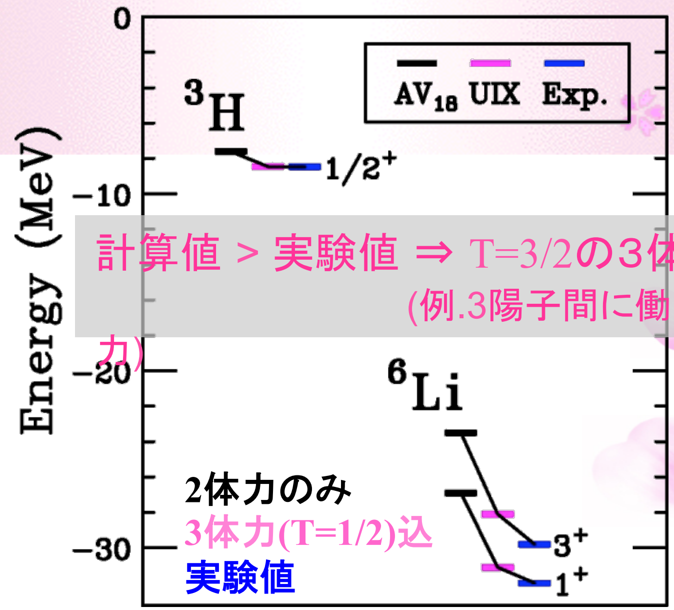
目的—アイソスピン3/2の３核子 共鳴状態の研究

- ３核子系

T=1/2　３体力の効果が証明されている。

一方・・・

T=3/2の３体力の有無は不明。
束縛状態がないため、実験データ不足



計算値 > 実験値 ⇒ T=3/2の3体力 (例.3陽子間に働く力)

^{3}He(*p*,*n*)3*p*反応

標的 : ^{3}He、反応 : (*p*,*n*) 、終状態 : 3*p*(T=3/2)

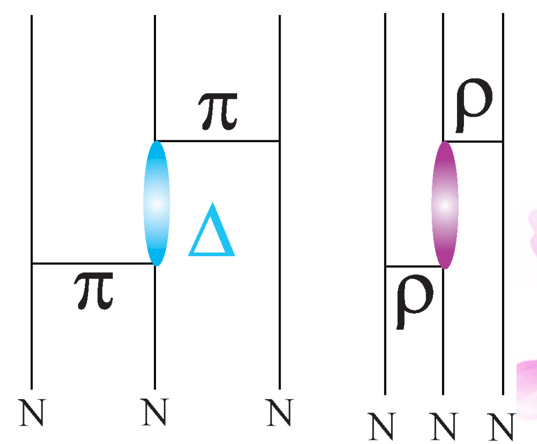
斥力→核子間距離　大

長距離力（ ππ型）

3*p* の共鳴状態の探査を通じて、長距離力T=3/2の3体力の有無を調べる。

最新の2体力のみの計算 : 共鳴状態　無
⇒共鳴状態が観測　⇒　**3体力の効果**

3体力
長距離力　　短距離力



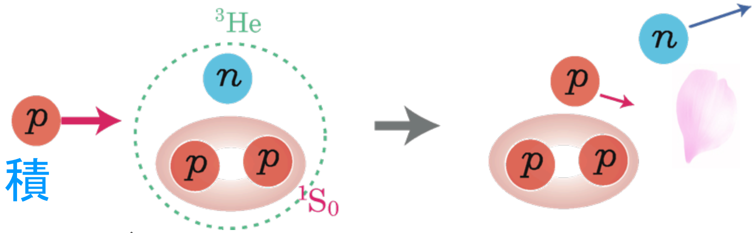
目的 − $^{3}\mathrm{He}(p,n)3p$ (T=3/2) T_p=350 MeV

中間エネルギー：反応機構が単純、準弾性散乱(QES)が主

(共鳴状態)+QES ➡ QESの記述が重要

フェルミ・ガス模型
(核子が低準位からフェルミ面までを占め、核子間相互作用を無視)

共鳴状態：運動量移行が小
⇒ 有限角度（運動量移行 大）でフェルミ・ガス模型と比較



有効中性子数 核子・核子散乱断面積

運動量 エネルギー

QES断面積 $$\frac{d^2\sigma}{d\Omega dE} = N_{\mathrm{eff}} \left(\frac{d\sigma}{d\Omega}\right)_{NN} S(q,E)$$

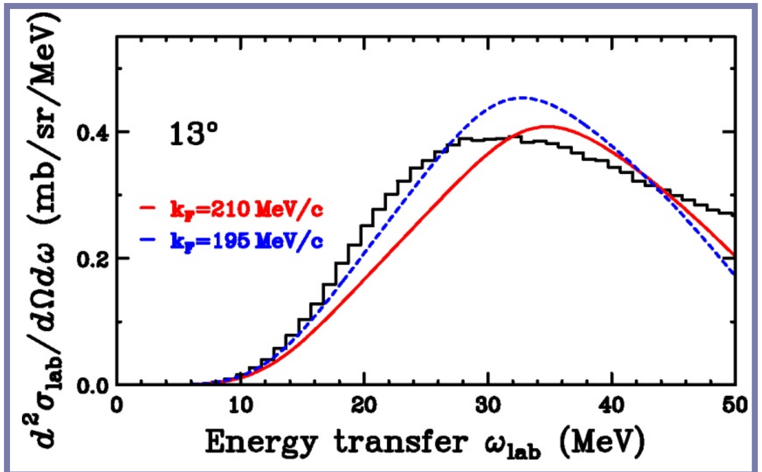
応答関数 (Lindhard関数虚部)

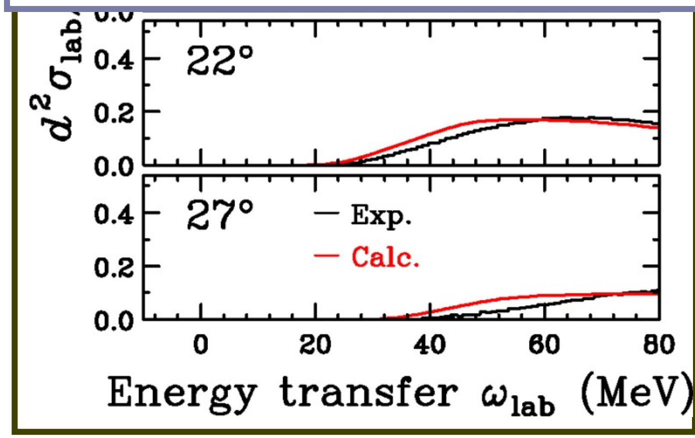
$$S(q,E) = \begin{cases} \dfrac{3m}{4qk_F^3} 2mE & (|2qk_F| > 2mE + q^2) \\ \dfrac{3m}{4qk_F^3}\left[k_F^2 - \left(\dfrac{1}{2}q^2 - mE\right)^2 / q^2\right] & (|2qk_F| < 2mE + q^2) \\ 0 & \left((q^2/2 - mE)^2 > k_F^2 q^2\right) \end{cases}$$

フェルミ波数

フェルミ・ガス模型

^{3}He(p,n) at 350 MeV





比較計算

k_F = 210 MeV/c ⬅ *From Indiana's ^{3}He(p,n) data*

N_{eff} = 1.0 ⬅ *From ^{2}H(p,n) data*

13°で不一致→ 高運動量成分粒子との散乱

立ち上がり部分

k_Fの違いで、QESの不定性が大きい

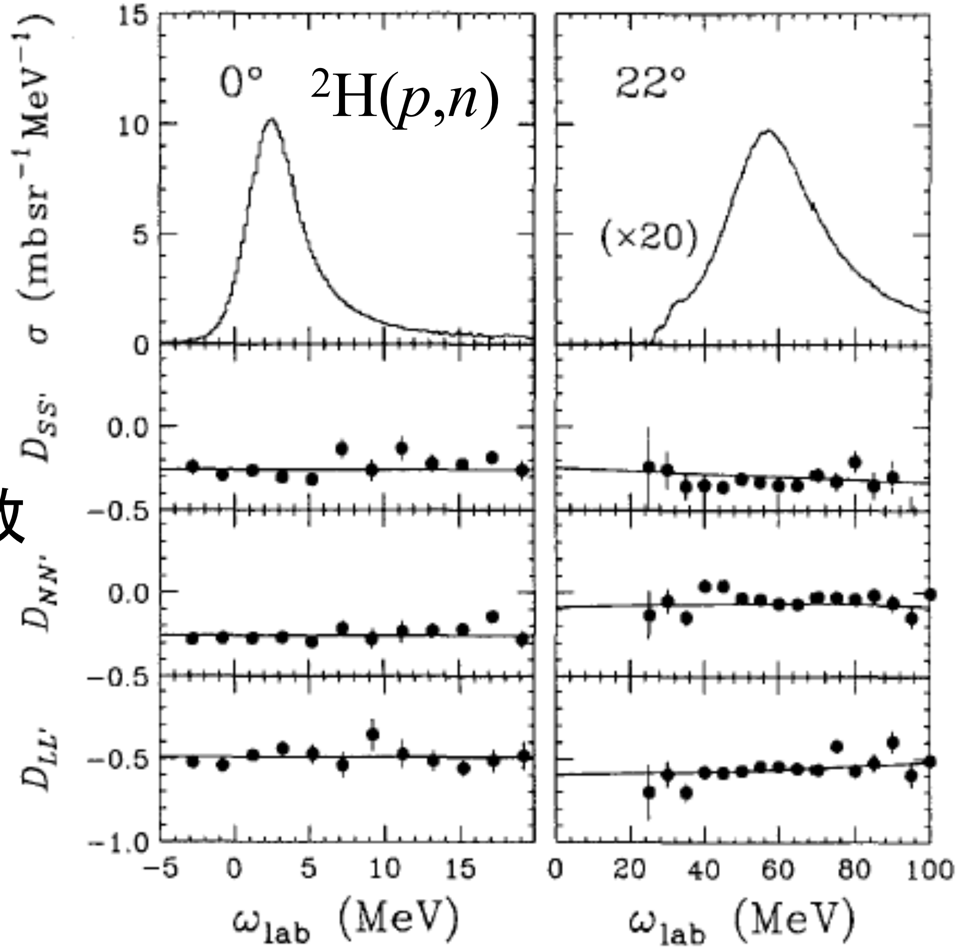
➡ 断面積のみの議論では、
共鳴状態の議論は困難

0°において、偏極観測量まで含めた実験結果を追加することで、
T=3/2の３核子系の共鳴状態を調べる。

QES – ^{2}H(p,n) D_{ii}

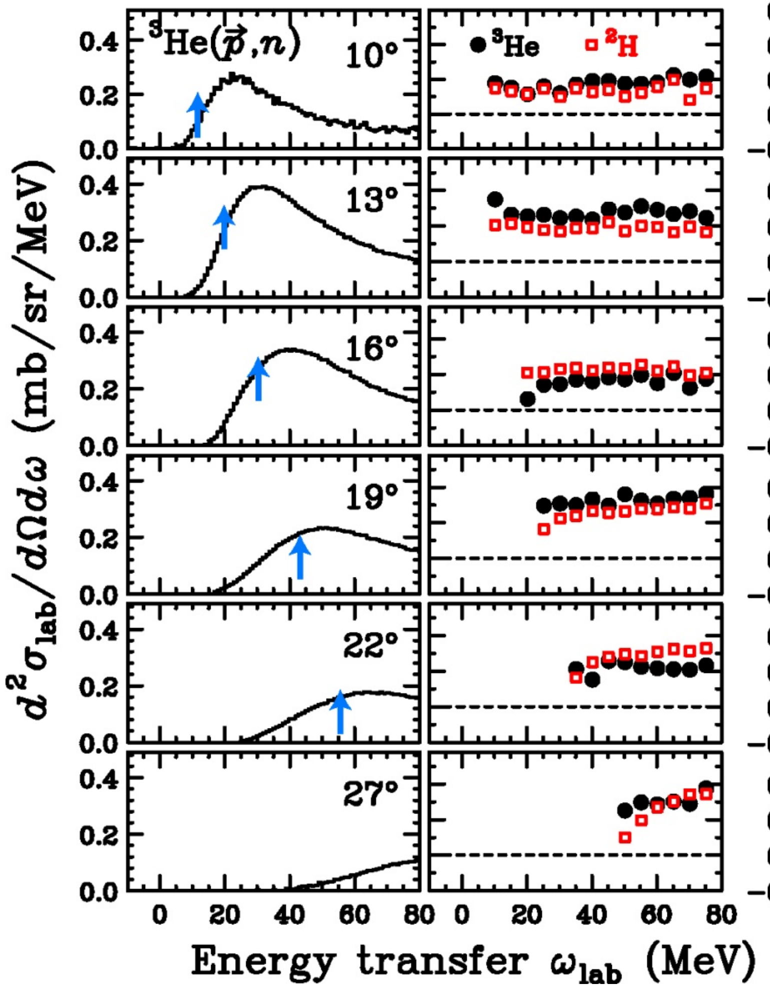
- ^{2}H(p,n) 共鳴状態がないため、QESのみ。

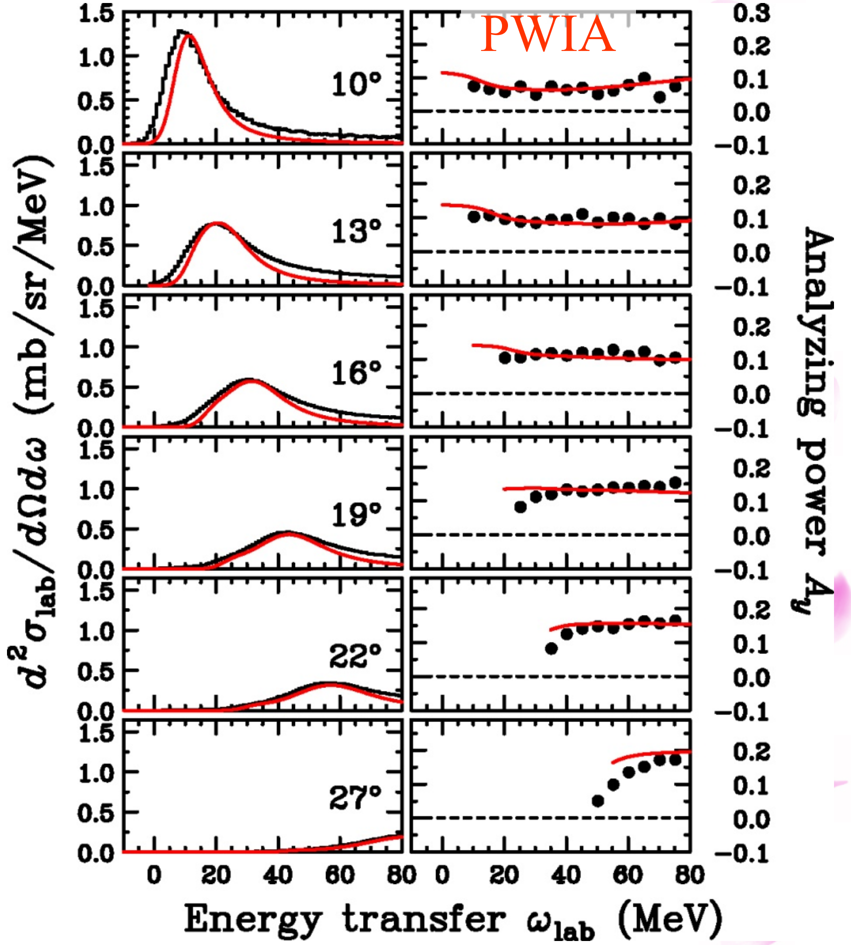
核子･核子散乱の計算値で一致



H. Sakai et al., Nucl. Phys. A 631 (1998) 757c.

$^{3}He(p,n)$ $^{2}H(p,n)$ — Ay

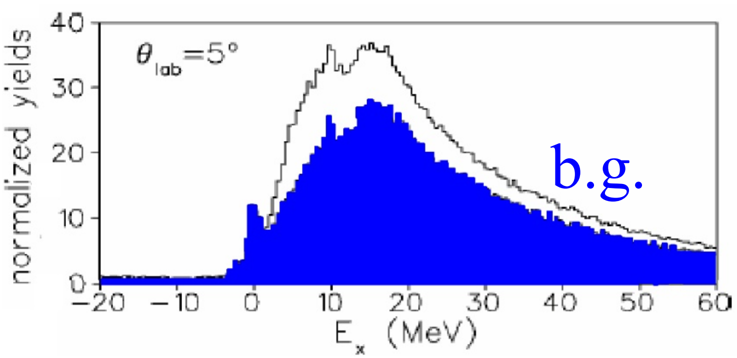




測定結果

- 高いS/Nで測定に成功
- Renormalizeなし(電荷比とlive ratio比のみ)で、
バックグラウンドの引き算(^{3}He = cell−empty)に成功。

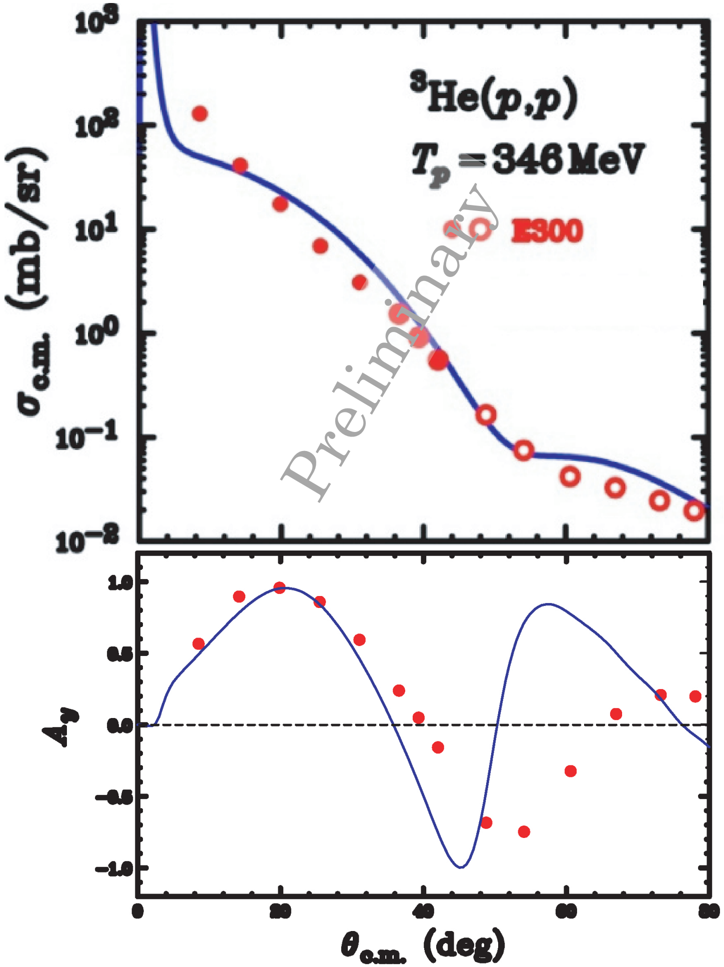
^{3}He(p,n) at 200 MeV at Indiana



Indiana data

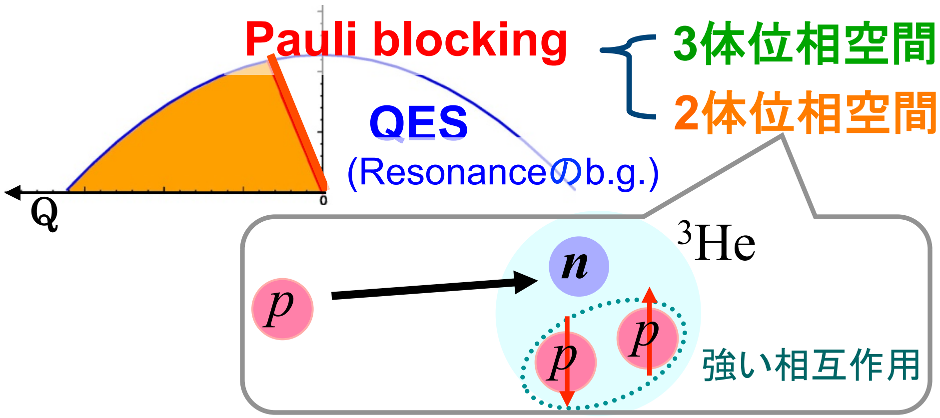
Havor foil
Co(42.5%), Cr(13%), Ni(13%), Fe(18.1%),
W(2.8%), Mo(2%), Mn(1.6%)

^{4}Heのポテンシャルを用いて^{3}He(p,p)の前方を再現。
⇒今後、^{3}He(p,p)の実験結果から^{3}He用の光学ポテンシャルを引き出す。



目的 — ^{3}He(p,n)3p (T=3/2)

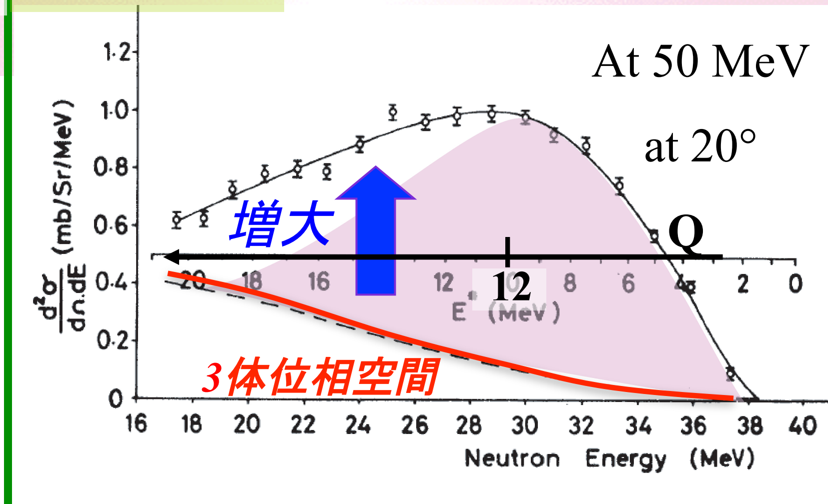
最新の2体力のみの計算：resonance　無
⇒resonanceが観測　⇒　3体力の効果



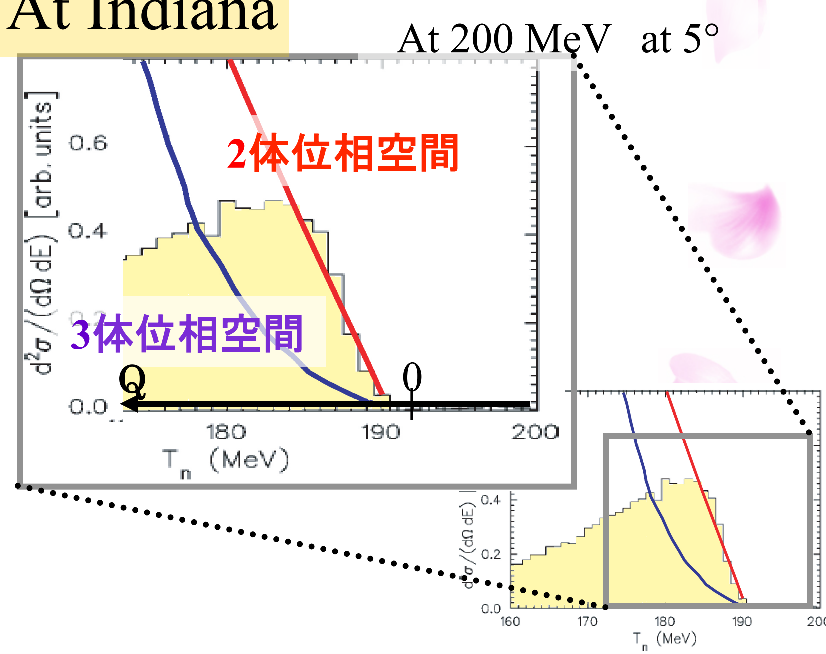
	Pauli blocking	Resonance
L. E. Williams et al at RHEL	3体位相空間	○
M. Palarczyk et al at Indiana	2体位相空間	?

3体位相空間と不一致
$\overset{?}{=}$ Resonance

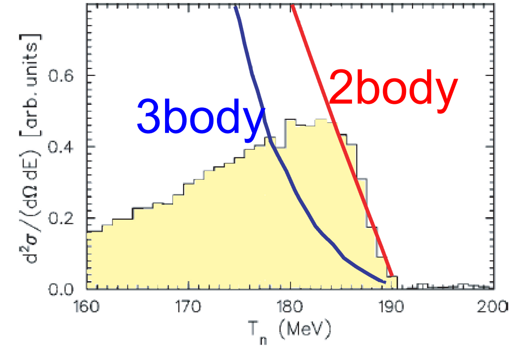
At RHEL



At Indiana



L. E. Williams et al., Phys. Rev. Lett. 23 (1969) 20.
M. Palarczyk et al., Phys. Rev. C 58 (1998) 645.



目的

- 過去の実験 ： 立ち上がり ２体位相空間　resonance ×
  ３体位相空間　resonance ○
  どちらがＱＥＳの計算として正確かはわからない。

断面積のみの議論では、QESの見積もりにより
resonanceの有無の不定性大。

➡ より詳細な情報が必要

偏極観測量まで含めた実験結果を追加することで、
T=3/2の３核子系の共鳴状態に関する知見を得る。

偏極観測量

ビーム偏極度

$$p_i' = p_i D_{ii}(0^\circ)$$

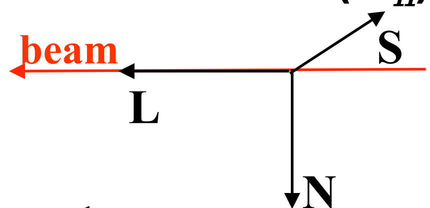
中性子偏極度　　偏極移行量 (i=L,N,S)

偏極移行量(D_{ii})：反応前後のスピン移行

スピン反転　-1

非反転　+1

(0°では$D_{NN}=D_{SS}$)



$\boxed{\text{横スピン移行量}}$ $$D_T(0^\circ) = \frac{1}{2}\left[1 - D_{LL}(0^\circ)\right]$$

$\boxed{\text{縦スピン移行量}}$ $$D_L(0^\circ) = \frac{1}{4}\left[1 - 2D_{NN}(0^\circ) + D_{LL}(0^\circ)\right]$$

各J

各J^πで特徴的な値
（PWIAによる予測
（⊿S=1））

⊿J^π	$D_L(0^\circ)$	$D_T(0^\circ)$	$D_{NN}(0^\circ)$	$D_{LL}(0^\circ)$
0^-	1	0	-1	+1
1^-	0	1	0	-1
2^-	2/5	3/5	-2/5	-1/5
QES	0.2	0.7	-0.17	-0.45

QESのD_L, D_T： Free NNから高い信頼度で計算可能

実験：^{3}He(*p*,*n*)3p (T=3/2)　断面積（0°）、D_{ii}(0°）を測定

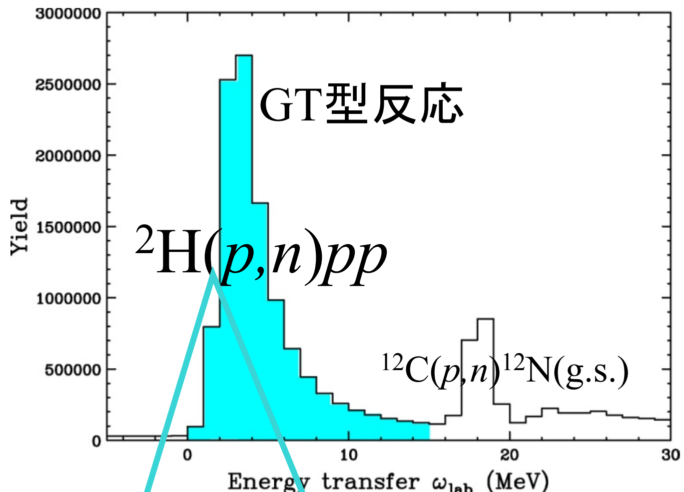
NPOL較正 ― 有効偏極分解能を求める

有効偏極分解能　測定量

偏極移行量

$$D_{LL}(0^\circ) = A_{y:\mathrm{eff}} / (p_L \cdot \varepsilon'_L)$$
$$D_{NN}(0^\circ) = A_{y:\mathrm{eff}} / (p_N \cdot \varepsilon'_N)$$

ビーム偏極度(既知)　散乱非対称度

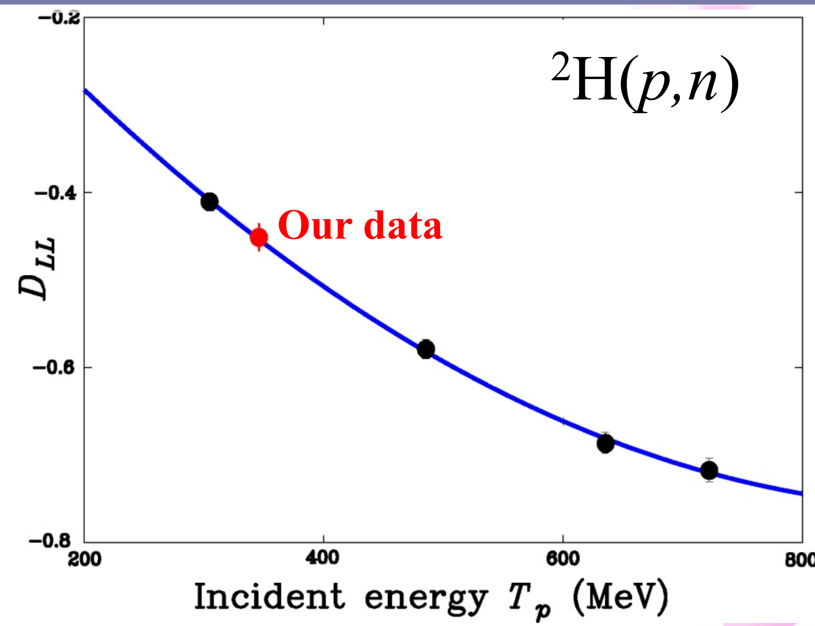


$$D_{LL}(0^\circ) + 2D_{NN}(0^\circ) = -1$$

$$A_{y:\mathrm{eff}} = -\frac{\varepsilon'_L}{p_L} - 2\frac{\varepsilon'_N}{p_N} = 0.131 \pm 0.005$$

D_{ii}を用いずに求めることができる。

M. W. McNaughton et al., Phys. Rev. C 45 (1992) 2564.



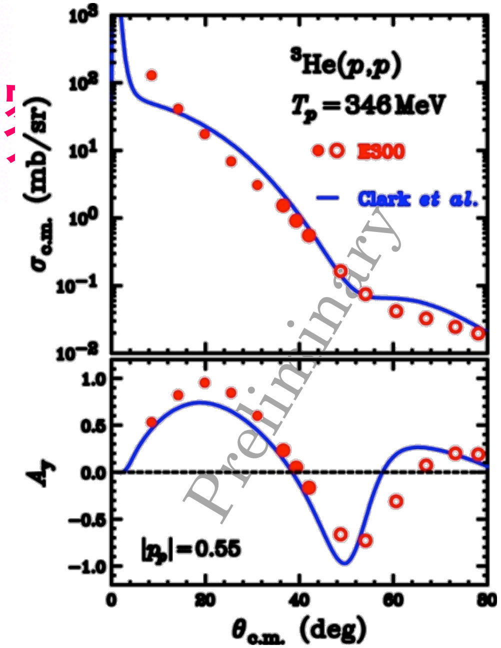
^{2}H(p,n)の偏極移行量

$$D_{LL} = -0.451 \pm 0.016$$

過去のデータと一致⇒高い信頼性

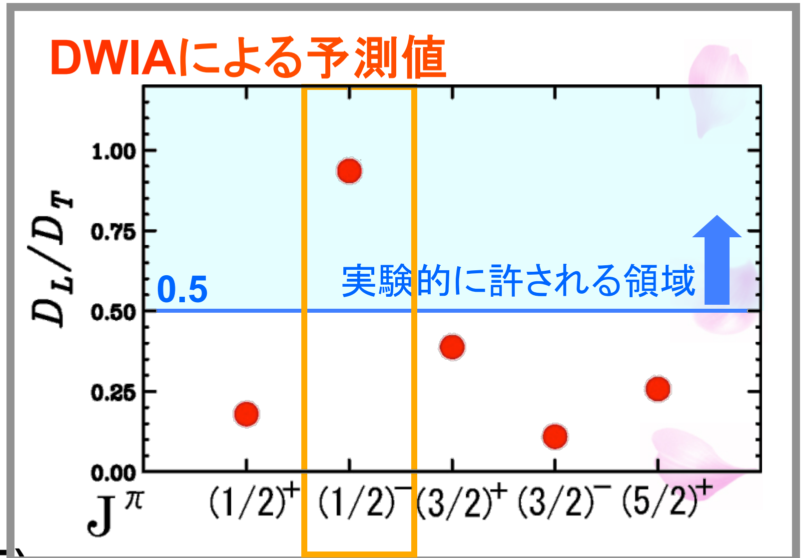
スピン・パリティに関する考

― *DWIA*計算との比較 ―



- 光学ポテンシャル
  - ^{4}Heに対する広域ポテンシャル（Clark et al.）
  - ^{3}He弾性散乱をおおよそ再現
- NN t-matrix
  - Franey and Love at 325 MeV
- 遷移行列要素
  - 殻模型計算（oxbash）
    - s-p-sd モデル空間
    - Wildenthal(sd)+Millener(other) Int.
  - $\boxed{\text{J=5/2(}2\hbar\omega\text{　)ま}}$で
- 実験値と計算値の比較(D_L/D_T > 0.5)

$$J^\pi = (1/2)^- \text{を示唆}$$



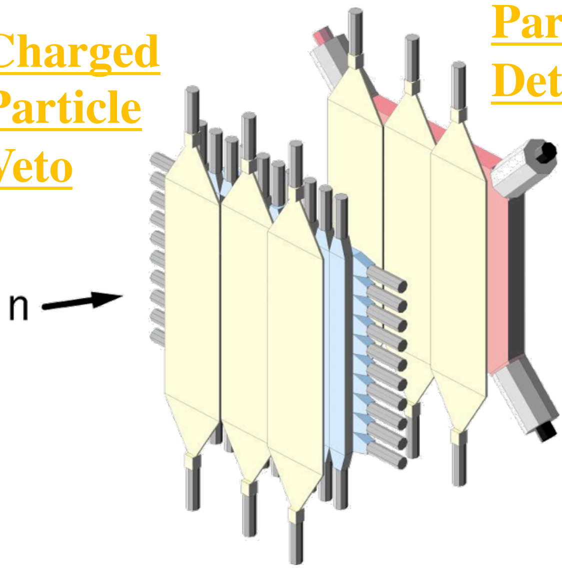
M. A. Franey and W. G. Love, Phys. Rev. C 31 (1985) 488.

D. Halderson el al., Phys. Rev. C 39 (1989) 336.

NPOL

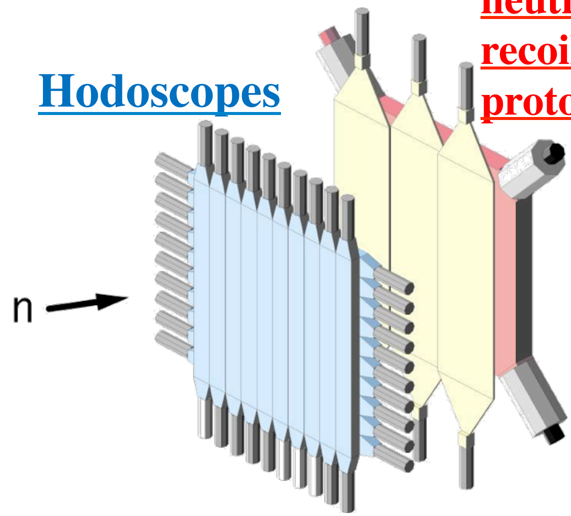
Charged Particle Veto

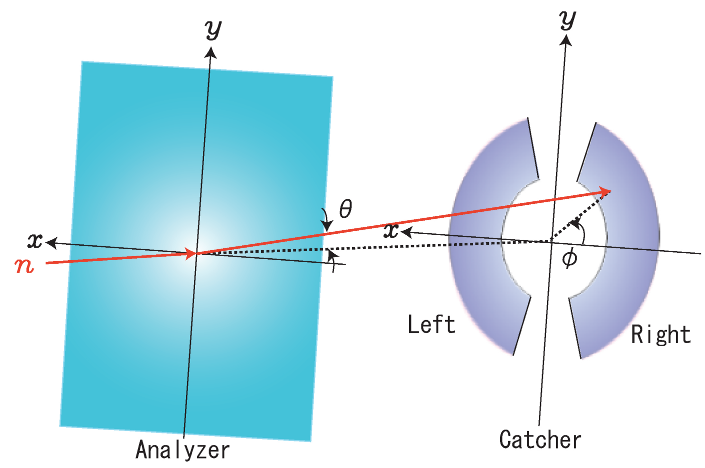
Charged Particle Detector



Hodoscopes

Catcher for Scattered neutrons and recoiled protons





偏極移行量　ー　Σ

- Initial 1/2$^+$ 、 Final 1/2$^-$

⇒⊿J$^\pi$=0$^-$ (⊿L=1)

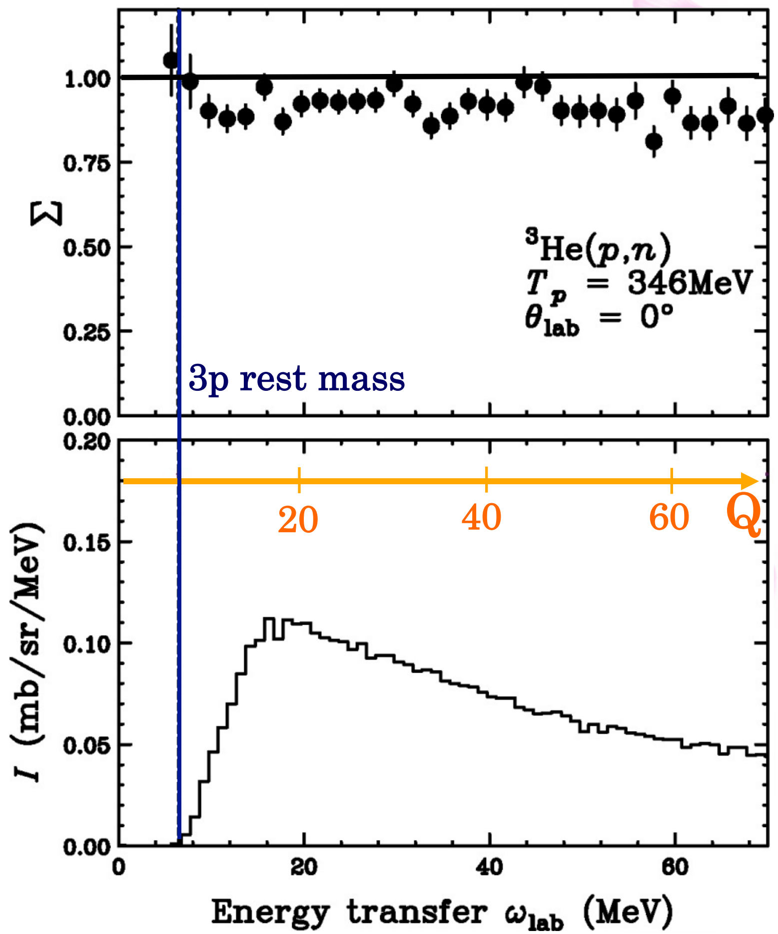
⊿S=1

Model 非依存

$$\Sigma = \frac{3-(D_{LL}+2D_{NN})}{4} \begin{cases} 0 : \varDelta S = 0 \\ 1 : \varDelta S = 1 \end{cases}$$

- 実験結果

⊿S＝１が支配的



D$_L$/D$_T$からの予測をサポート

T. Suzuki, Prog. Theor. Phys. 103 (2000) 859.

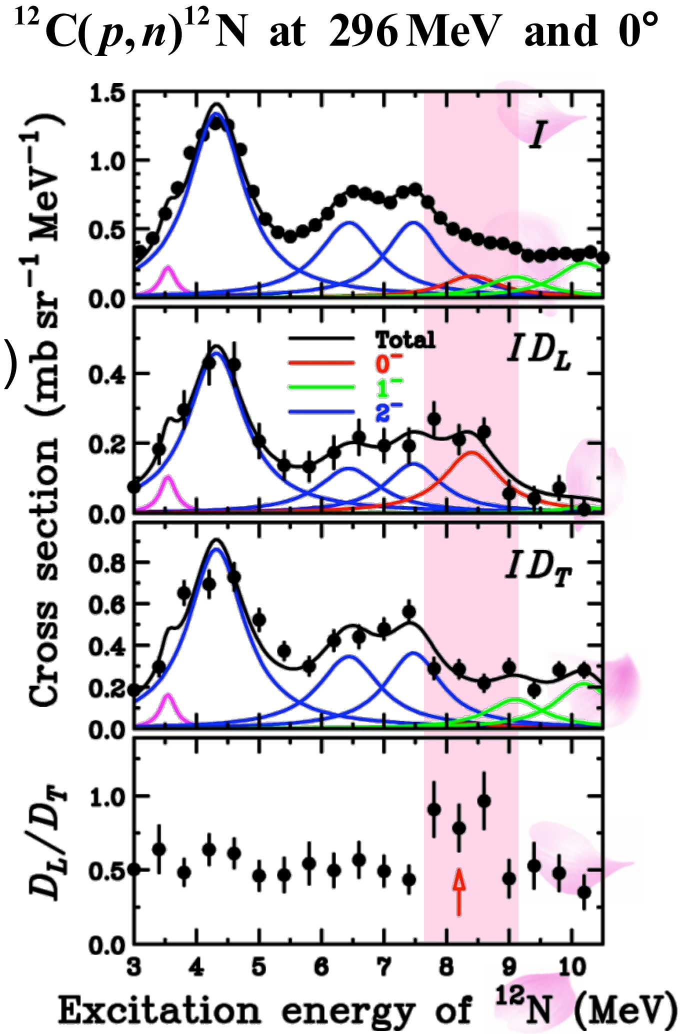
Power of Polarization Observables

Filter to Spin-Parity

- Resonance has definite spin-parity
  - Spin-parity sensitive probe (filter) is useful to identify resonances
  - Polarization observables are powerful
    - Sensitive to spin-parity
    - Insensitive to other effects (distortion etc.)
- Example for $0^+ \rightarrow J^\pi$ ($\Delta S=1$) transition
  - PWIA with central only

Significantly different

J^π	D_L	D_T	D_L/D_T
1^+	0.33	0.67	0.50
0-	1.00	0.00	∞
1-	0.00	1.00	0.00
2-	0.40	0.60	0.66
QES	0.20	0.70	0.29



Measure D_{ii} (D_L/D_T) for $^3He(p,n)$ → Identify resonance and its J^π