「RCNP入射器更新で展開される新しい研究」
2007.2.19～20 核物理研究センター

偏極軽重イオン直接反応

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- ✓ (d,^{2}He) @理研 ・・・ 0^{-}, spin-dipole
- ✓ (^{6}Li,^{6}He) @RCNP・偏極 ^{6}Li 計画
- ✓ (^{3}He,t) の状況・(p,n) との対比

複合粒子反応による精密核分光研究に向けて

Classification of nuclear direct reactions

➢ Nucleon reaction (at intermediate energies)

(p,p') (p,n) (n,p)

- smallest distortion (σ_{NN} minimum @ ~300 MeV)
- exact treatment of single-nucleon knockon exchange (SNKE)
- well-studied effective interaction (medium effect), ρ-dependence
- extensively studied using *polarized* beams
- but *low selectivity*

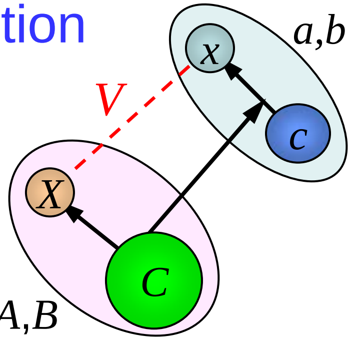
➢ Light heavy-ion reaction

$({}^3\mathrm{He},t)$, $(d,{}^2\mathrm{He})$, (d,d'), (α,α'), $({}^6\mathrm{Li},{}^6\mathrm{He})$, $({}^7\mathrm{Li},{}^7\mathrm{Be})$, ····

- high selectivity
- possible use of (tensor) polarized beams
- characteristic wave func. (not by shell model)
- C.C. with breakup channels
- sequential process ? (at lower energies)
- not extensively studied at intermediate energies, although *theoretical tools are well prepared !*

➢ Heavy-ion reaction

${}^{12}\mathrm{C}$, ${}^{16}\mathrm{O}$, ····



- high selectivity
- proj.-target *symmetric* treatment w/ *shell model*
- small recoil effect
- C.C. with *bound* excited-states
- but complicated spectrum

(d,^{2}He) reaction

^{2}He = p-p in $^1S_0$

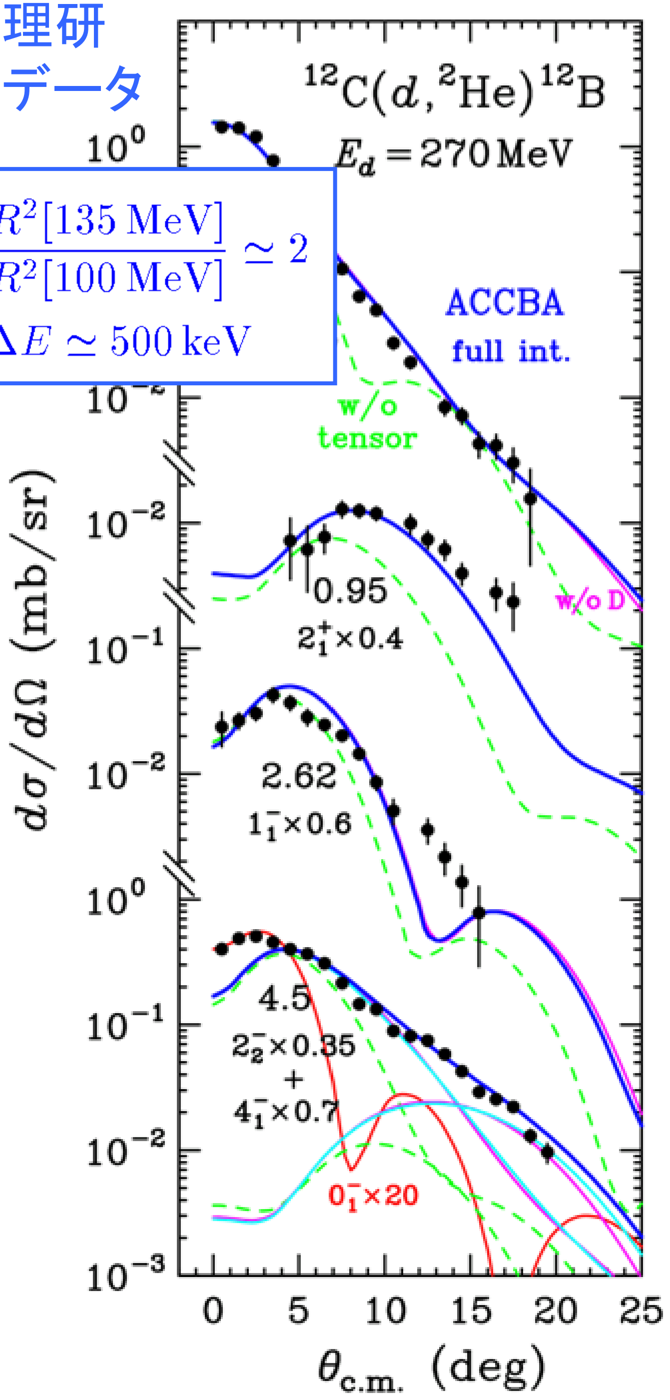
measured by coin. detection of p-p with small relative energies
p-p FSI enhances $^1S_0$ amplitude (purity? → next slide)

✓ (n,p)-type charge-exchange reaction (ΔT=1, ΔT_z=+1)
with spin-transfer (ΔS=1; because $d[1^+] \rightarrow {}^2\mathrm{He}[0^+]$)
✓ involves only charged particles (primary beam)
→ relatively high-efficienty & resolution

Suitable to extract β_+-strength by $d\sigma/d\Omega[q\sim0] \propto F(q,\omega)\, B(\mathrm{GT})$
and study of spin-flip dipole states by tensor-pol. obs.,
for (more) *neutron-rich residuals,* in particular.

At intermediate energies:
SATURNE (300 MeV/A), RIKEN (135 MeV/A), Texas A&M (64 MeV/A)
RCNP (100 MeV/A), and most extensively KVI (85 MeV/A)

理研
データ



$$\frac{R^2[135\,\mathrm{MeV}]}{R^2[100\,\mathrm{MeV}]} \simeq 2$$

$\Delta E \simeq 500$ keV

✓Data are reasonably well described by 1-step Born approximation

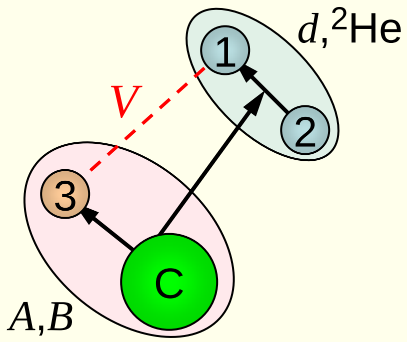
✓ Norm. consts. are consistent with those of (p,n) reactions

Adiabatic Coupled-Channels Born Approx. (ACCBA)

H.Okamura, PRC 60 ('99) 064602

A(d,^{2}He)B reaction

$$T = \left\langle \Psi_{ppB} \middle| V_{13} \middle| \varphi_d \, \chi_{dA} \right\rangle$$



Ψ_{ppB} 3-body wave func. is solved by C.C. [^1S-^1D] with adiabatic approx.

Charge-exchange transition is treated in Born approx.

SKNE by short-range aprox. (central)

Simple projectile form-factor

— advantage over other composite projs.

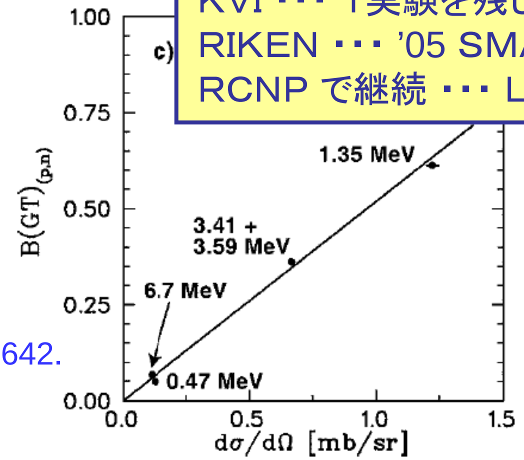
(d,^{2}He) extensively used @ KVI, E_d = 85 MeV/A (ΔE~150 keV)

KVI ･･･ １実験を残して核物理プログラム終了
RIKEN ･･･ ’05 SMART シャットダウン（→ fRC）
RCNP で継続 ･･･ LAS 高分解能化進行中（w/ 野呂G）

Exp.

$$\frac{d\sigma}{d\Omega} = \boxed{\hat{\sigma}_{\mathrm{GT}}}\,\boxed{F(q,\omega)}\,B(\mathrm{GT})$$

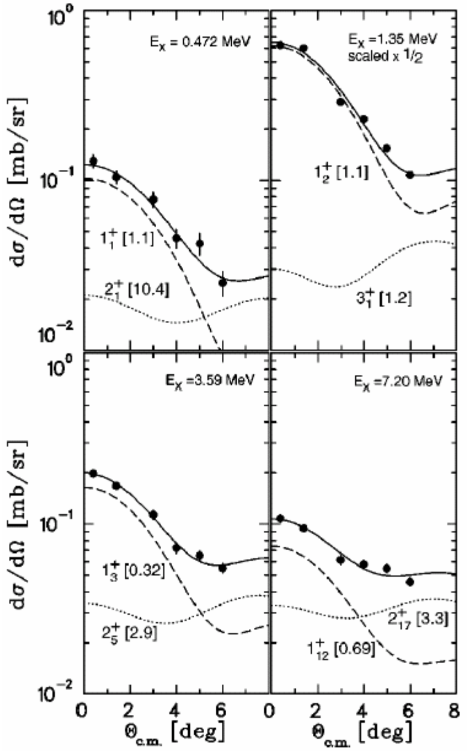
ACCBA
H.Okamura
PRC 60(1999)060642.

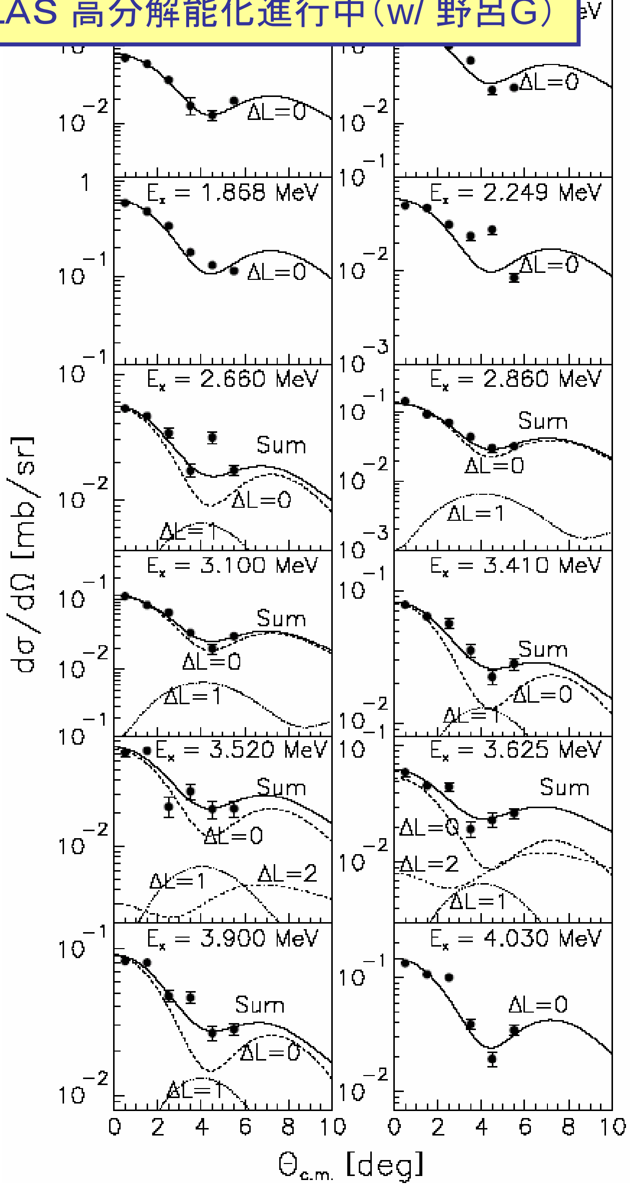


for studies of
- ββ-decay matrix elements
- astrophysical interest

^{7}Li	PLB **639** (2006) 623
^{14}N	PRL **97** (2006) 062502
^{24}Mg	PRC **65** (2002) 044323
^{32}S	PRC **69** (2004) 064325
^{48}Ca	PRC **70** (2004) 054302
^{50}V	PRC **71** (2005) 024603
^{51}V	PRC **68** (2003) 031303
^{58}Ni	PRC **71** (2005) 014606
^{116}Sn	PRC **71** (2005) 054313

citing ACCBA

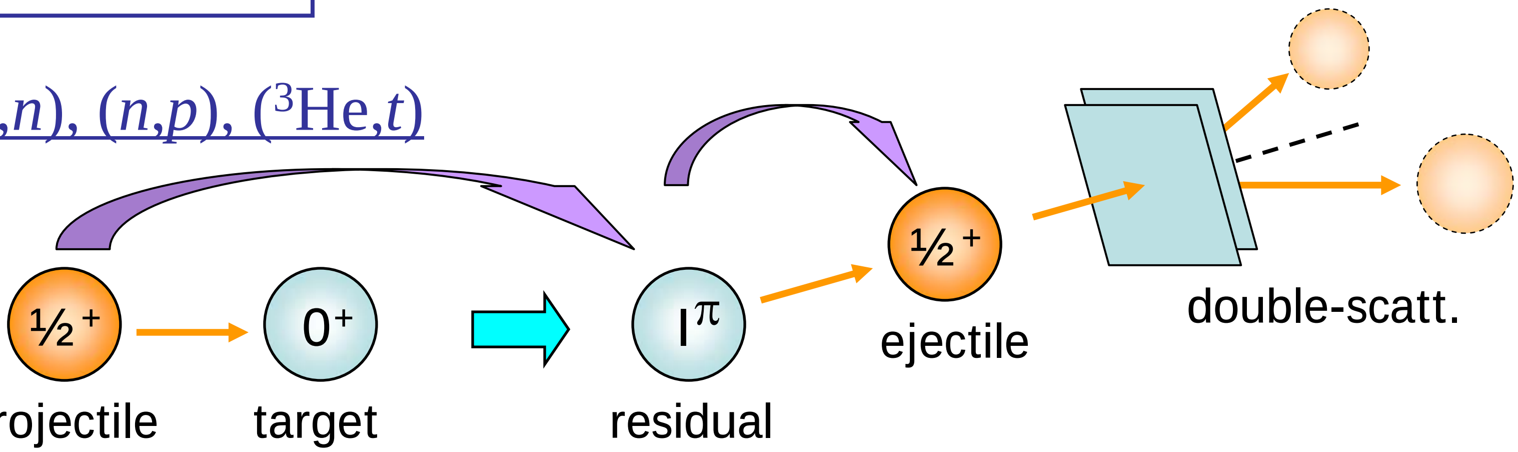




スピン励起観測量

— 核子散乱 vs. スピン1粒子反応 —

(p,p'), (p,n), (n,p), $(^{3}\mathrm{He},t)$



$\frac{1}{2}^{+}$ projectile

0^{+} target

I^{π} residual

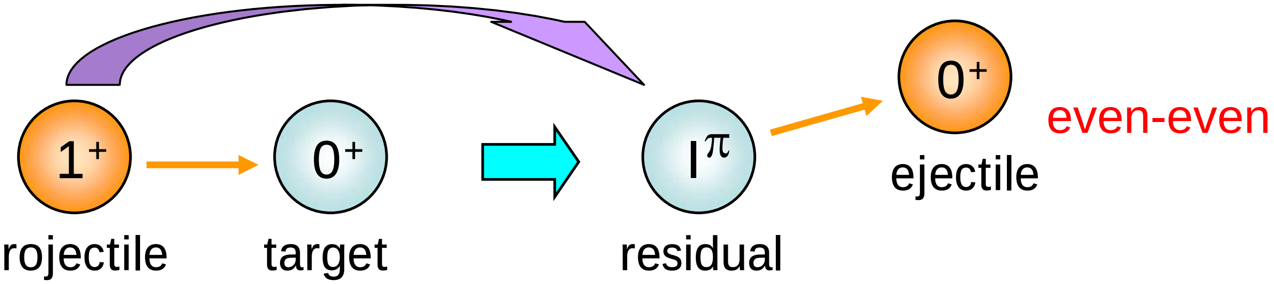
$\frac{1}{2}^{+}$ ejectile

double-scatt.

残留核 I^{π} ⇔ 入射-出射粒子スピン状態変化

観測量は偏極移行･･･二回散乱（測定困難）

$(d,{}^{2}\mathrm{He})$, $({}^{6}\mathrm{Li},{}^{6}\mathrm{He})$



1^{+} projectile

0^{+} target

I^{π} residual

0^{+} ejectile

even-even

odd-odd

only 4 stable nuclei

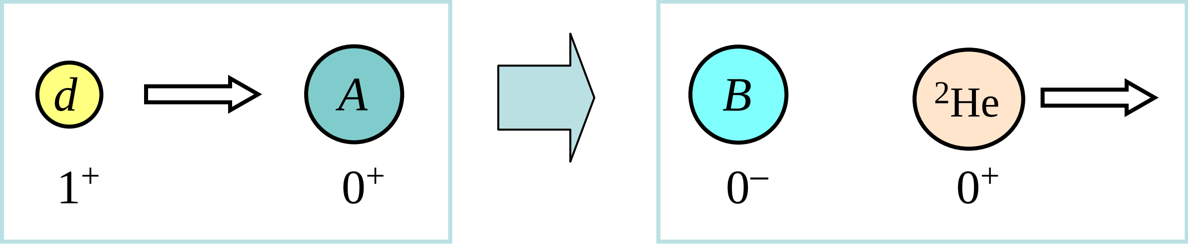
^{2}H, ^{6}Li, (^{10}B,) ^{14}N

残留核 I^{π} ⇔ 入射粒子スピン状態

観測量は偏極分解能･･･測定容易

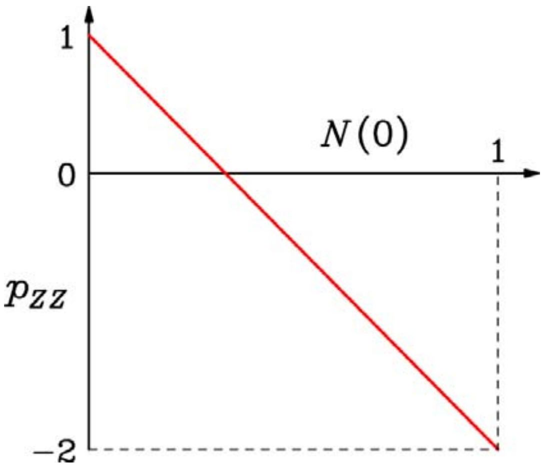
テンソル偏極ビームを用いた $(d,{}^2\mathrm{He})$ 反応による0⁻励起

$A(d,{}^2\mathrm{He})B(0^-)$
at θ=0°



$m=0$（$p_{ZZ}=-2$）のとき反応は起こり
$m\neq0$（$p_{ZZ}=+1$）ならば反応は起こらない

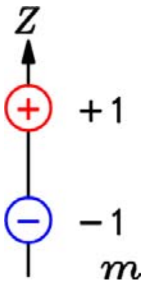
断面積の p_{ZZ} 依存性 ⇔ 0^- 励起のサイン
i.e. テンソル偏極分解能 A_{ZZ}

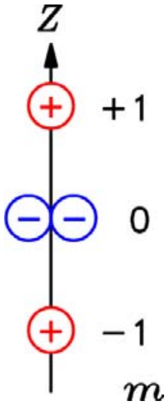


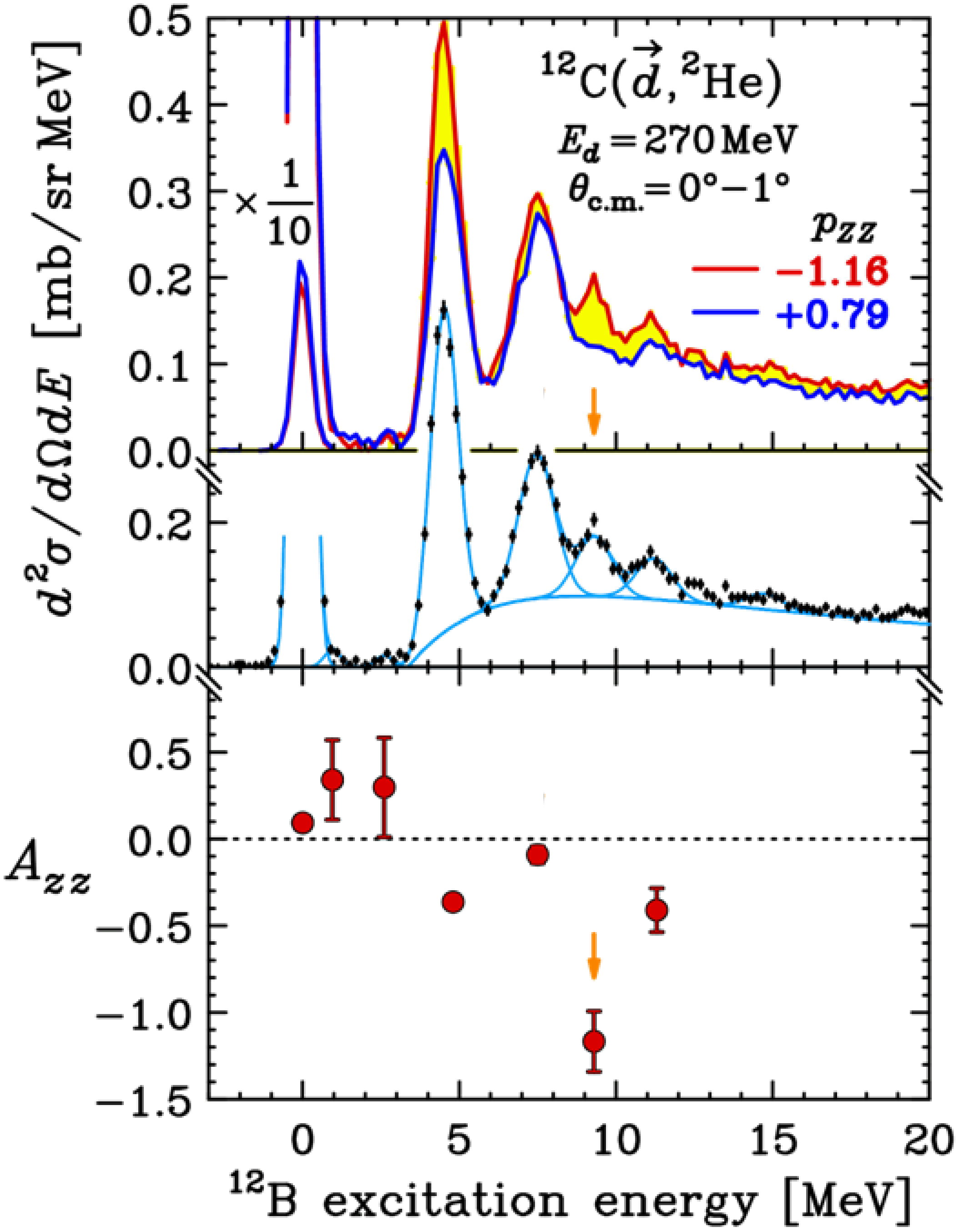
$$p_Z = \sum_m N(m) = N(+1) - N(-1)$$

$$p_{ZZ} = N(+1) - 2N(0) + N(-1)$$

$$= 1 - 3N(0)$$







RIKEN-SMART の測定例

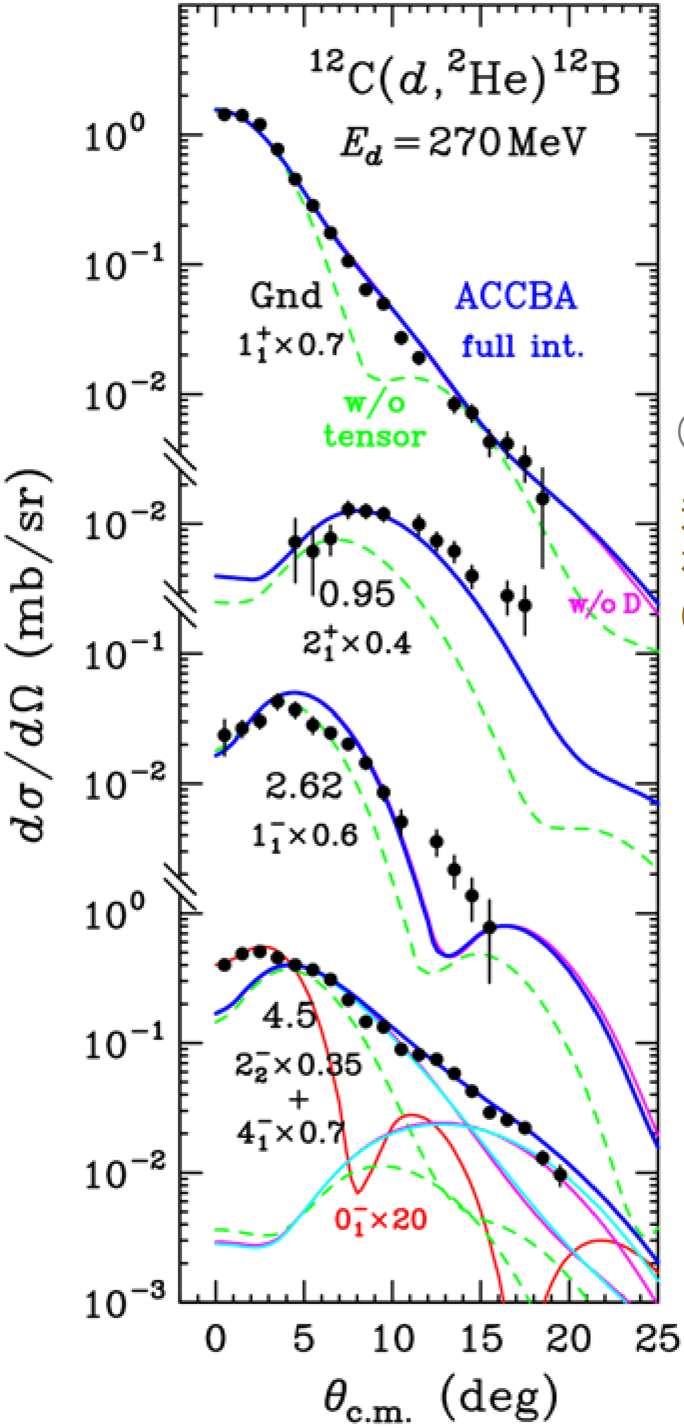
H. Okamura *et al*. PRC 66 (2002) 054602

	0^-	n.p.
$p_{ZZ}=-2$	$3\sigma_0$	0
$p_{ZZ}=+1$	0	$3\sigma_0/2$

A = 12 系で初の 0^- 発見

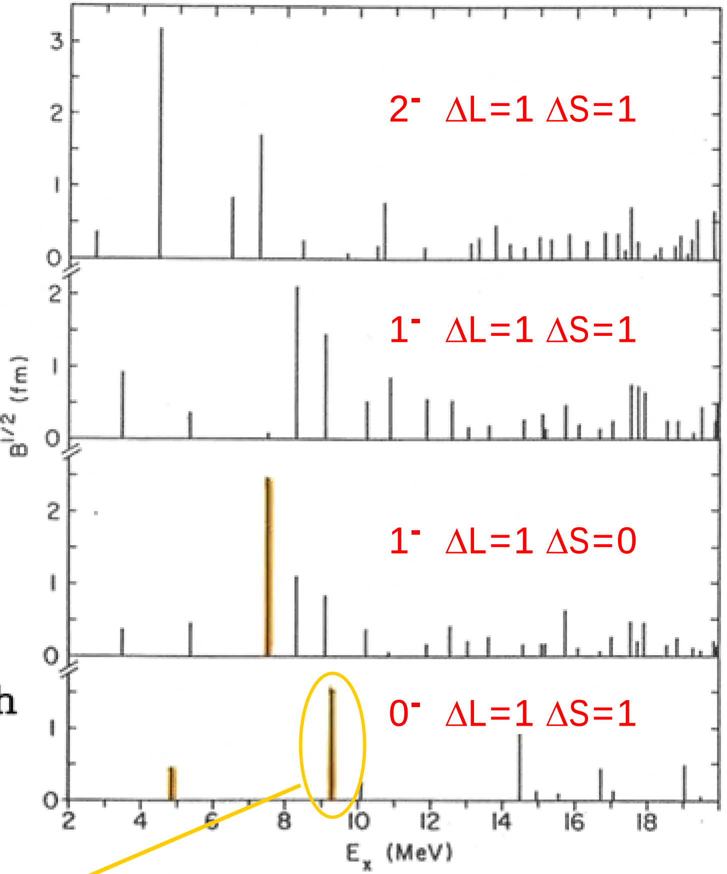
(p,p'), (p,n) でも
$D_{NN}(0^-) = -1$
だが見つかっていない
⇒ Selectivityの重要性

微分断面積
角度分布

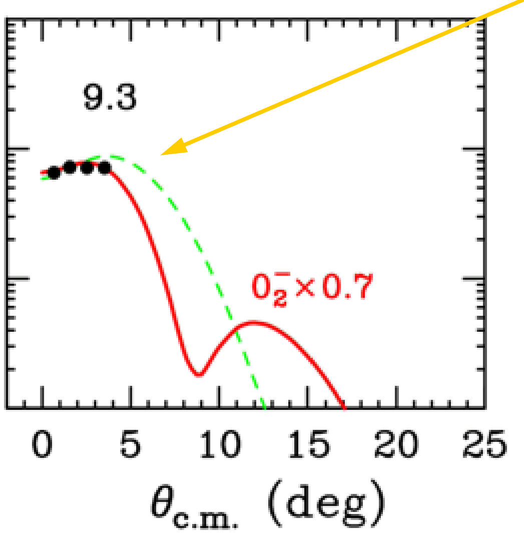


Adiabatic
Coupled-Channels
Born Approx.
（後で議論）

規格化因子は
相対値として
(p,n) とconsistent

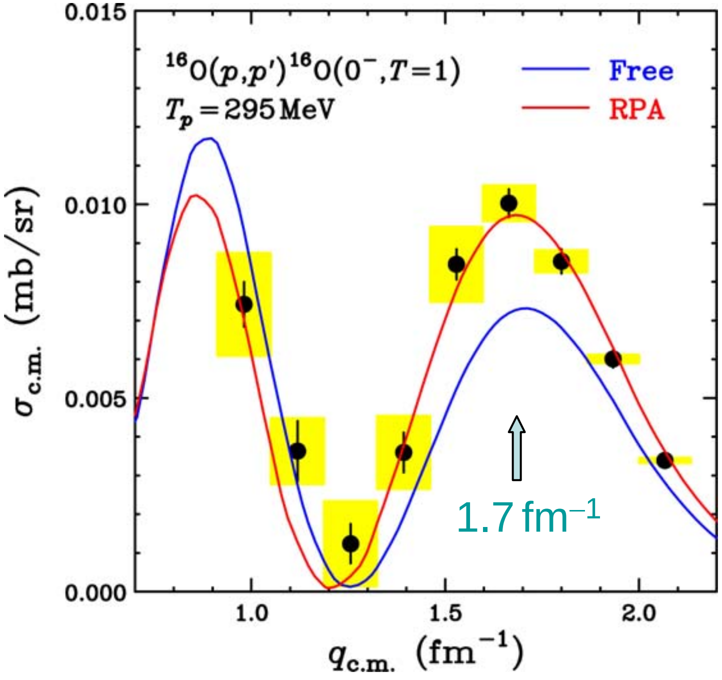


Millener & Kurath
shell-model w. f.



“通常”の殻模型の予想で
0^-の励起エネルギーと
微分断面積を再現
（実は期待通り？）

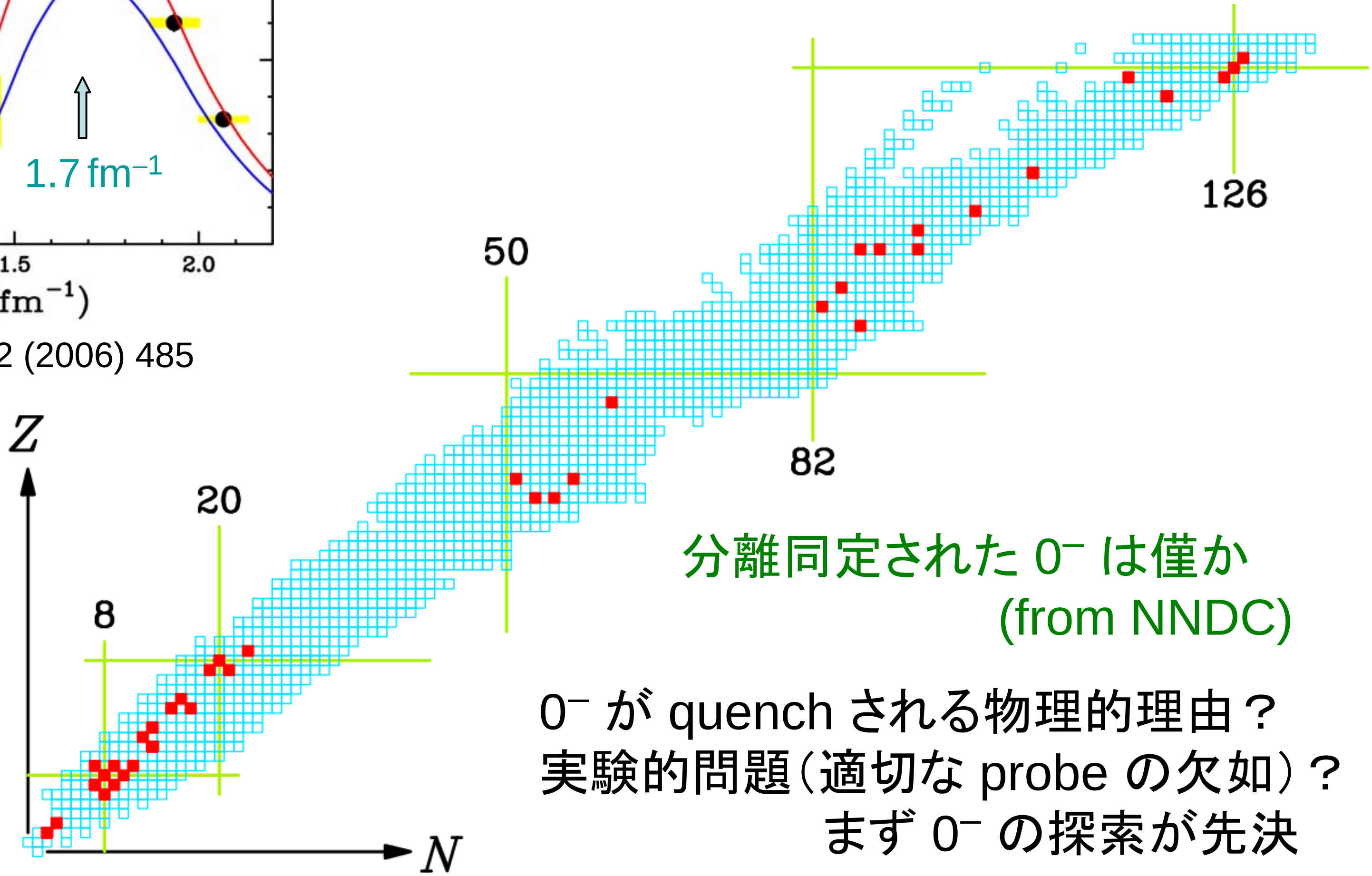
Isovector $0^+ \to 0^-$ excitation



$1.7\ \mathrm{fm}^{-1}$

T.Wakasa *et al*. PLB 632 (2006) 485

- carries quantum numbers of π
- purely sensitive to spin-longitudinal response
- direct evidence of π-enhancement at large q



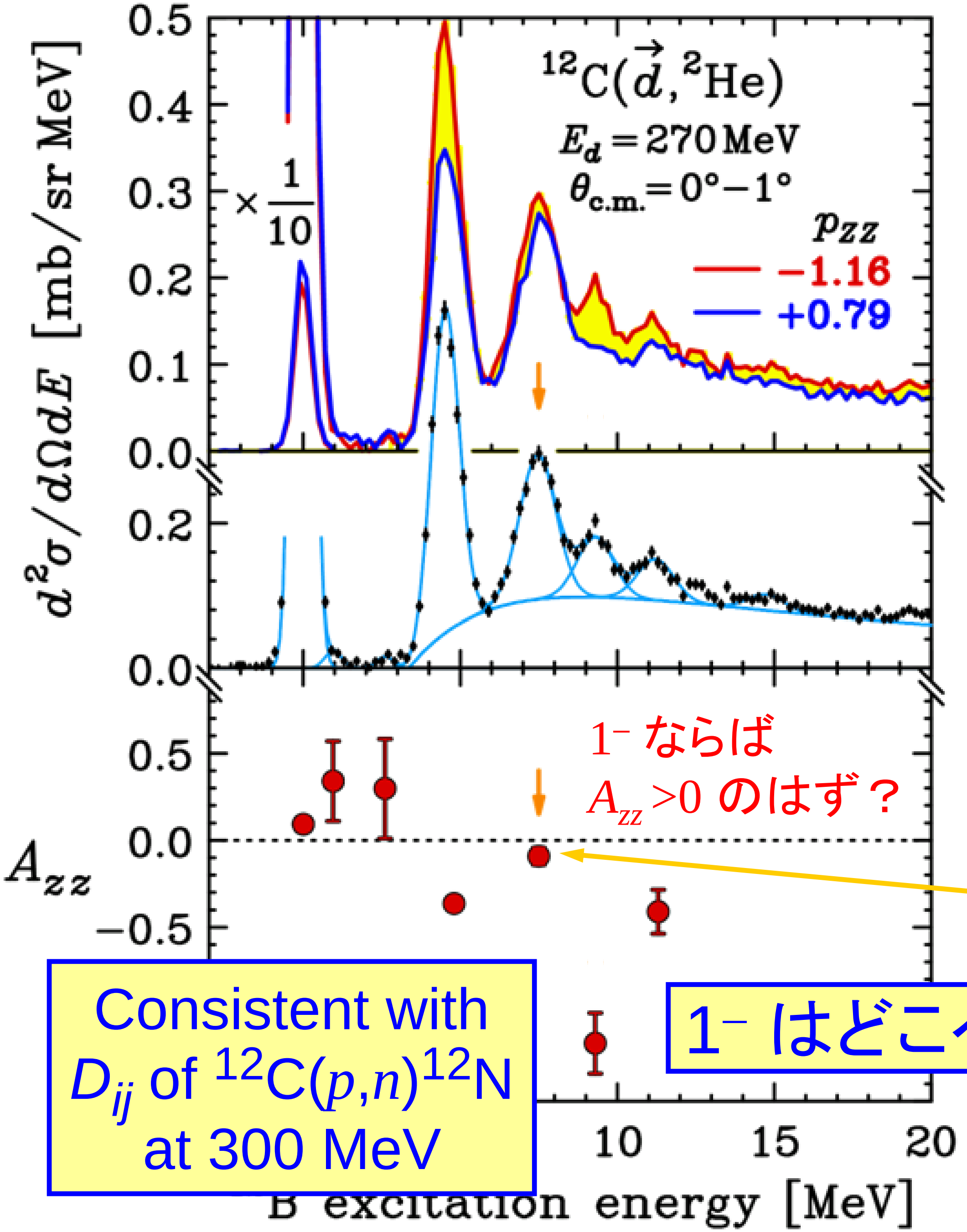
分離同定された 0^- は僅か

(from NNDC)

0^- が quench される物理的理由？

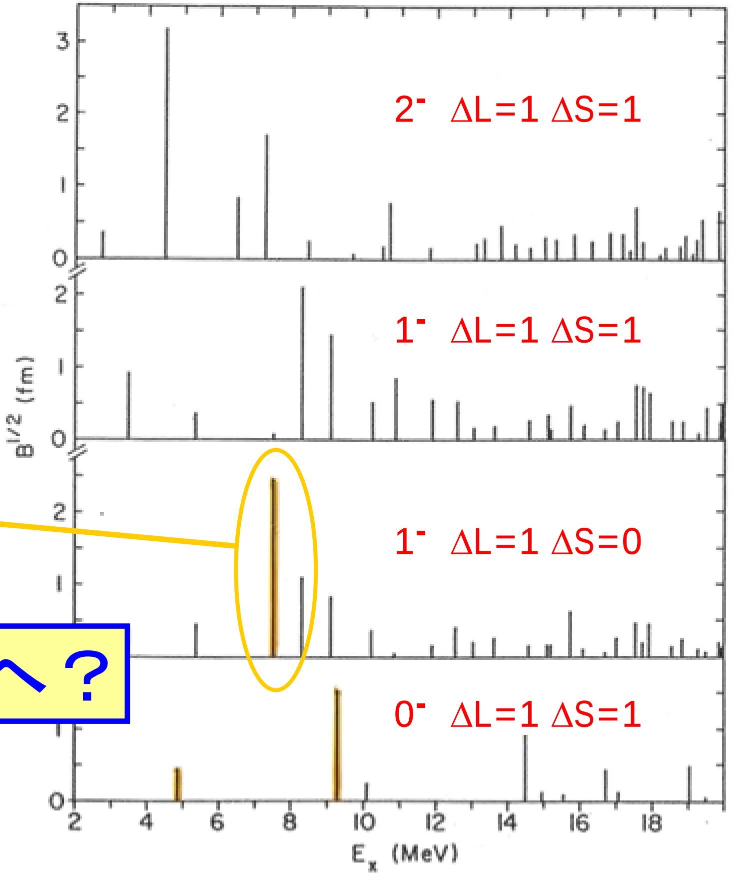
実験的問題（適切な probe の欠如）？

まず 0^- の探索が先決



1⁻ ならば
$A_{zz}>0$ のはず？

	0^-	n.p.
$p_{ZZ}=-2$	$3\sigma_0$	0
$p_{ZZ}=+1$	0	$3\sigma_0/2$



Consistent with
D_{ij} of ^{12}C(p,n)^{12}N
at 300 MeV

1⁻ はどこへ？

$(d,{}^{2}\mathrm{He})$反応

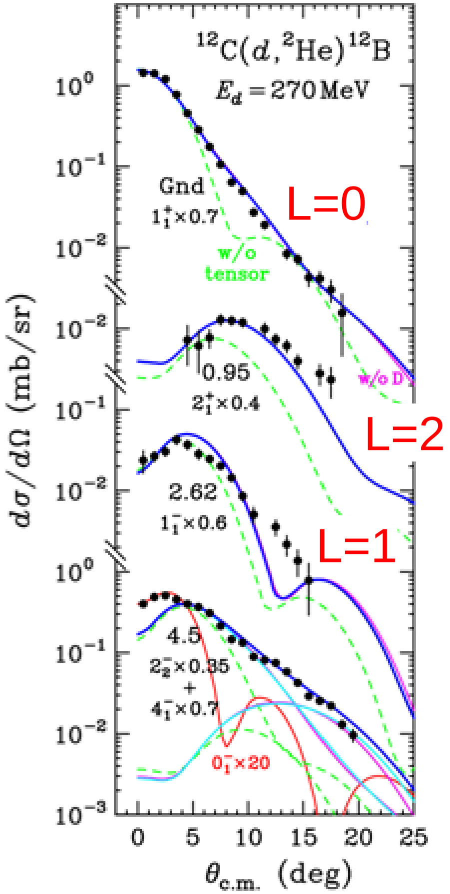
$^{2}\mathrm{He} = p\text{-}p$ in $^{1}S_{0}$ ･･･ enhanced via $p\text{-}p$ FSI

相対エネルギー 1 MeV 以下の $p\text{-}p$ を同時計数

$^{1}\mathrm{H}(d,pp)n$ の PWIA によれば P 波以上の寄与は数%

$\Delta S=1$, $\Delta T=1$, $\Delta T_{Z}=+1$ (n,p) 型反応

ビーム･検出粒子とも荷電粒子 ･･･ 高効率･高分解能



問題点：

✓大口径スペクトログラフ ･･･ 分解能に限界

✓高い偶発同時計数率 ･･･ ビーム量に制限

$\sigma(d,pX)$ は $A^{2/3}$ に比例 ･･･ 重核は難しい

cf. $\sigma({}^{3}\mathrm{He},dX) \propto A^{1/3}$

✓$\psi[d]$, $\psi[{}^{2}\mathrm{He}]$ の空間広がり大 ･･･ 単調な角度分布

他の反応の可能性

bound & compact ejectile (0^+) & projectile (1^+) w/o excited state

even-even　　odd-odd

安定な odd-odd 核 : **^{2}H (1^+) , ^{6}Li (1^+) , ^{10}B (3^+) , ^{14}N (1^+)   4つ**

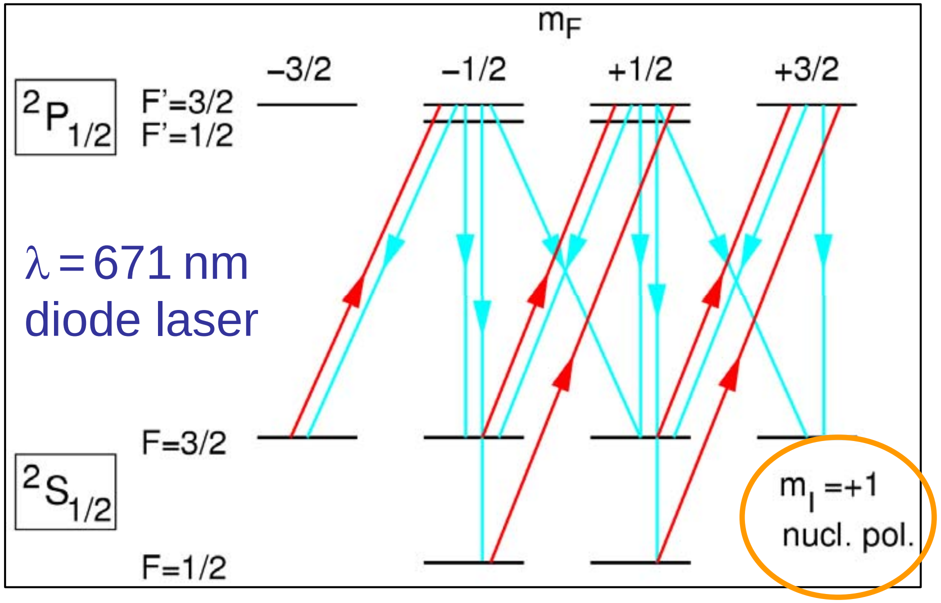
^{6}Li : アルカリ金属 ･･･ 円偏光レーザーで大強度偏極ビーム

^{6}He : 束縛粒子（$t_{1/2}$=807ms） ･･･ 高効率･高分解能測定

有望な反応 : (^{6}Li,^{6}He)

ただし (p,n) 型

（^{6}Be は unbound）



反応機構をシンプルに

⇒ 100 MeV/u 以上

⇒ ^{6}Li^{3+} が必要

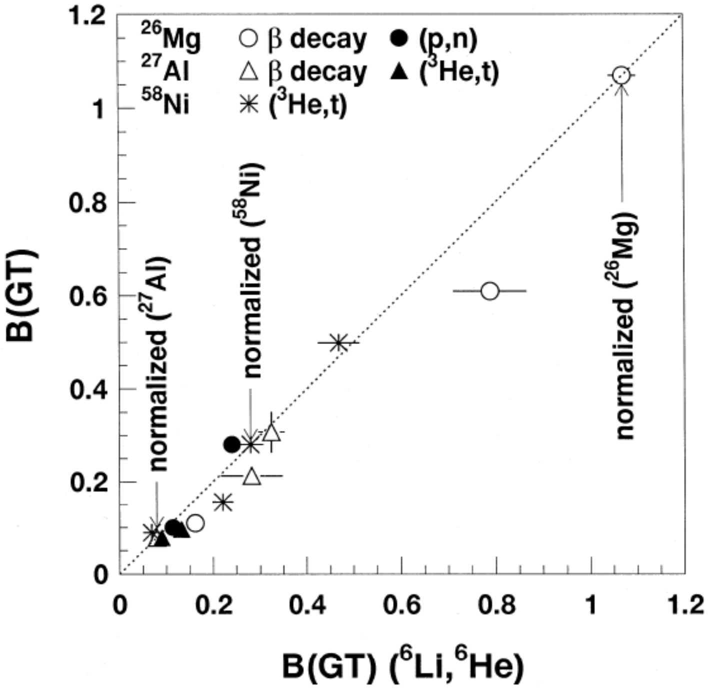
(^{6}Li,^{6}He) E/A=100 MeV @ RCNP

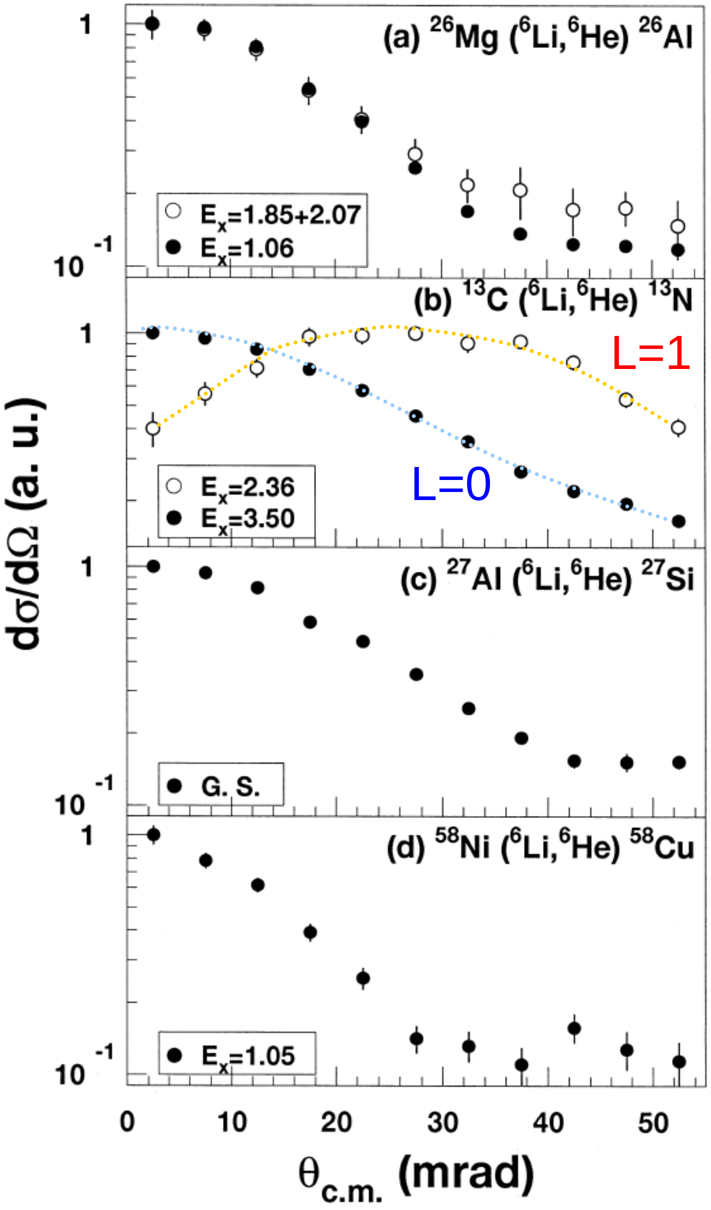
H.Ueno *et al*., PLB 465 (1999) 67

ΔE~400 keV, but w/ old operation of G-Raiden

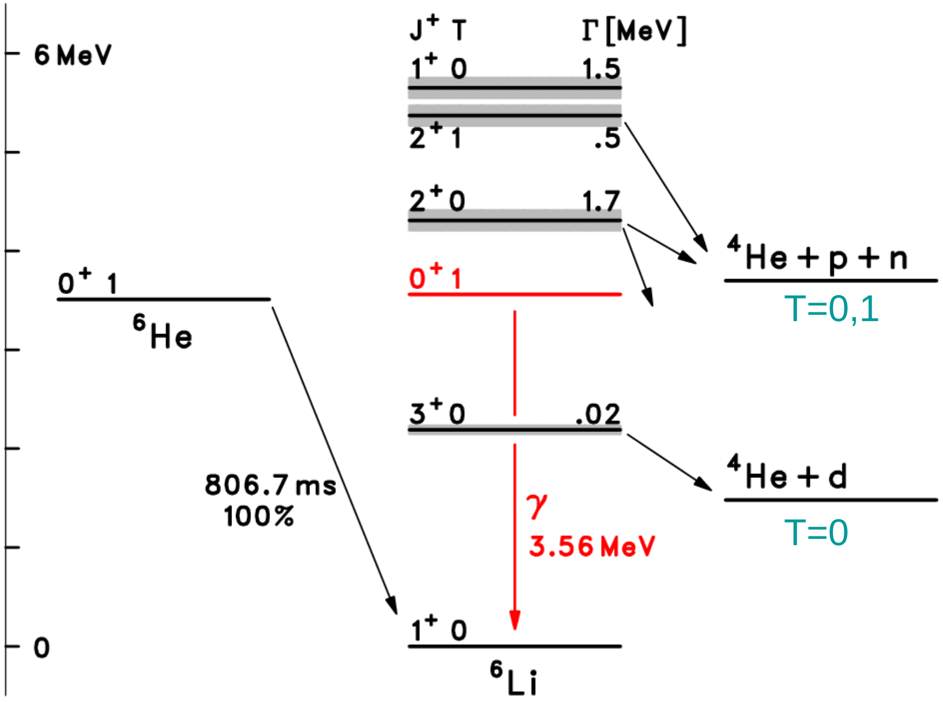
looks like 1-step direct reaction

···· promising





Other applications of polarized lithium



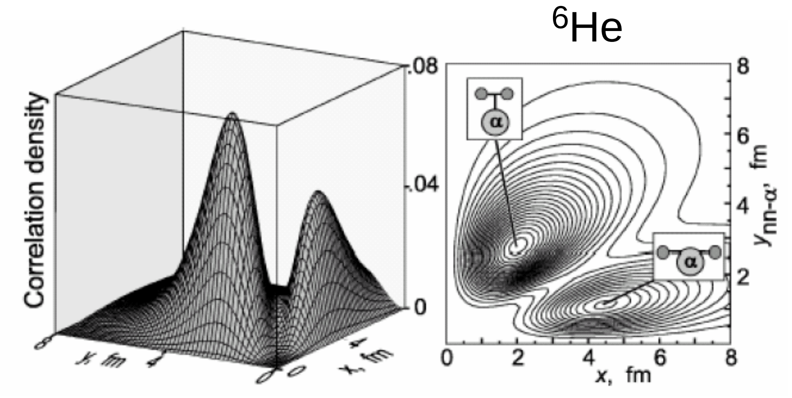
$({}^6\text{Li},{}^6\text{Li}[0^+;1]\,\gamma)$ ・・・ M1 excitation

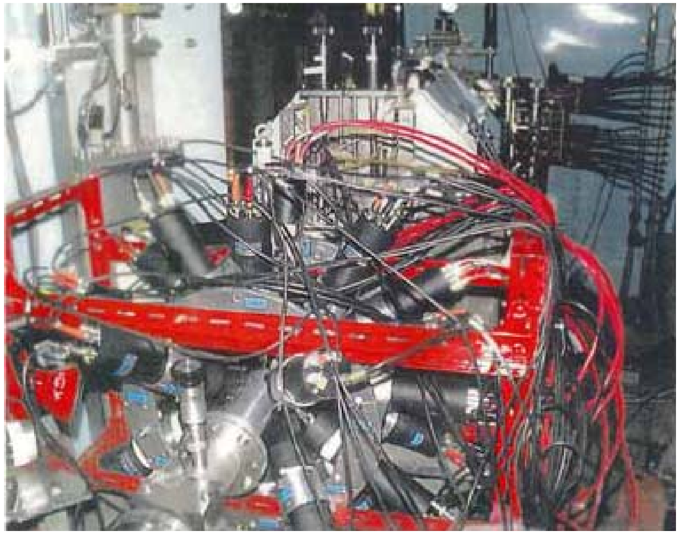
$({}^7\text{Li},{}^7\text{Be}\,\gamma)$ ・・・ (n,p) channel

Li elastic-scatt./breakup
・・・ reaction mechanism

Spin structure of
cluster states, di-nucleon, …?

$$\mu[{}^6\mathrm{Li}] \simeq \mu[d]\ ,\ Q[{}^6\mathrm{Li}] \simeq \frac{1}{3}Q[d]$$


^{6}He



S.Nakayama *et al.*, NIM A404 (1998) 34.

偏極 $^{6/7}$Li ビーム加速実績

- MPI Heidelberg　1977~199?

Optical Pumping + Surface Ionizer + Charge Exch. + Tandem

(Initially Sextupole Mag.)

$^{6}\mathrm{Li}^{+}$: ~20μA , $^{6}\mathrm{Li}^{-}$: ~0.3μA , $^{6}\mathrm{Li}^{3+}$: ~80nA　p = 80%

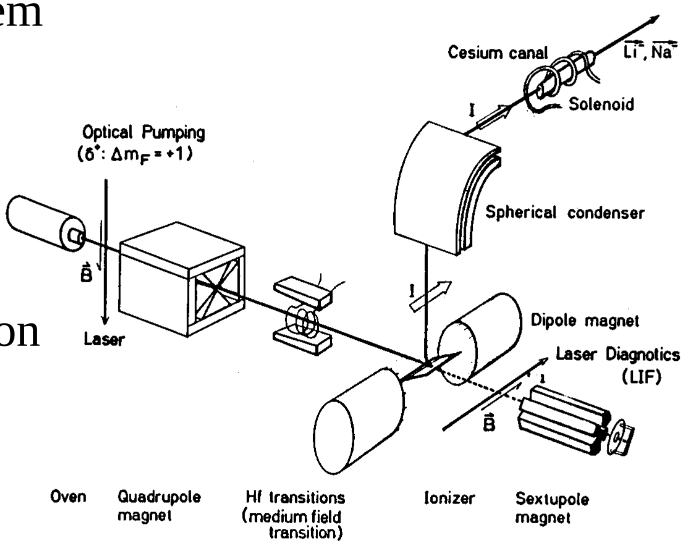
E_{max} = 24 MeV

- Saturne　1990~1992

Sextupole Mag. + Surface Ionizer + EBIS (5T) + Synchrotron

$^{6}\mathrm{Li}^{+}$: 20~35μA , $^{6}\mathrm{Li}^{3+}$: 7×10^{8} /spill　p = 70%

pulse beam　E_{max} = 4.5 GeV

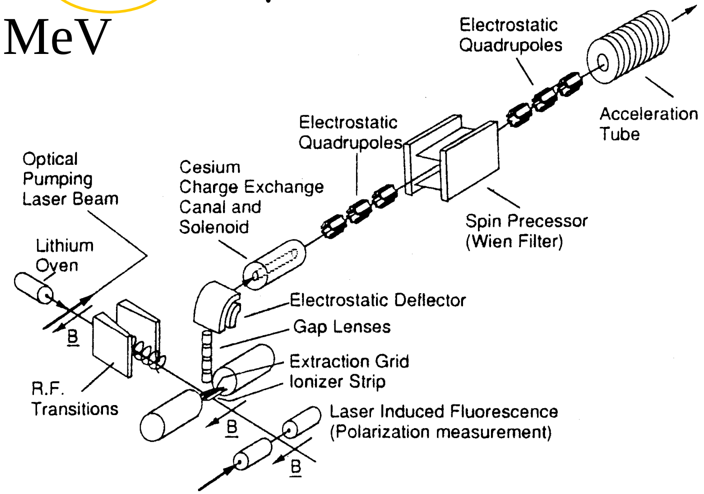


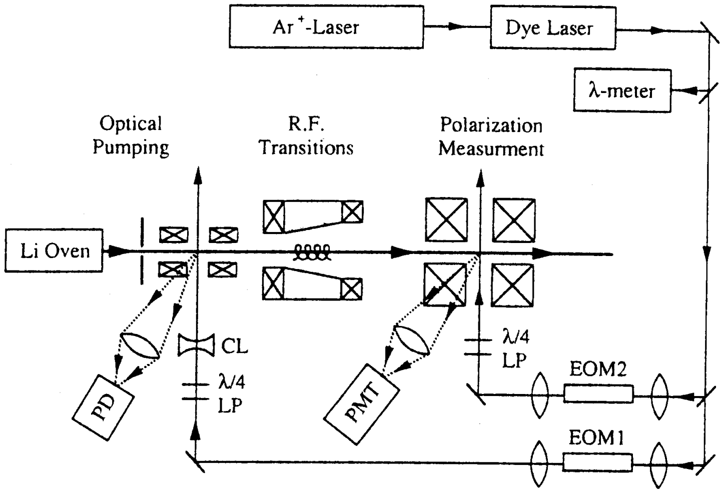
- Florida State Univ.　1991~ (active)

Optical Pumping + Surface Ionizer + Charge Exch. + Tandem + LINAC

$^{6}\mathrm{Li}^{+}$: ~8μA , $^{6}\mathrm{Li}^{-}$: ~0.2μA , $^{6}\mathrm{Li}^{3+}$: ~150nA　p = 86%

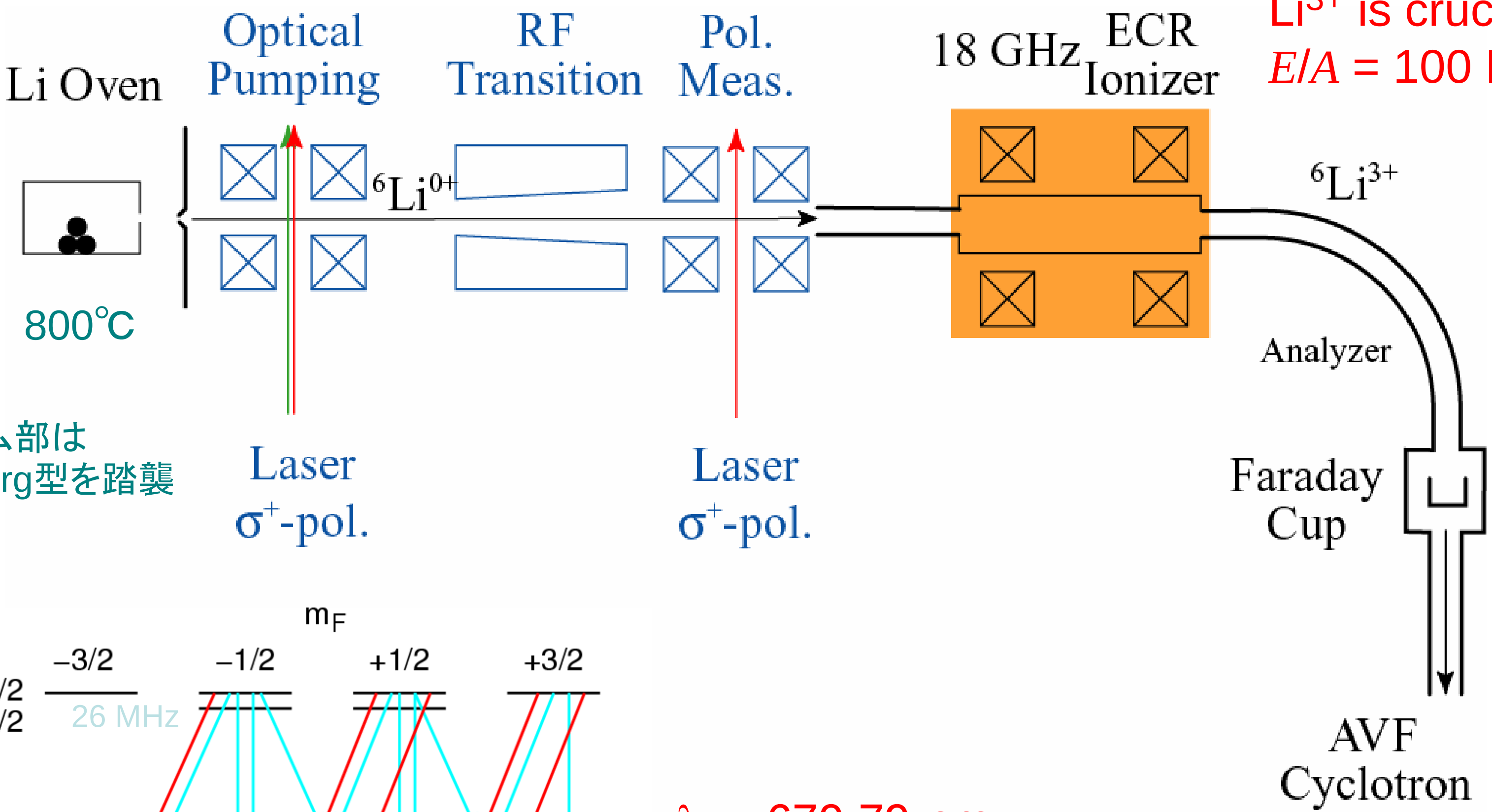
E_{max} = 60 MeV



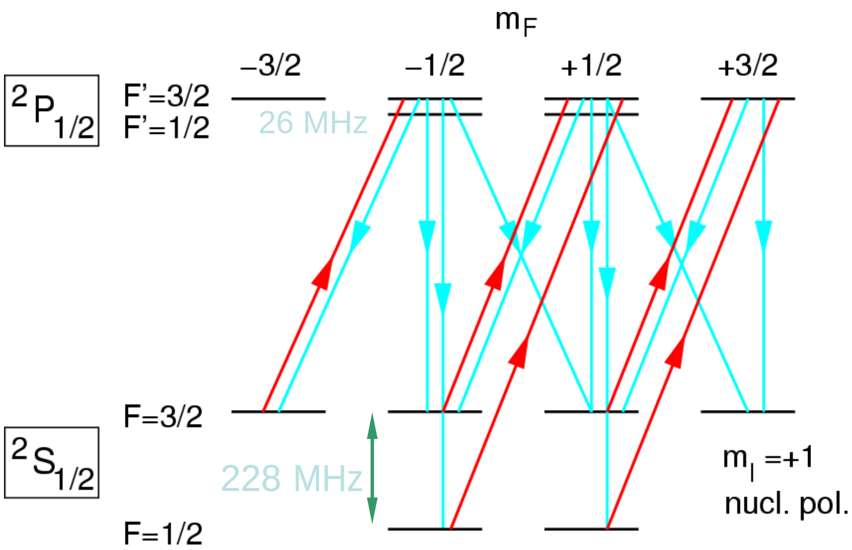


RCNP 偏極リチウムイオン源計画

Li^{3+} is crucial for E/A = 100 MeV



偏極原子ビーム部は
FSU・Heidelberg型を踏襲



λ = 670.79 nm

lifetime 27 ns (γ = 37 MHz)

$\upsilon_{max} \approx$ 3 km/s

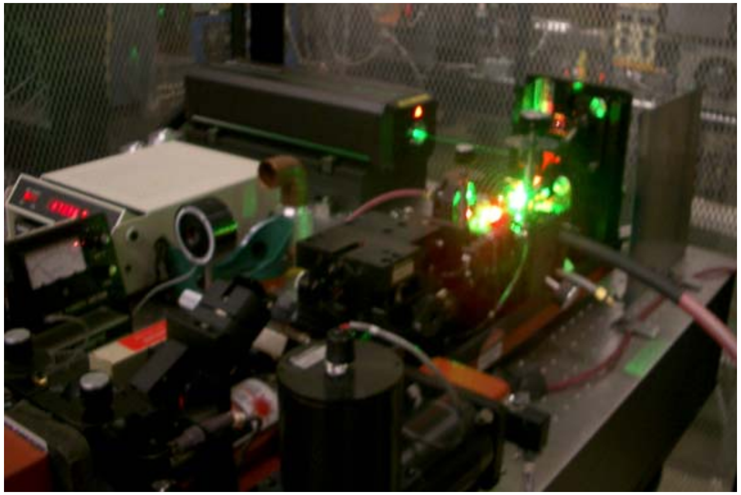
$\Delta\theta_{ds} \approx \pm(\upsilon_{max}/c)(\gamma/2\omega)$ = ±0.66 mr (0.037°)

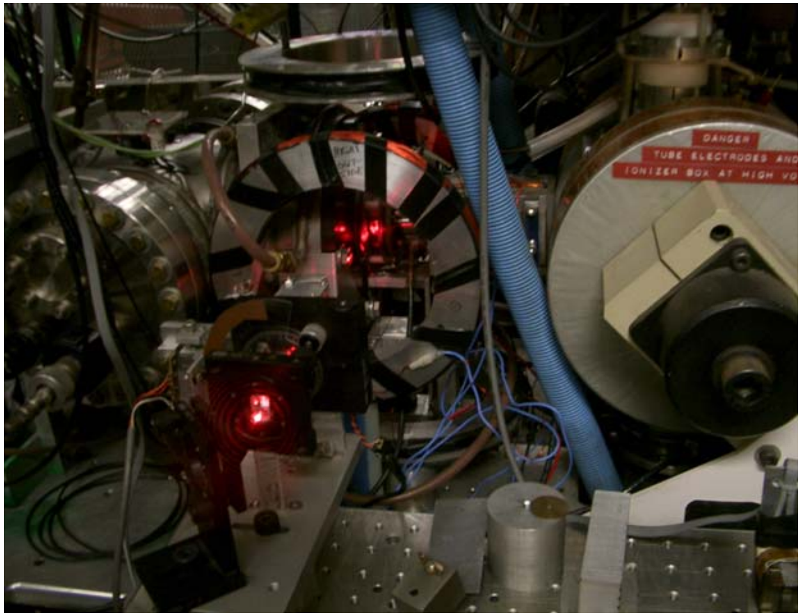
⇒ 2波長光必要　　single-mode (~1MHz)

Florida State Univ.

1991~

Ar + Dye Lasers (30~60 mW) + EOM





RCNP

TOPTICA DL100

Littrow-type ECLD

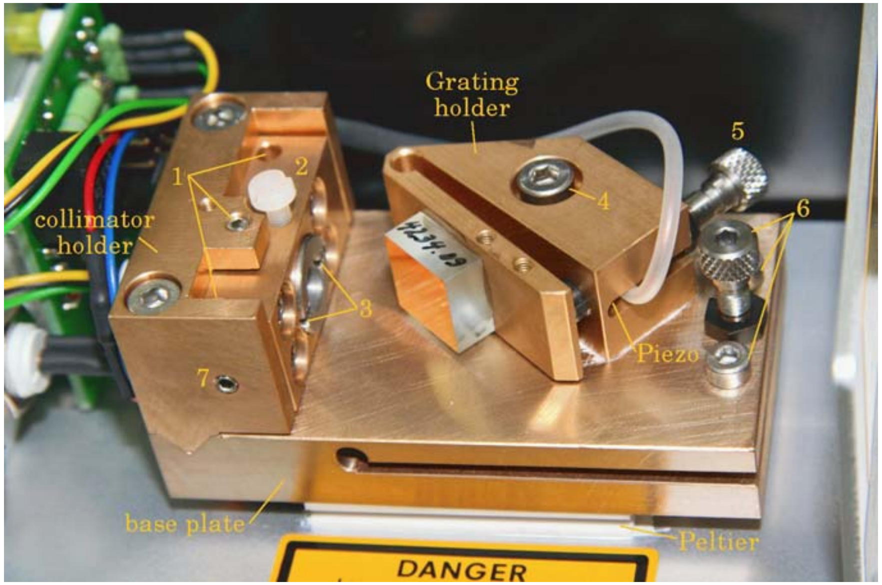
15 mW@671 nm ×3

2 for pumping

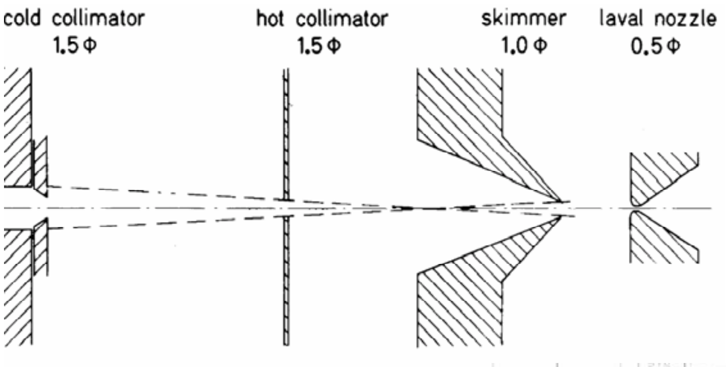
1 for LIF

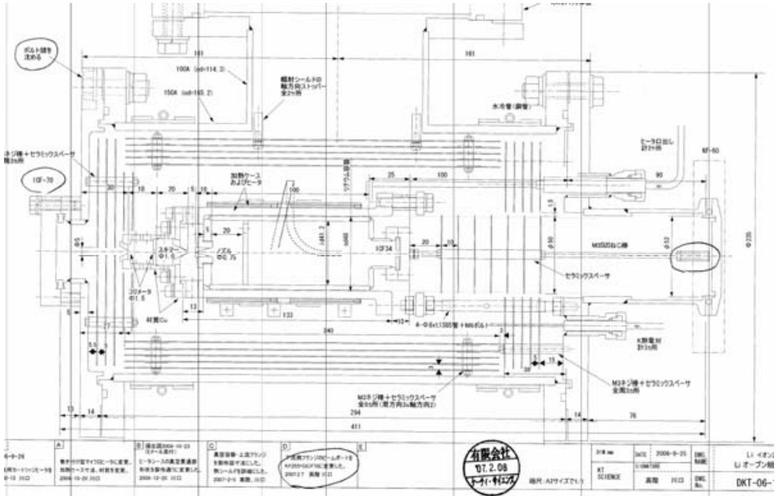
Feed-Forward [Piezo→Power]

⇒ 80 GHz scan w/o mode-hop

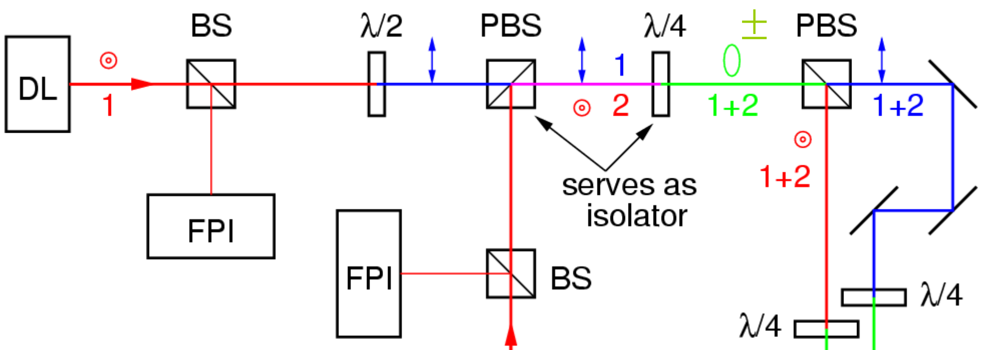
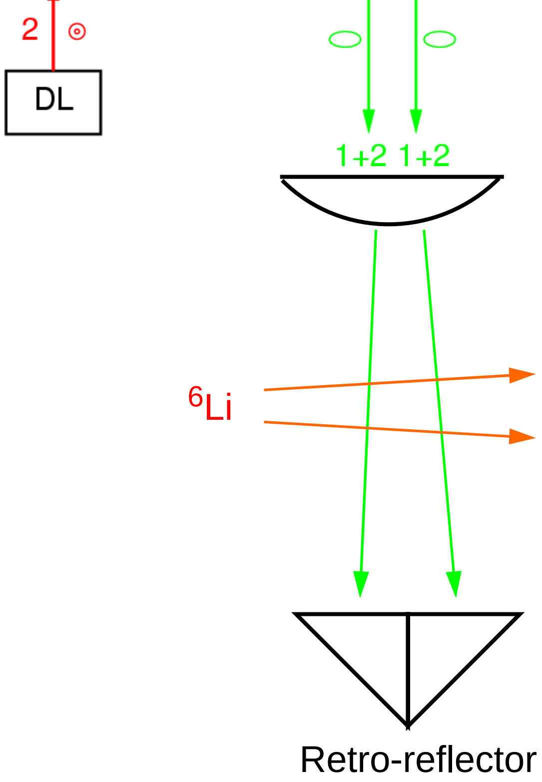


ノズル・スキマー幾何はFSU・Heidelberg型を踏襲





Optics Layout

^{6}Li 消費量
25g/2weeks (3K円/g)

Li 原子線強度

800°C (⇔ 3 Torr),
ϕ0.5 mm orifice,
±20 mr collimation

$$N(0^\circ)d\Omega \sim 1\times10^{15}\ \mathrm{s}^{-1}\ (\Leftrightarrow 160\ \mathrm{p}\mu\mathrm{A})$$

cf. $2.6\times10^{16}\ \mathrm{s}^{-1}\ (\Leftrightarrow 4\ \mathrm{mA})$ 理研偏極重水素イオン源

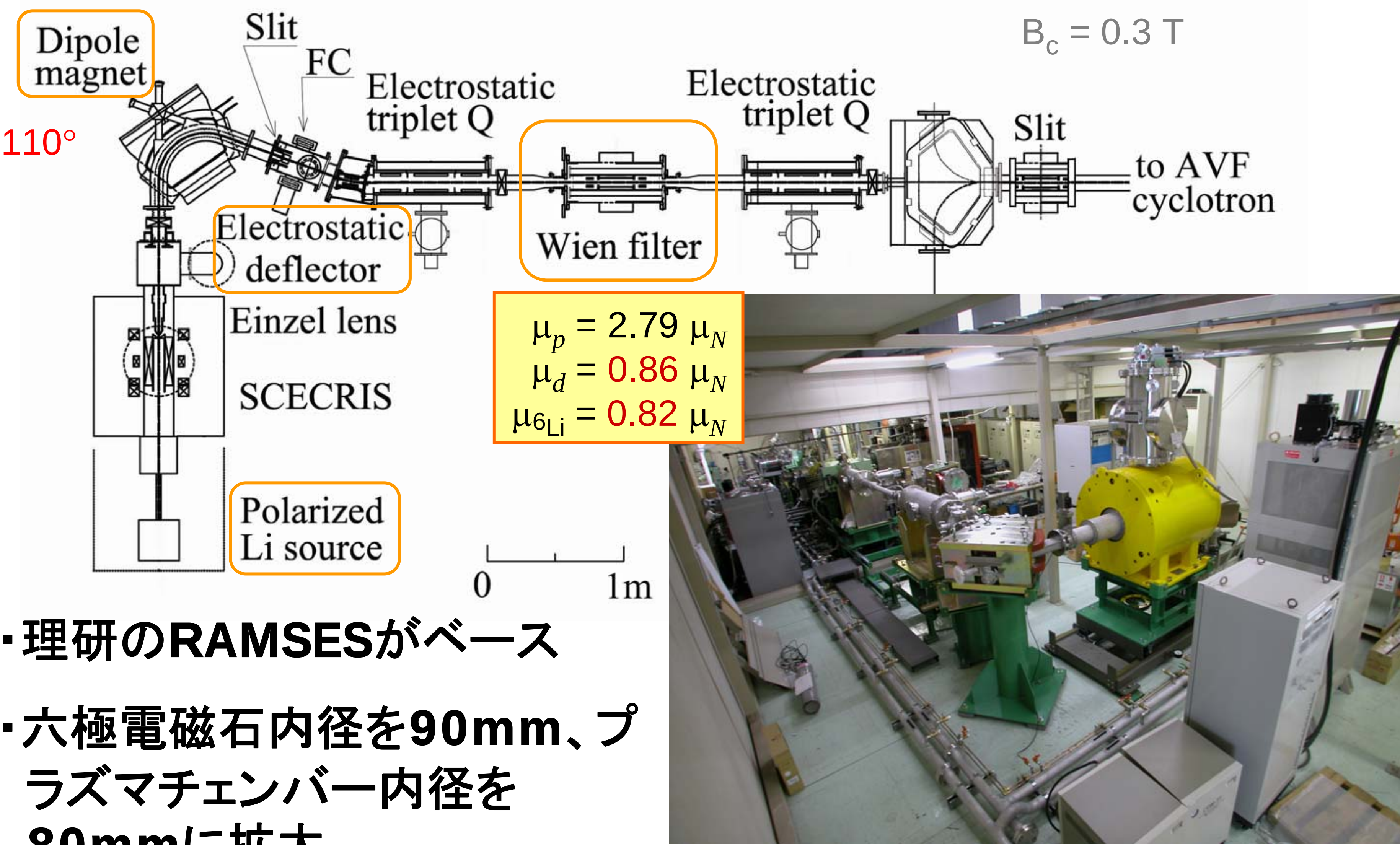
炭素厳禁!!
Li + C =
リチウムイオン
電池の反応

	融点[℃]	熱伝導度[W/m/K]	キュリー点[℃]
SS	1535	80	770
SUS	1400	15	
Ni	1455	91	359

イオン源系のアップグレード

◎18GHz超伝導ECRイオン源

$B_{ECR} = 0.64$ T
V
$B_c = 0.3$ T



$\mu_p = 2.79\ \mu_N$
$\mu_d = 0.86\ \mu_N$
$\mu_{^6\mathrm{Li}} = 0.82\ \mu_N$

- 理研のRAMSESがベース
- 六極電磁石内径を90mm、プラズマチェンバー内径を80mmに拡大

スピン回転方法 I

磁気モーメント $\mu = \dfrac{e\hbar}{2m_p c}(1+a)$

Dirac 粒子： $a=0 \Leftrightarrow \omega_s=\omega_c$

磁場 B 中　軌道回転角速度 $\omega_c = \dfrac{eB}{m\gamma}$

Cyclotron Freq.

スピン回転角速度 $\omega_s = \dfrac{eB}{m\gamma}(\underline{\gamma a}+1)$

Larmor＋Thomas歳差

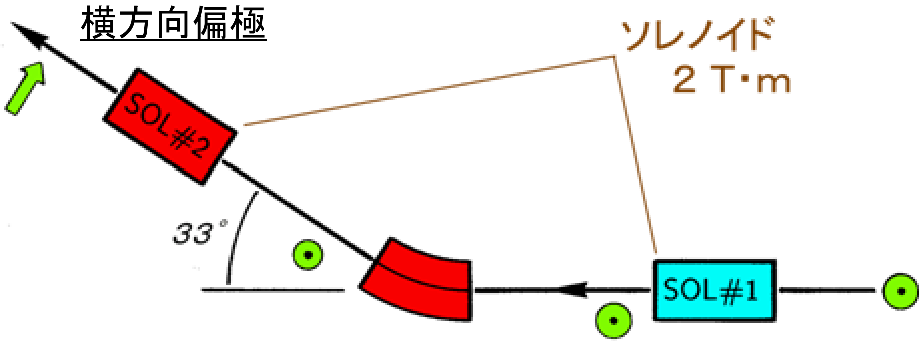
陽子: $\mu_p = \mu_N \times \boxed{2.793}$

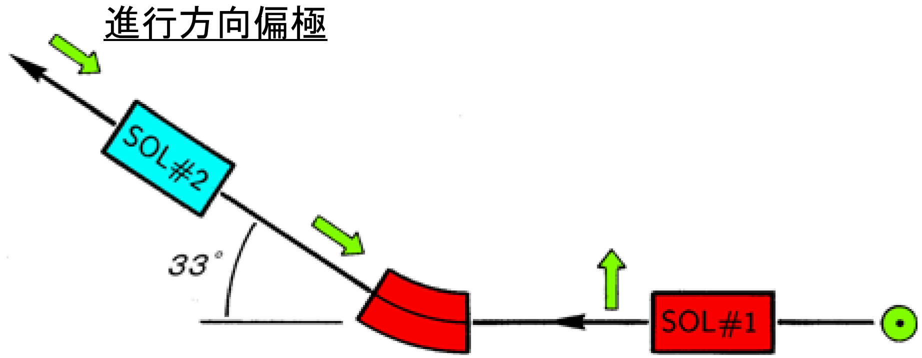
^{3}He: $\mu_{\mathrm{He}} = \mu_N \times \boxed{-2.128}$

重陽子: $\mu_d = \mu_N \times \boxed{0.857}$

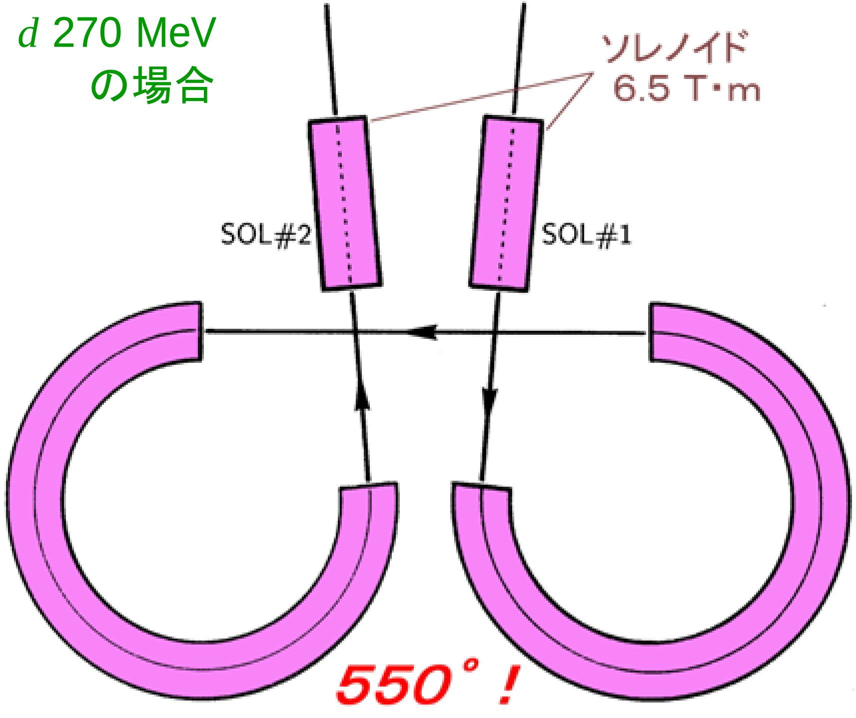
^{6}Li: $\mu_{\mathrm{Li}} = \mu_N \times \boxed{0.822}$

p 500 MeV の場合



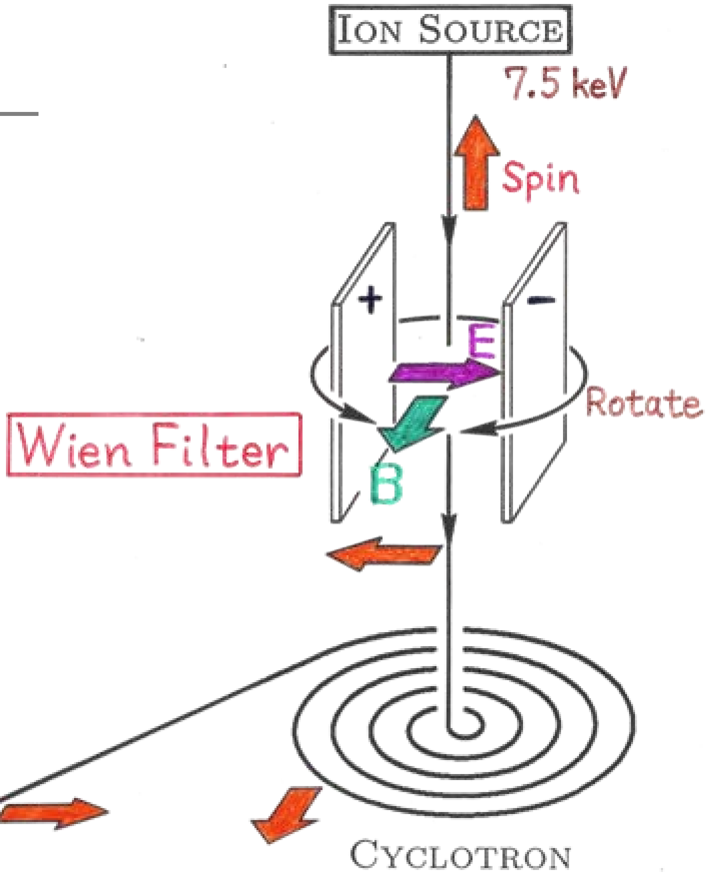


d 270 MeV の場合



スピン回転方法 II

— 理研RARFで
採用した方法 —



磁場でスピン回転
電場を併用して軌道は戻す

加速器入射前の
低エネルギーならば可能

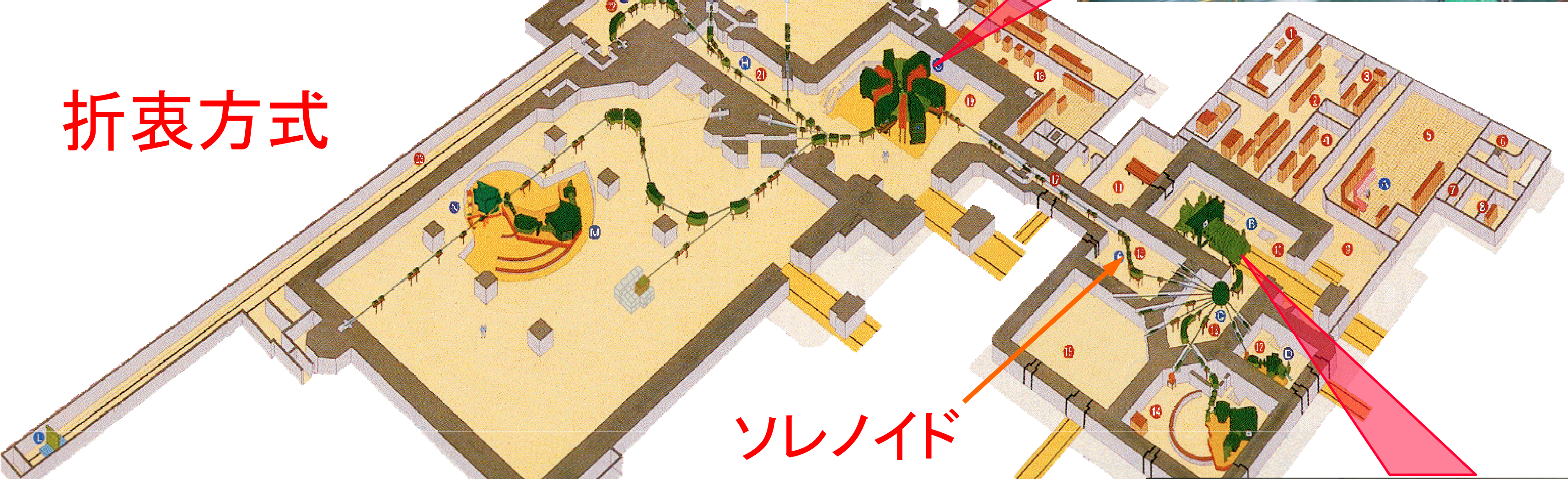
バン・デ・グラフでは一般的だが
サイクロトロンでは加速中にスピン歳差運動

- 特定のターンのみを引き出す必要有り（single-turn extraction）
  等時性 ・・・ 連続エネルギーで加速可能 ⇔ 位相安定性
  - リングサイクロトロン ・・・ 可（入射ビーム整形・Phase Compression）
  - AVF サイクロトロン ・・・ 難（中心部弱収束領域で制限）
- 加速後のスピンの向きを高効率でモニターする偏極度計必要

RCNP
サイクロトロン
施設

リングサイクロトロン
K=400 MeV
$\Delta E/E \sim 10^{-4}$
1992~

折束方式



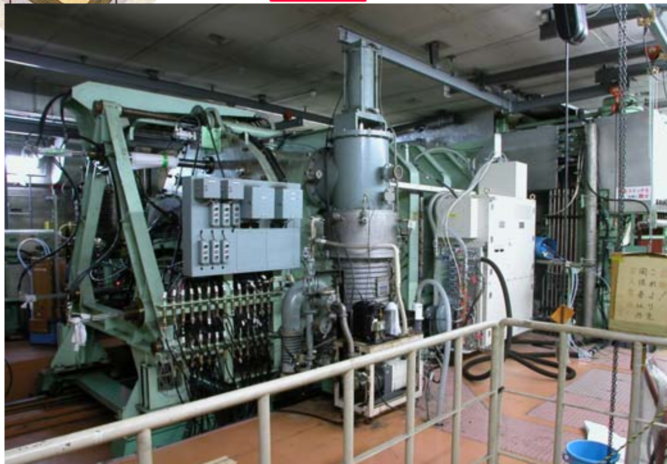
ソレノイド
×2

- ソレノイド調整の度にリング調整が必要
- *d* は任意回転できない（~60°間隔）

⇩

AVFでもシングルターン加速
できればイオン源で回転可能

AVFサイクロトロン
K=140 MeV
1973~

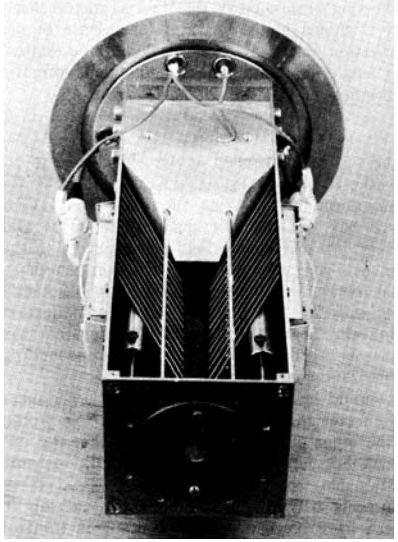


偏極度計@AVF下流

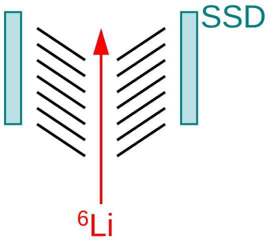
$$^4\mathrm{He}(^6\vec{\mathrm{Li}},\alpha)^6\mathrm{Li}$$

$$E_{^6\mathrm{Li}} \le 60\ \mathrm{MeV}\,,\quad \theta_\alpha = 30^\circ$$

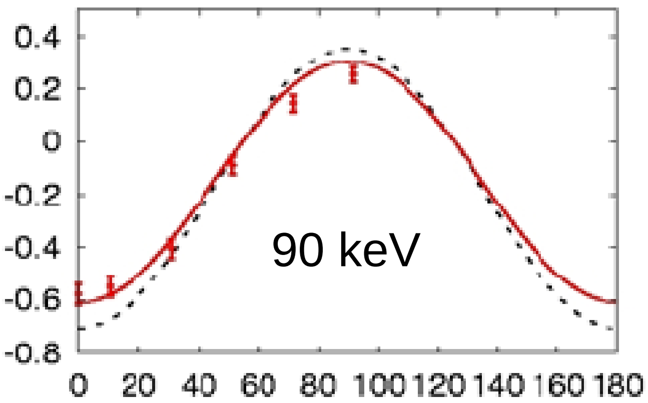
FSU, MPI-Heidelberg で豊富な実績



Venetian-blind type collimator



^{6}Li(d,α) , T_{20}



90 keV

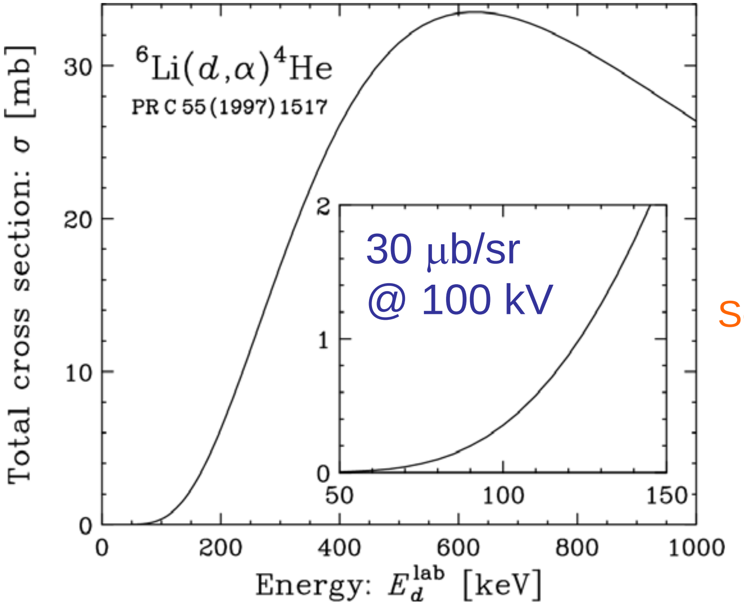
M.Yamaguchi et al. @Tsukuba

偏極度計@イオン源

$$A_{yy}\left[^2\mathrm{H}(^6\vec{\mathrm{Li}},\alpha)\alpha\right] = A_{yy}\left[^6\mathrm{Li}(\vec{d},\alpha)\alpha\right]$$

by parity conservation

$E_\alpha \cong 11$ MeV



30 µb/sr
@ 100 kV

$V_{\mathrm{SCECR}} = +19$ kV

$\Rightarrow V_{\mathrm{target}} \le -80$ kV

Secondary electron suppression

$V_{\mathrm{acc.}} > V_{\mathrm{target}}$ by 0.5~few kV

Neutron Generator (D+D)
http://www.thermo.com/

複合粒子反応機構に関してコメント

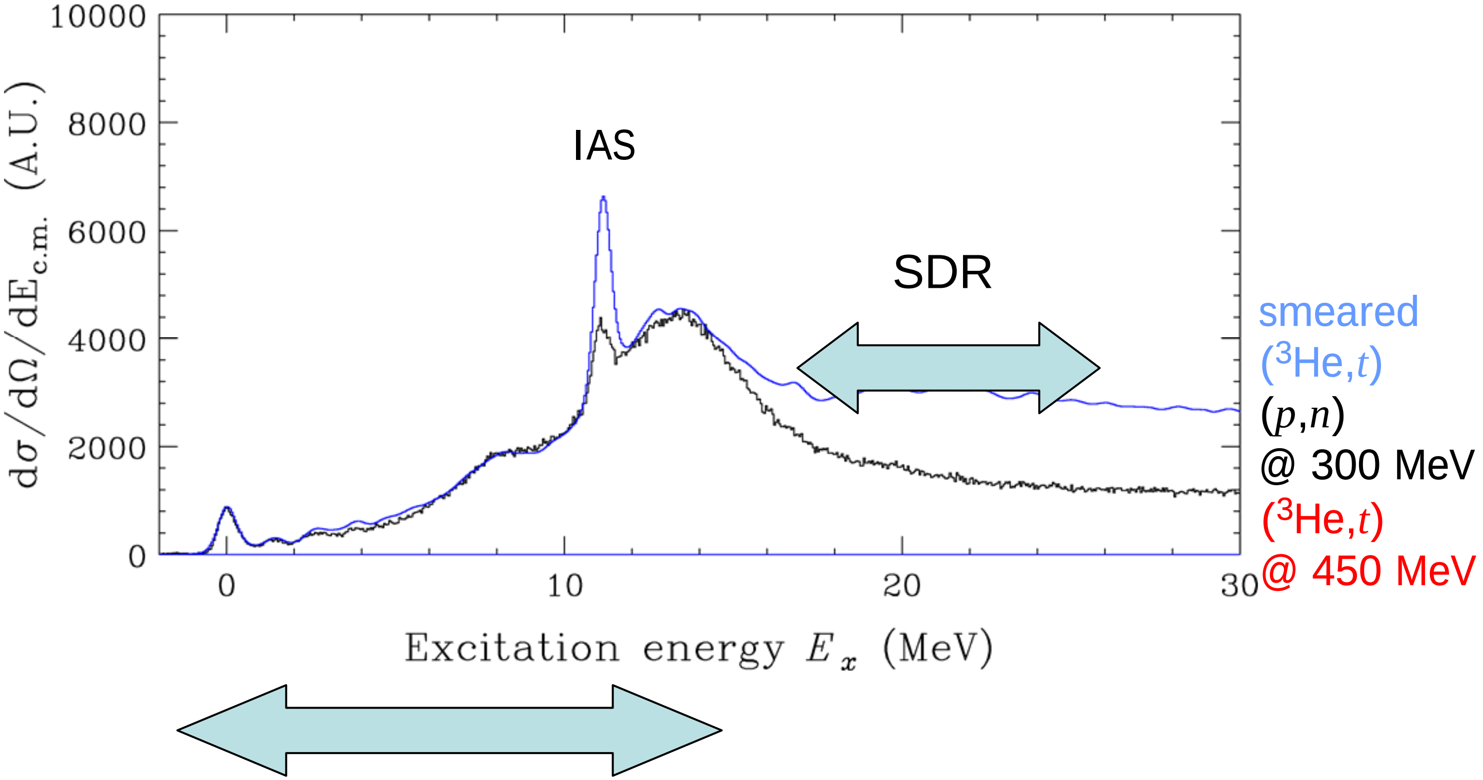
$$\frac{d\sigma}{d\Omega}(q\sim 0, E_x) = \hat{\sigma}(E_i, A)F(q,\omega)B(\mathrm{GT})$$

e.g. T.N. Taddeucci et al., NPA 469 (1987) 125

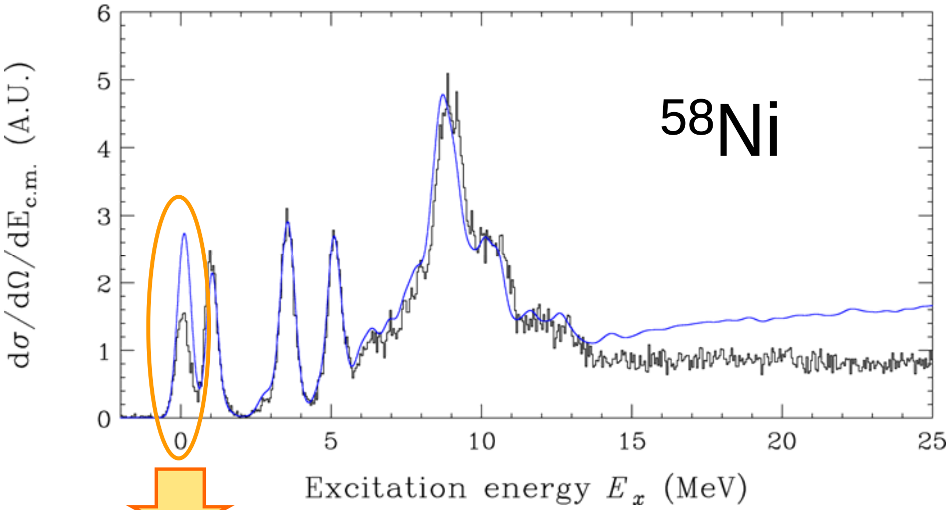
笹野（東大）氏の解析
含 Preliminary データ

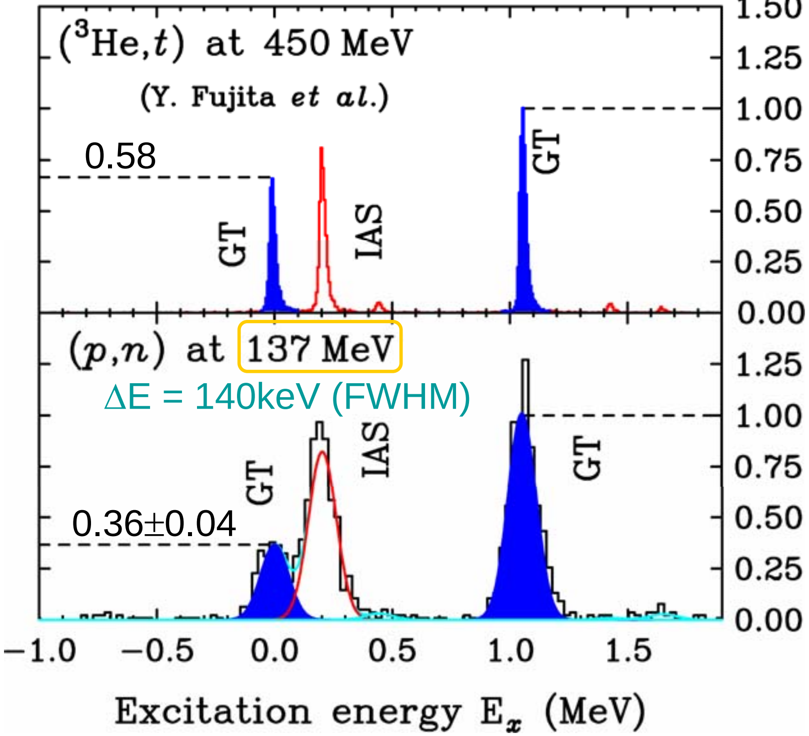
Comparison: (^{3}He,t) & (p,n)

^{100}Mo



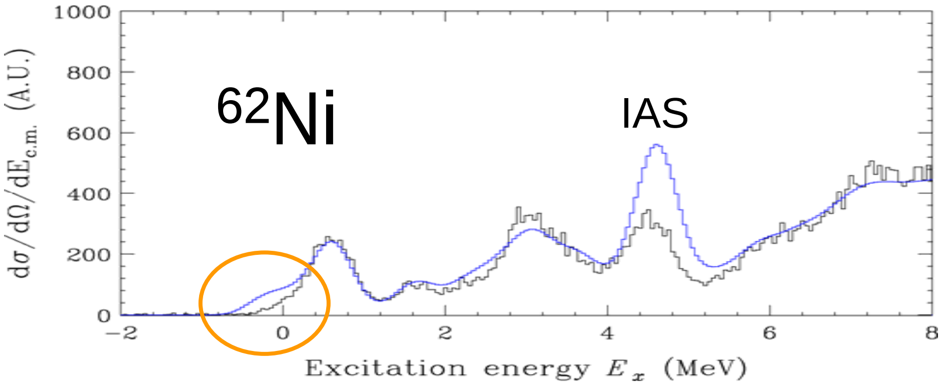
Good agreement up to GTGR region

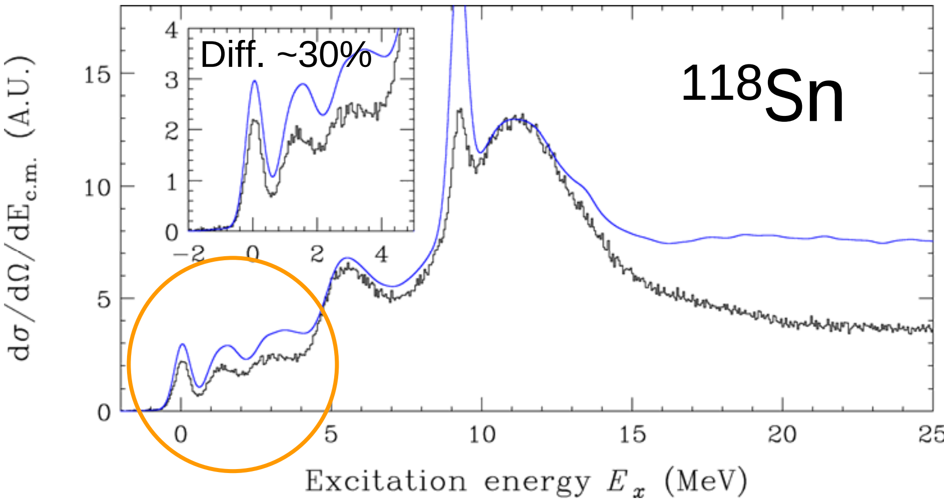




0.41±0.03 @ 198MeV

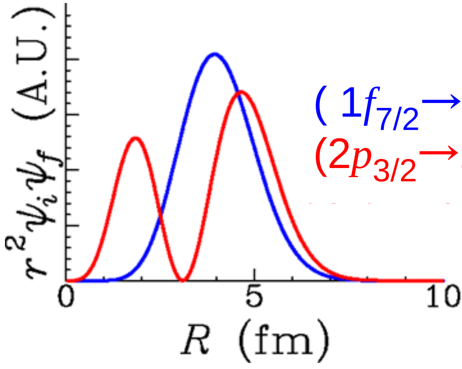
0.38±0.01 @ 297MeV (^{3}He,t) > (p,n) by 40%





- transition density

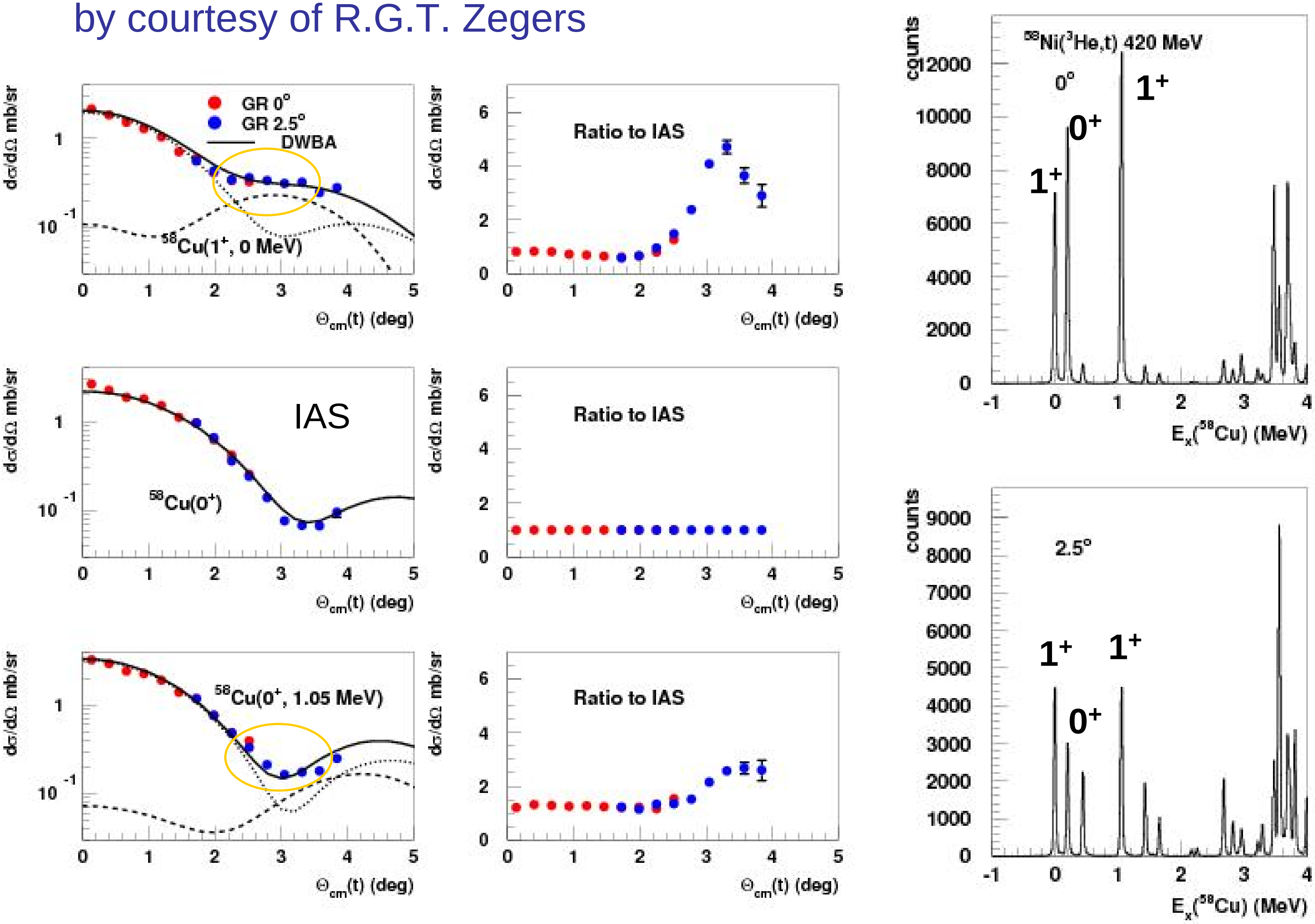
(^{3}He,t) overestimates
(due to n=2 term ?)



mean free path
- (p,n) @ 300 MeV: 5 fm
- (^{3}He,t) @ 450 MeV: 2 fm

New ^{58}Ni(^{3}He,t) data: very preliminary

by courtesy of R.G.T. Zegers



Proportionality between q=0 cross section & B(GT)

$$\frac{d\sigma}{d\Omega}(q{\sim}0, E_x) = \hat{\sigma}(E_i, A)F(q,\omega)B(\mathrm{GT})$$

T.N. Taddeucci et al., NPA 469 (1987) 125

Assumptions:

- Only $\ell = 0$ form factor contributes.

  But $\ell = 2$ components can be important, while it is negligible in β-decay.

- Only central interaction $V_{ST}(r)$ contributes.

  But tensor int. can be important

  event at $\theta = 0°$ & $\ell = 0$

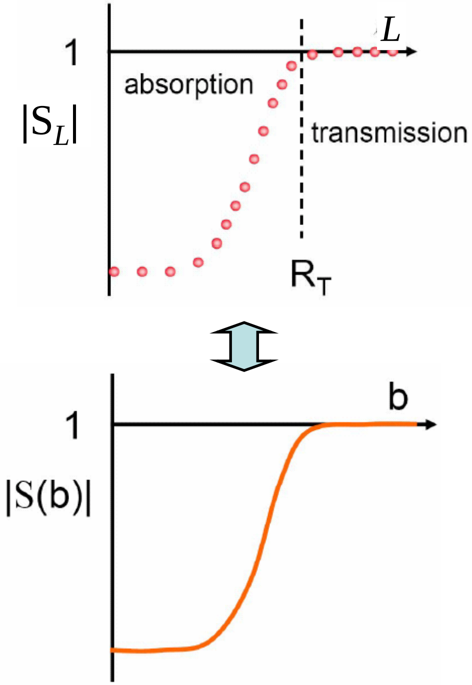
  through knock-on exchange processes.

  T=1 : ok
  T=0 : not

- Eikonal approximation & $b \to 0$!?

  $$\chi_f^*(\boldsymbol{k}_f;\boldsymbol{r})\chi_i(\boldsymbol{k}_i;\boldsymbol{r}) \xrightarrow{\text{eikonal}} \exp(i\boldsymbol{q}\cdot\boldsymbol{r})S(b),$$

  where $b \simeq L/k$, but $L \neq \ell = 0$!!



Systematic analyses desired ···· need more reliable calc. code for (^{3}He,t)

まとめ

軽重イオン直接反応

- 選択性＆RCNPの高分解能を利用したユニークな核分光が可能
- $(d,{}^{2}\mathrm{He})$, $({}^{6}\mathrm{Li},{}^{6}\mathrm{He})$ ・・・ $1^{+}+0^{+}\to 0^{+}+I^{\pi}$ 型反応
  テンソル偏極分解能 $A_{zz}(0°)$ による
  0^{-} 1^{-}（自然パリティ）の模型非依存・高感度識別
  ⇒ テンソル相関（π 中間子相関）の情報
- 偏極 6Li イオン源・スピン回転制御（シングルターン）の整備が進行中
- 複合粒子反応解析の精度向上の提案 — 例：$({}^{3}\mathrm{He},t)$ vs. (p,n) —
  - ✓ 散乱粒子分解チャネルを結合した散乱波解の利用
  - ✓ 散乱粒子・標的核内の相互作用二核子の正しい反対称化（含テンソル相互作用）
  - ✓ 密度依存型有効相互作用による媒質効果の導入
  - ✓ （できればCCBAでなく）荷電交換も含むチャネル結合計算

が強く望まれる

個々の理論的道具は揃っている
（＝古い技術：反応理論家には魅力に乏しいかも知れないが・・・）
組み合わせて利用可能範囲を拡大する事が重要

⇒ 不安定核による直接反応（理研RIBF）の発展へ

Backup

もう少しまじめに基本的対称性から・・・

鏡映（空間反転＋回転）不変性

$$P\,R_y(180^\circ)\left|\pi\, I\, M\right\rangle = \pi\,(-)^{I-M}\left|\pi\, I\, -M\right\rangle$$

$$\begin{aligned}&\left\langle \pi_B I_B M_B + 0\,0 \right| T \left| +0\,0 + 1\,M_a \right\rangle\\ &\quad = -\pi_B (-)^{I_B}\\ &\qquad \times \left\langle \pi_B I_B\, -M_B + 0\,0 \right| T \left| +0\,0 + 1 -M_a \right\rangle\end{aligned}$$

$$I_b = I_A = 0\,,\ I_a = 1$$

$$\pi_b \pi_A \pi_a = +$$

$M_B = M_a$ at $\theta = 0^\circ$

⇒ 0^+ は励起できない

一般化

$$A_{zz}(0^\circ) = \begin{cases} +1 & \text{for} \quad \text{natural parity } [\pi_B = (-)^{I_B}] \\ -2 & \text{for} \quad 0^- \end{cases}$$

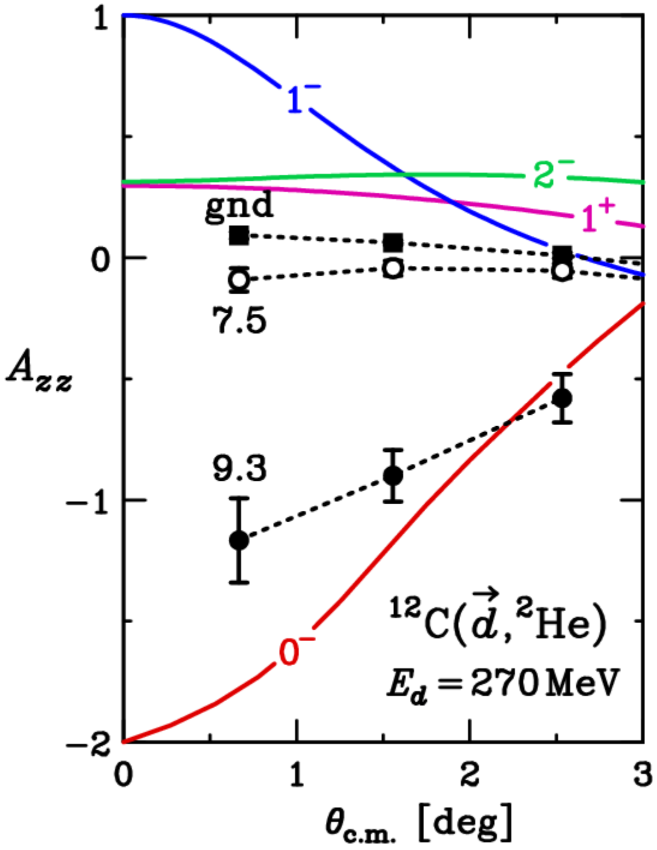
反応断面積 （スピン量子化軸 Z // ビーム軸 z）

$$\sigma = \sigma_0\left(1 + \tfrac{1}{2} P_{ZZ} A_{zz}\right) = \begin{cases} \sigma_0\left(1 - A_{zz}\right) & \cdots P_{ZZ} = -2 \\ \sigma_0\left(1 + \tfrac{1}{2} A_{zz}\right) & \cdots P_{ZZ} = +1 \end{cases}$$

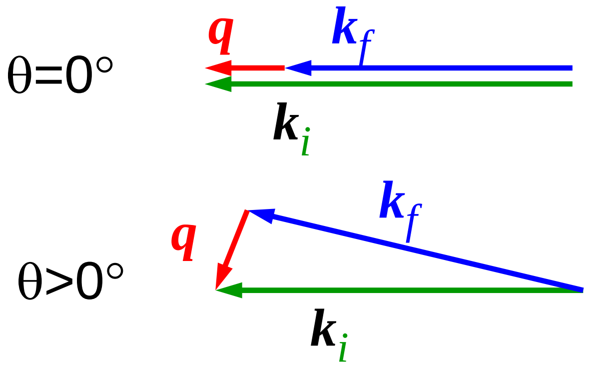
σ_0：非偏極断面積

	$p_{ZZ} = +1$	$p_{ZZ} = -2$
n.p.	$\frac{3}{2}\sigma_0$	0
0^-	0	$3\sigma_0$

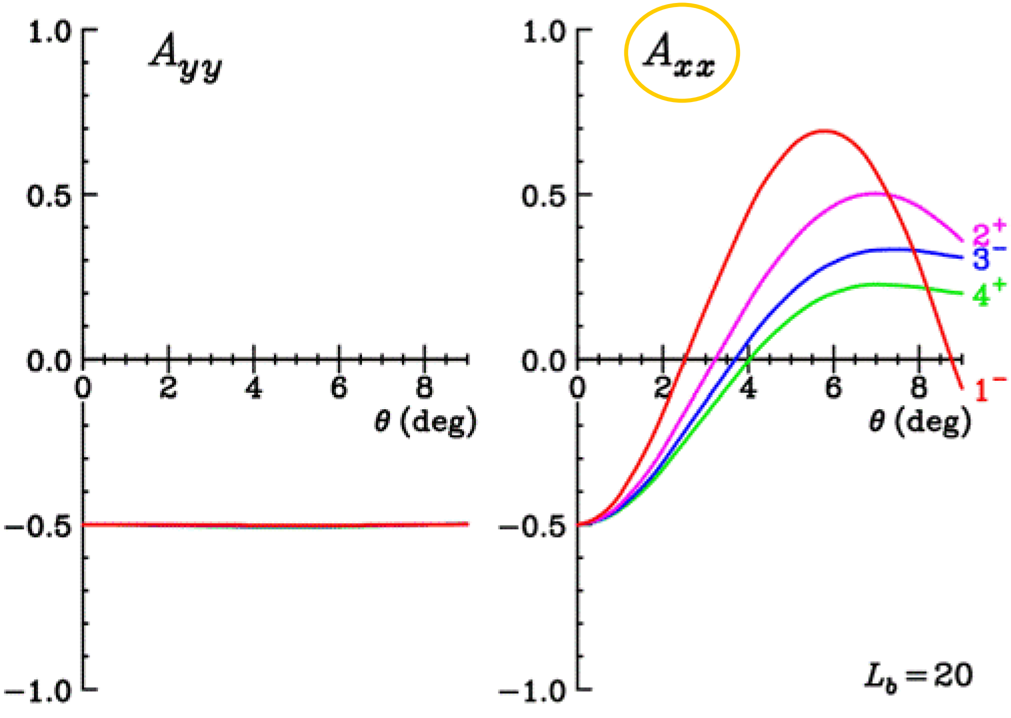
A_{zz} angular distribution



Steep A_{zz} (A_{xx}) dist. is a general feature



rapid $\boldsymbol{q}$ rotation at θ~0°



fairly independent of form-factor and distortion.

cf. In PWIA (Breit frame),

A_{xx}~+1 for 1⁻ at q~0

D.V.Bugg, C.Wilkin, NPA 467 (1987) 575.

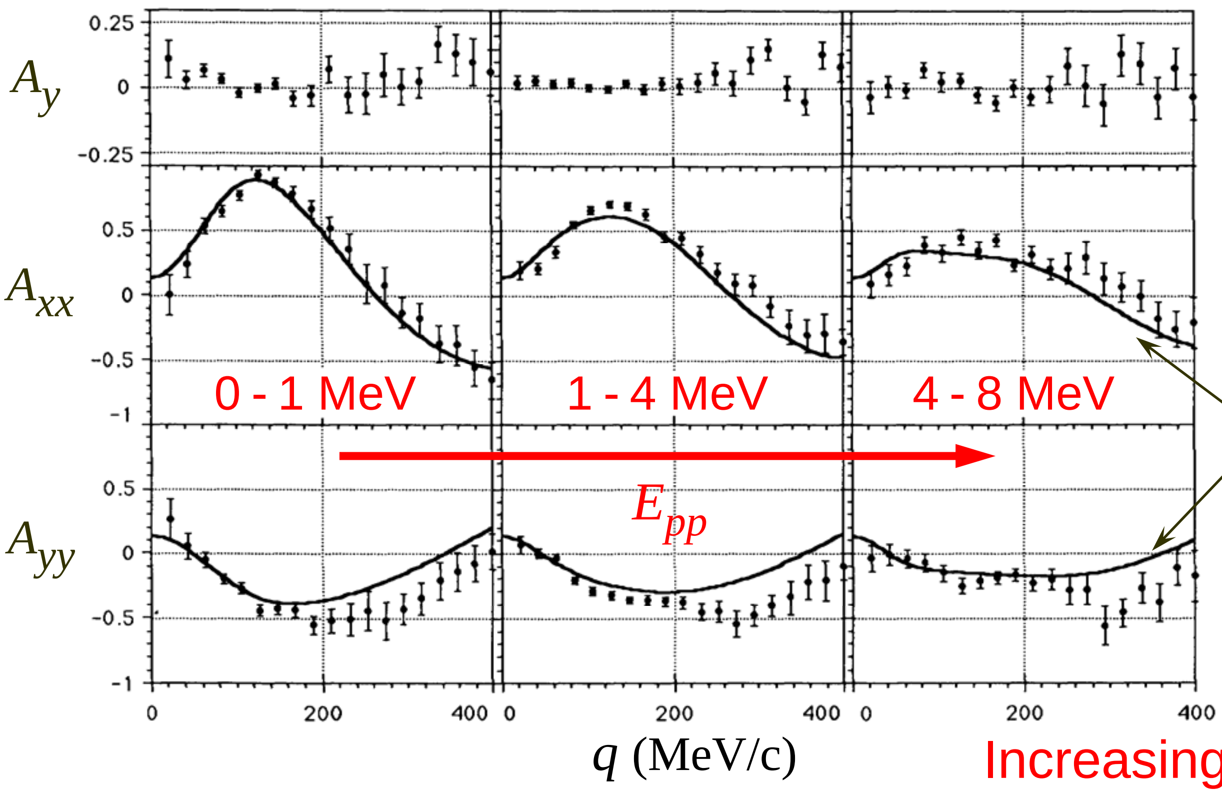
$$D^2_{00}(0°,90°,0°) = -\frac{1}{2}$$

$$A_{xx} + A_{yy} + A_{zz} = 0$$

Purity of ${}^1S_0$ in detected *p*-*p*

No study for nucleus target.
For ^{1}H target, impurity is few percent if E_{pp} < 1 MeV according to PWIA

Thus, customary
$$\frac{d\sigma}{d\Omega}\left[(d,{}^2\mathrm{He})\right] \equiv \frac{1}{2}\int_{4\pi}\int_0^{1\,\mathrm{MeV}} \frac{d^3\sigma}{d\Omega_{^2\mathrm{He}}\, d\Omega_{pp}\, d\varepsilon_{pp}}\, d\Omega_{pp}\, d\varepsilon_{pp}$$

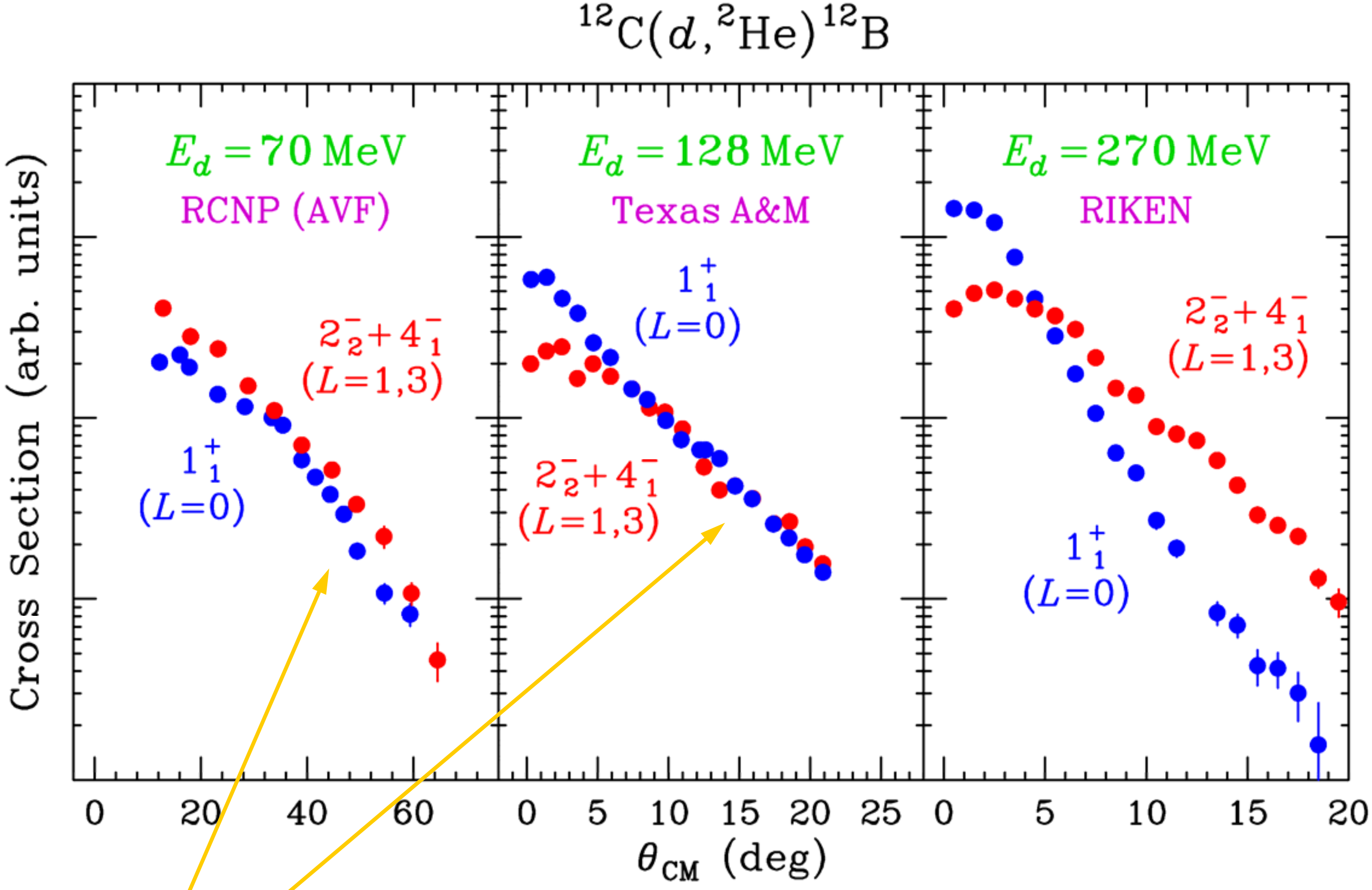


^{1}H(*d*,*pp*)*n*
E_d = 350 MeV

S. Kox *et al.*
Nucl. Phys. A556 (‘93) 621

Increasing effect of higher partial-wave as increasing E_{pp}

1-step direct reaction ?



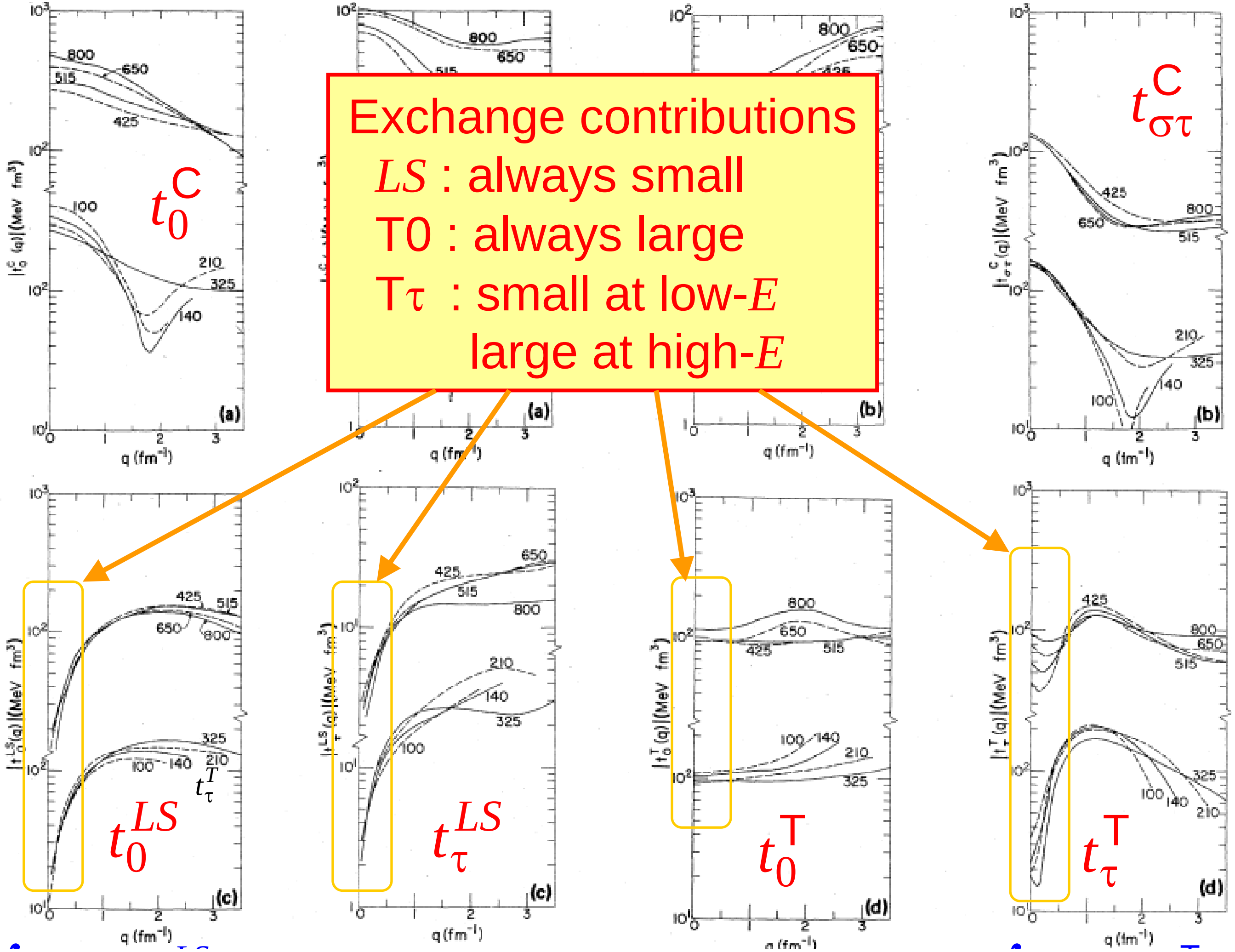
monotonous

L-dependence becomes clear as E_d increases

Sequential processes,
(d,p)-(p,^{2}He), (d,t)-(t,^{2}He), etc
may be dominant at $E < 100$ MeV/A ?

t-matrix (direct+exchange) for A=28 target W.G.Love, M.A.Franey, PRC 24 (1981) 1073

$\int j_0(qr)V^{\mathrm{C}}(r)d\vec{r}$



Exchange contributions
LS : always small
T0 : always large
Tτ : small at low-E
large at high-E

Non-negligible effects of exchange-tensor on D_{NN}(0°) event at 300 MeV
T.Wakasa *et al*., PRC 51 (1995) R2871.