Polarized experiment with medium energy hadron beam

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What do we learn from polarized experiment ?

unpolarized

polarized

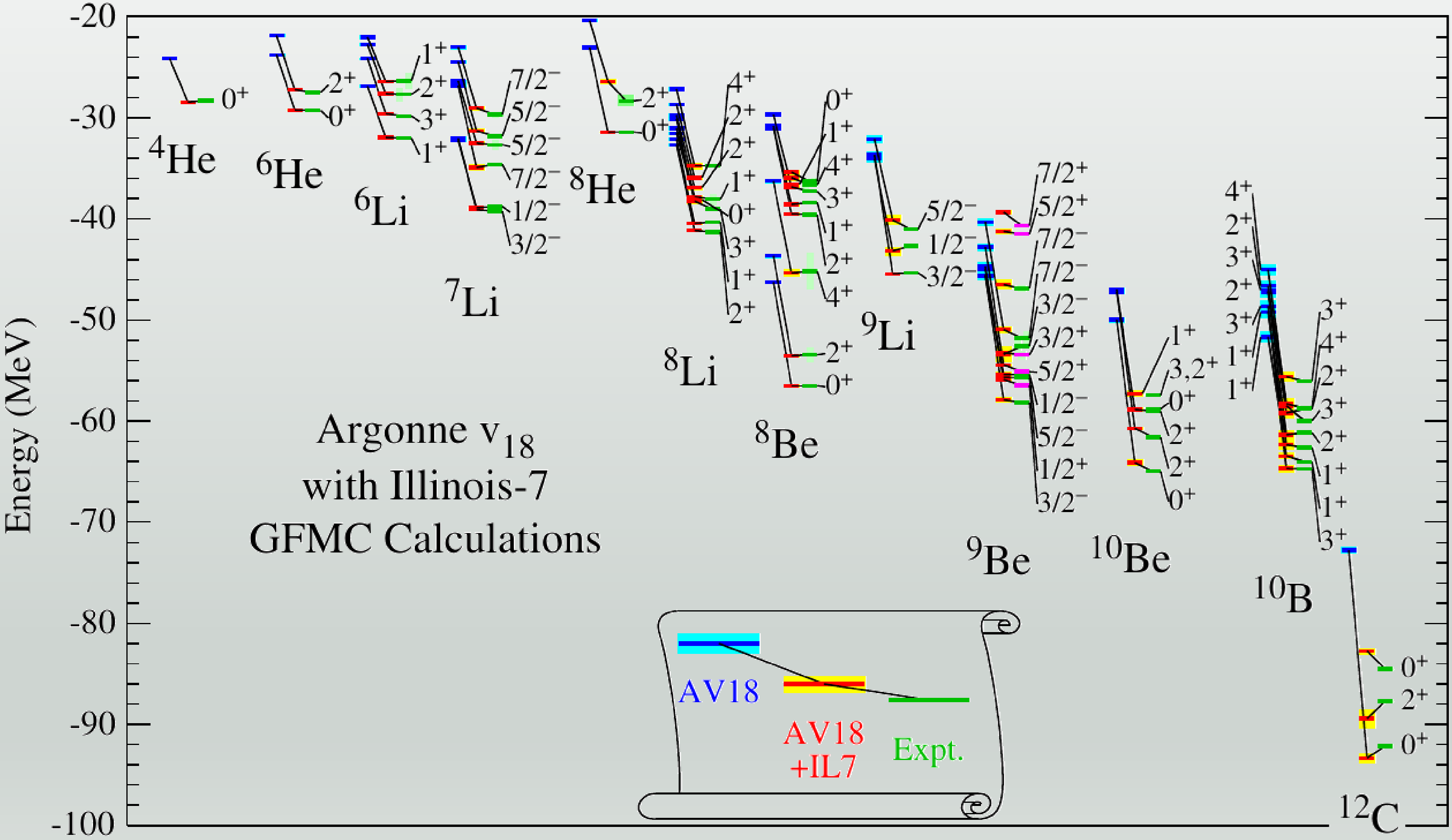
Outline

- Three-body Nuclear Force (TNF) in polarized scattering
- Polarized charge exchange reaction with inverse kinematics
- R&D of polarized ^{3}He target in Lanzhou Univ.

Three-body Nuclear Force (TNF) in polarized scattering

Effect of TNF——spectrum of light nucleus

J. Carlson, et al., Rev. Mod. Phys., 87 (2015) 1067



common, significant

binding state

unpolarized

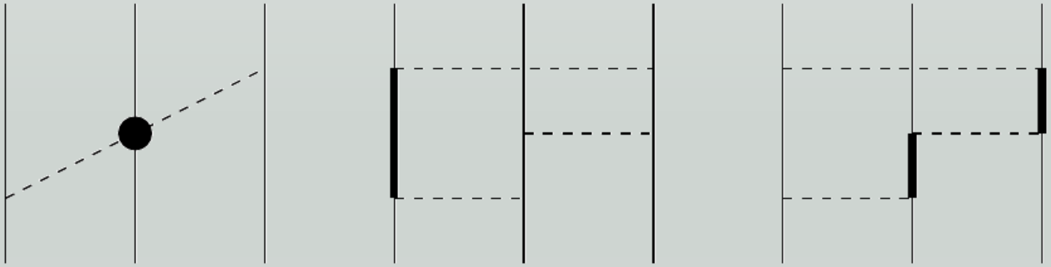
Phenomenological NN potential

- Two body interaction (AV18, CD-Bonn…)

$$\begin{aligned} O^p_{ij} = & [1, \sigma_i \cdot \sigma_j, S_{ij}, \mathbf{L} \cdot \mathbf{S}, \mathbf{L}^2, \mathbf{L}^2(\sigma_i \cdot \sigma_j), (\mathbf{L} \cdot \mathbf{S})^2] \\ & + [1, \sigma_i \cdot \sigma_j, S_{ij}, \mathbf{L} \cdot \mathbf{S}, \mathbf{L}^2, \mathbf{L}^2(\sigma_i \cdot \sigma_j), (\mathbf{L} \cdot \mathbf{S})^2] \otimes \tau_i \cdot \tau_j \\ & + [1, \sigma_i \cdot \sigma_j, S_{ij}, \mathbf{L} \cdot \mathbf{S}] \otimes T_{ij} \\ & + [1, \sigma_i \cdot \sigma_j, S_{ij}, \mathbf{L} \cdot \mathbf{S}] \otimes (\tau_i + \tau_j)_z \end{aligned}$$

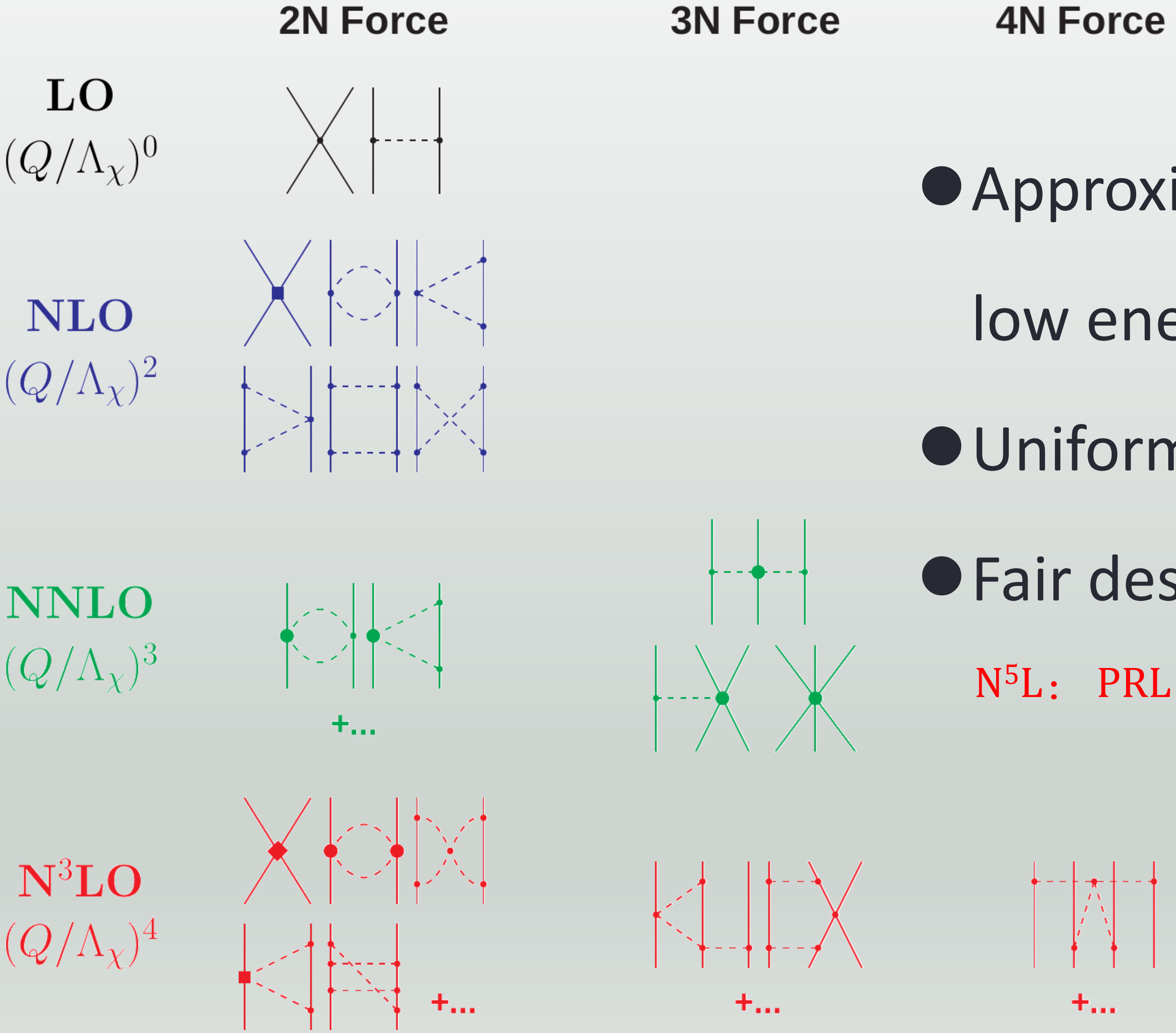
- Three body interaction (TM’, IL7, NJIM…)

$$\text{Illinois } V_{ijk} = V^{2\pi P}_{ijk} + V^{2\pi S}_{ijk} + V^{3\pi \Delta R}_{ijk} + V^{R}_{ijk}$$



- Global fitting of (un)polarized scattering data

Description of chiral EFT



2N Force

3N Force

4N Force

LO
$(Q/\Lambda_\chi)^0$

NLO
$(Q/\Lambda_\chi)^2$

NNLO
$(Q/\Lambda_\chi)^3$

+...

N^{3}LO
$(Q/\Lambda_\chi)^4$

+...

+...

+...

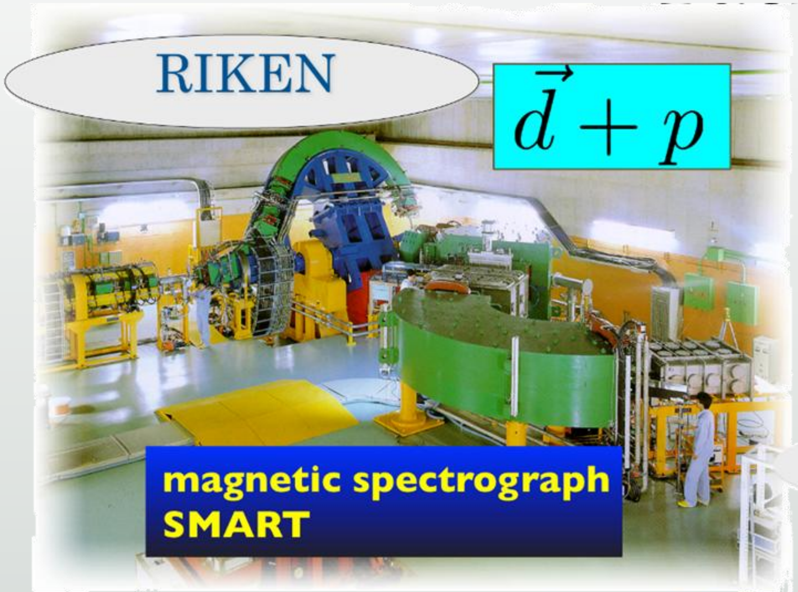
- Approximation of QCD in low energy
- Uniform framework
- Fair description of data

N^{5}L: PRL 115, 122301 (2015)

Polarized scattering on light nuclei

- Experimental observable
  - a↑(b ,c) d : Analyzing power
  - a↑(b↑,c) d : Spin correlation
  - a↑(b ,c↑)d : Polarization transfer
  - a (b ,c↑)d : Polarization
  - a (b ,c↑)d↑: Spin correlation
- Theoretical analysis tools
  - Faddeev-Yakubovsky (FY) equation (3N)
  - AGS equation(4N)
  - hyperspherical harmonics expansion method

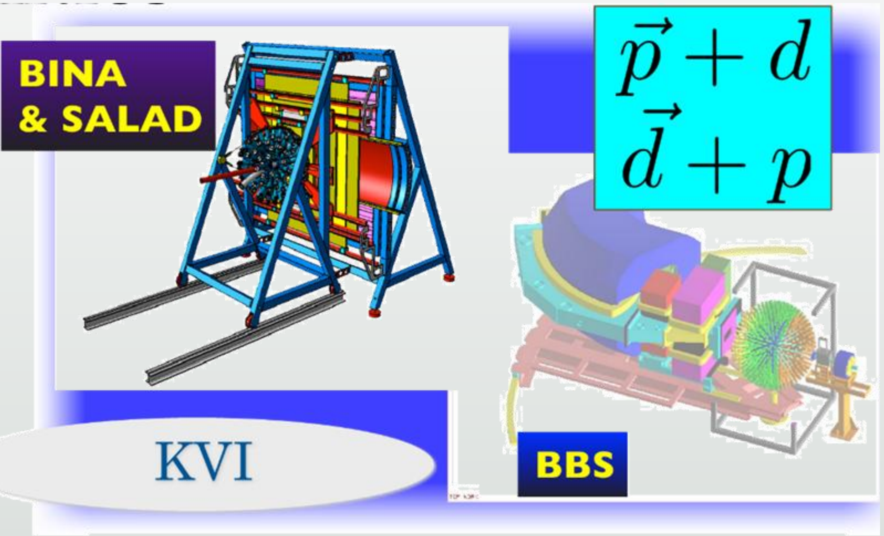
Experiments over the world



RIKEN

$\vec{d}+p$

magnetic spectrograph SMART



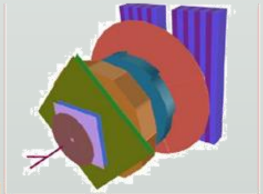
BINA & SALAD

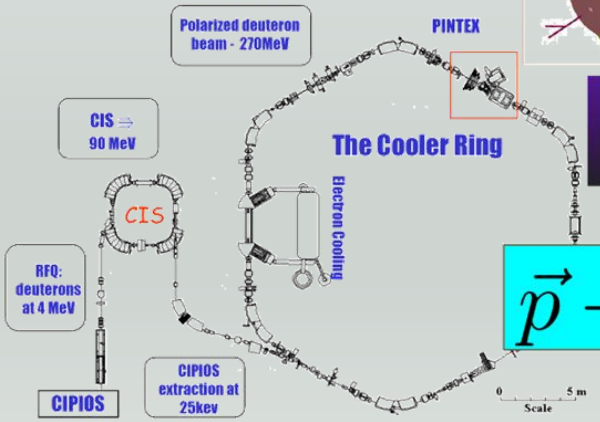
$\vec{p}+d$

$\vec{d}+p$

KVI

BBS

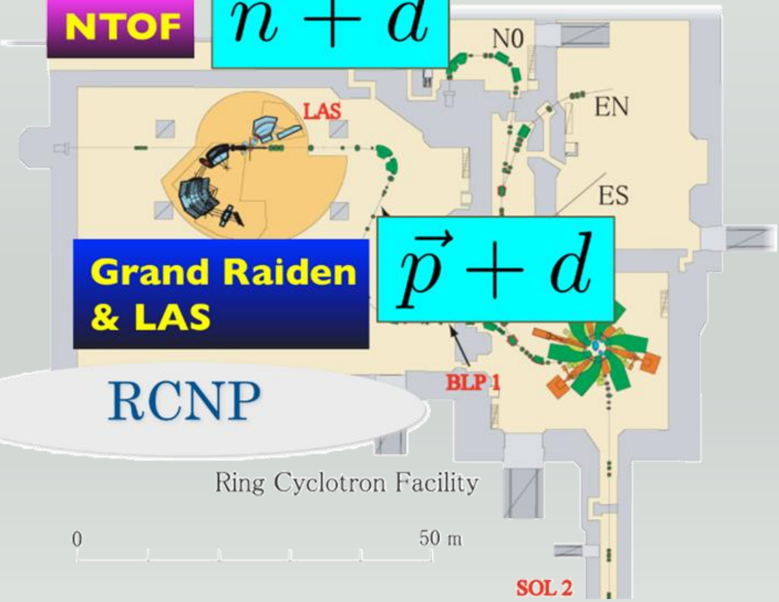




IUCF

Cooler Ring + PINTEX

$\vec{p}+\vec{d}$

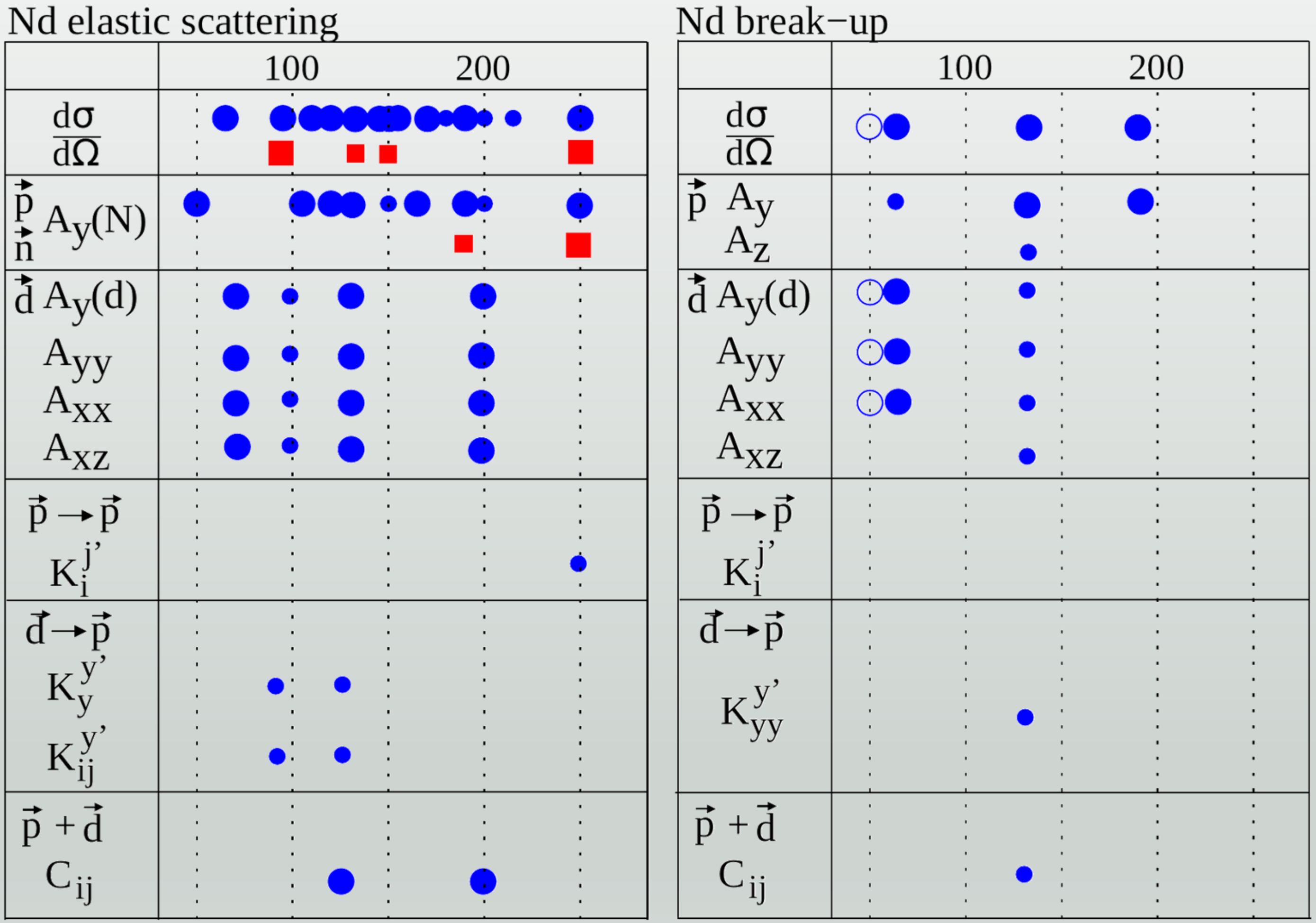


NTOF $\vec{n}+d$

Grand Raiden & LAS $\vec{p}+d$

RCNP

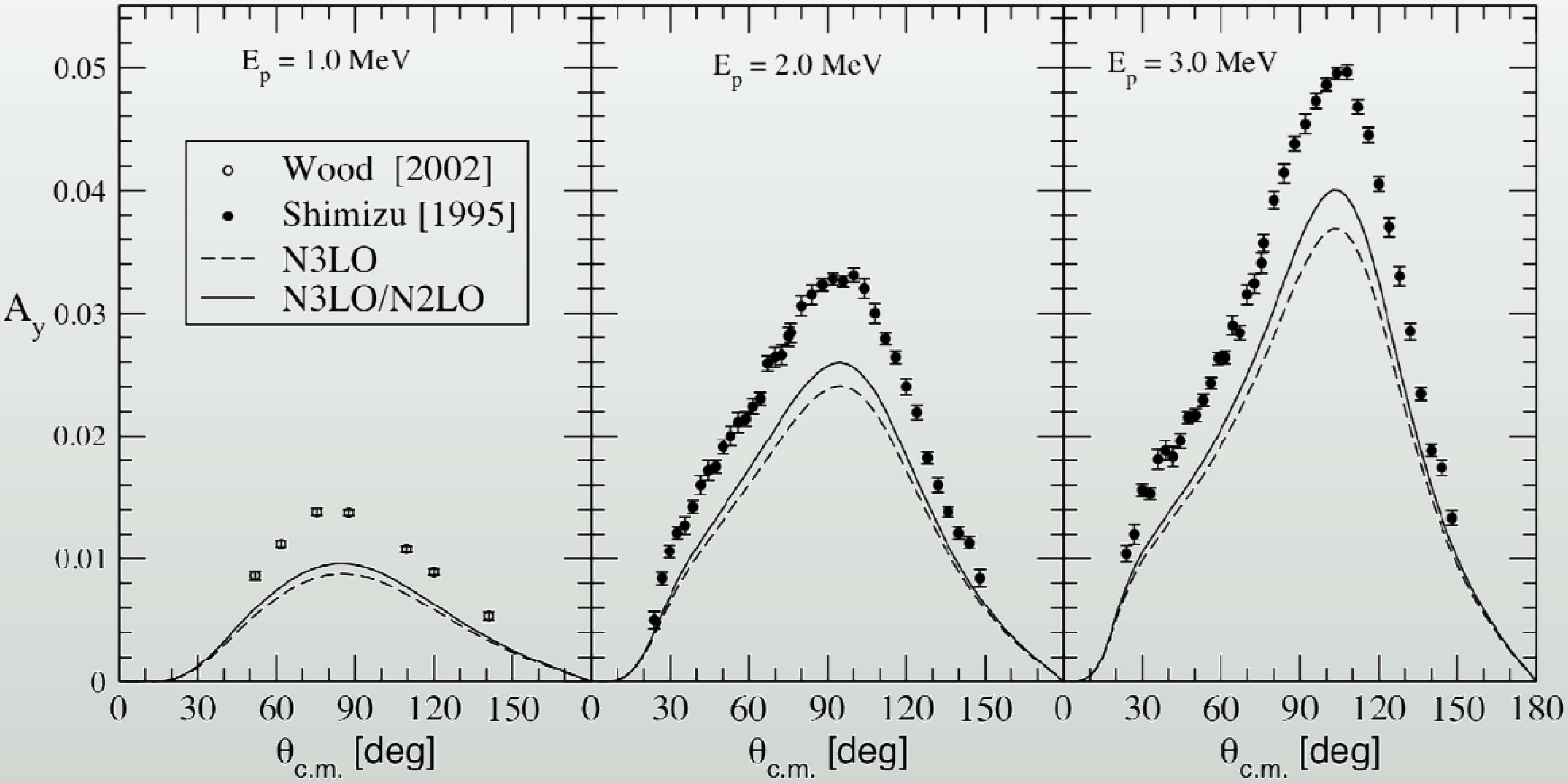
3-N system scattering



- Elastic scattering
- Low energy
- Ay puzzle

Rep. Prog. Phys. 75 (2012) 016301

$\vec{p} + d \rightarrow p + d$



$$\sigma = \sigma_0 (1 + pA_y \cos\varphi)$$

$$\Rightarrow A_y = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R}$$

Phys. Rev. C80, 034003(2009)

p(d)+d in mediate energy since 2010

- Complete set of deuteron analyzing powers for dp elastic scattering at 250–294 MeV/nucleon and the three-nucleon force

  K. Sekiguchi et al. **Phys. Rev. C** 89 064007 (2014)

- Vector analyzing powers of the deuteron-proton elastic scattering and breakup at 100 MeV

  E. Stephan et al. **Eur. Phys. J. A** 49 36 (2013)

- Measurement of the vector and tensor analyzing powers for dp-elastic scattering at 880 MeV

  P.K. Kurilkin et al. **Physics Letters B** 715 61 (2012)

- Three nucleon force effects in intermediate-energy deuteron analyzing powers for dp elastic scattering

  K. Sekiguchiet al. **Phys. Rev. C** 83, 061001(R)

- Vector and tensor analyzing powers in deuteron-proton breakup at 130 MeV

  E. Stephan et al. **Phys. Rev. C** 82 014003 (2010)

- Spin observables in the three-body break-up process near the quasi-free limit in deuteron–deuteron scattering

  A. Ramazani-Moghaddam-Aran et al. **Physics Letters B** 725 282 (2013)

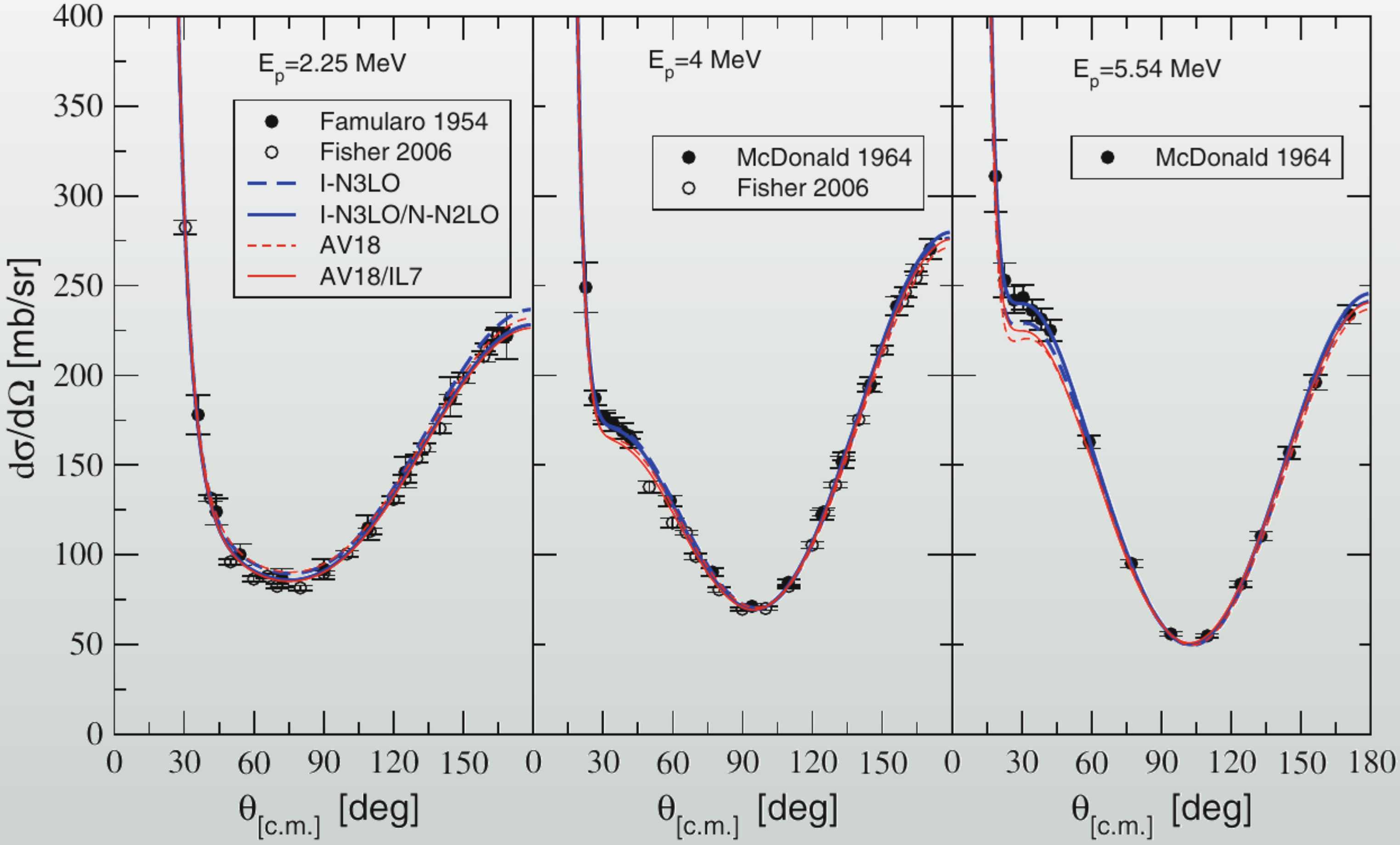
- Angular distributions of the vector A_{y} and tensor A_{yy}, A_{xx}, A_{xz} analyzing powers in the dd→^{3}Hp reaction at 200 MeV

  A. K. Kurilkin et al. **Phys. Rev. C** 87 051001 (2013)

- Three-body break-up in deuteron-deuteron scattering at 65 MeV/nucleon

  A. Ramazani-Moghaddam-Aran et al. **Phys. Rev. C** 83 024002 (2011)

4-N system scattering (p+^{3}He)

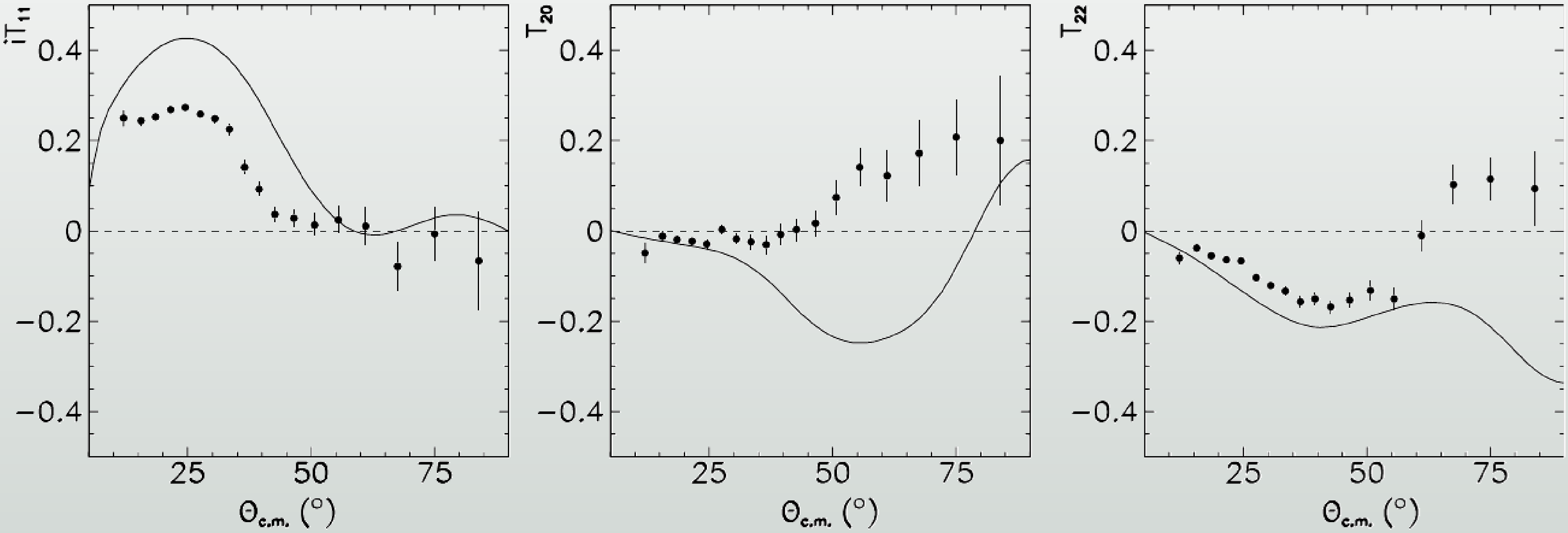


Unpolarized case： theory consists with measurement

Few-Body Syst (2013) 54:885–890

4-N system scattering (d ↑ +d)

Phys. Rev. C 75 (2007) 054001



IUCF: d ↑ +d elastic @241MeV

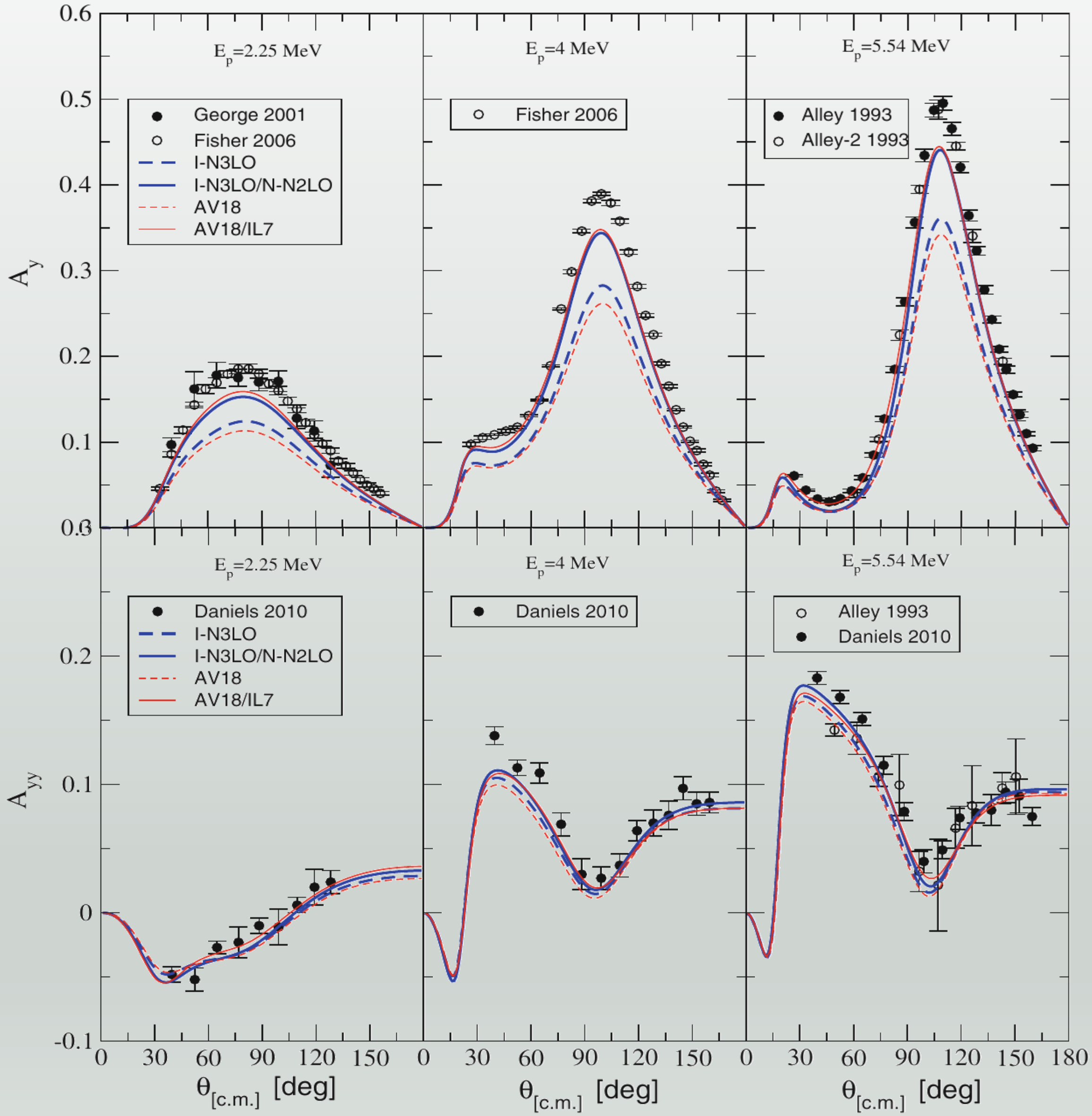
KVI : d ↑ +d elastic @135MeV (BBS)

d ↑ +d -> d+p+n @135MeV (BINA)

d +d -> d+p+n @160MeV (BINA)

Rep. Prog. Phys. 75 (2012) 016301

4-N system scattering (p+^{3}He)



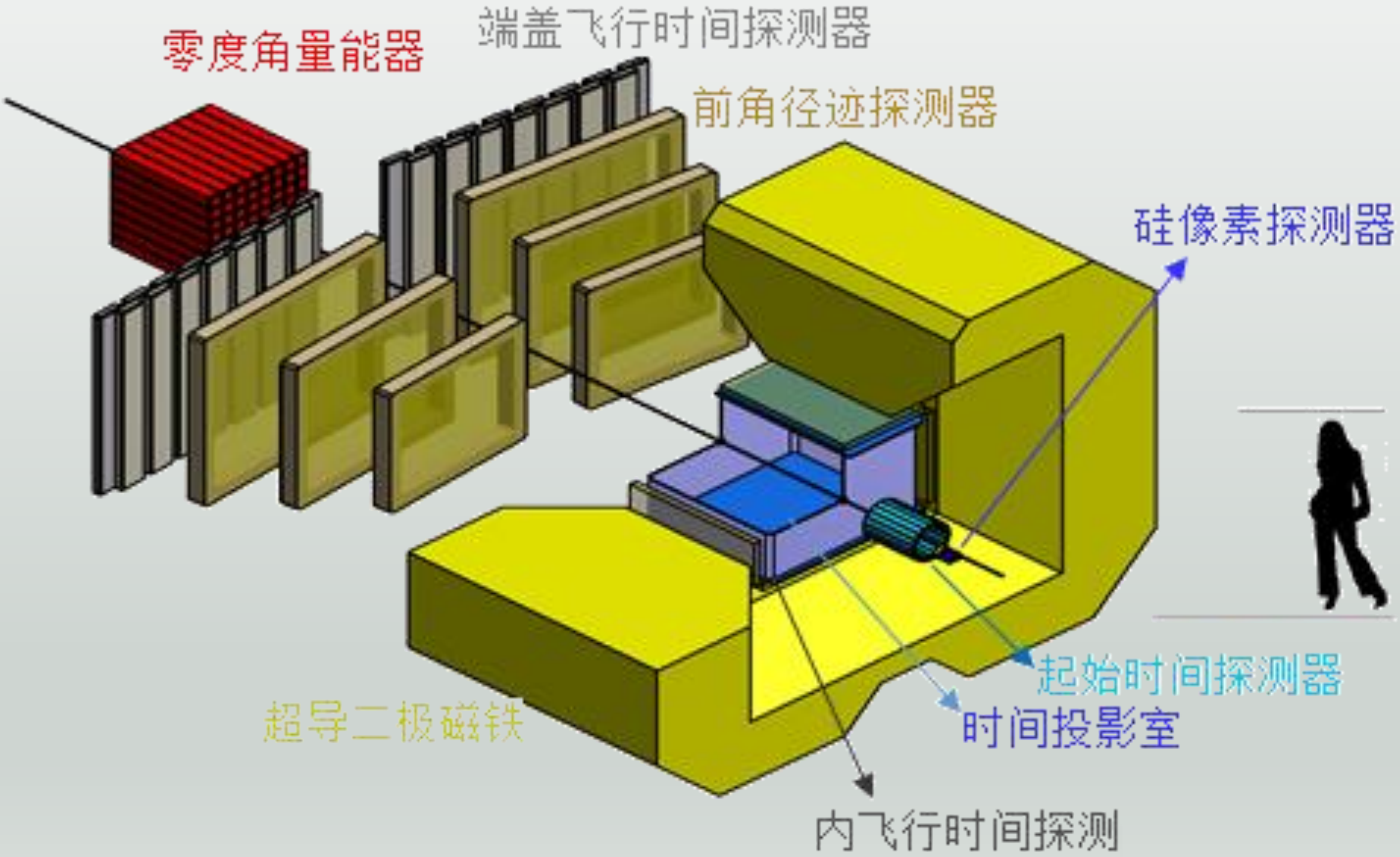
Polarized case： Ay puzzle

Lack of data in medium energy region

p + ^{3}He -> d + p + p ?

Few-Body Syst (2013) 54:885–890

CSR External target Experiment (CEE)

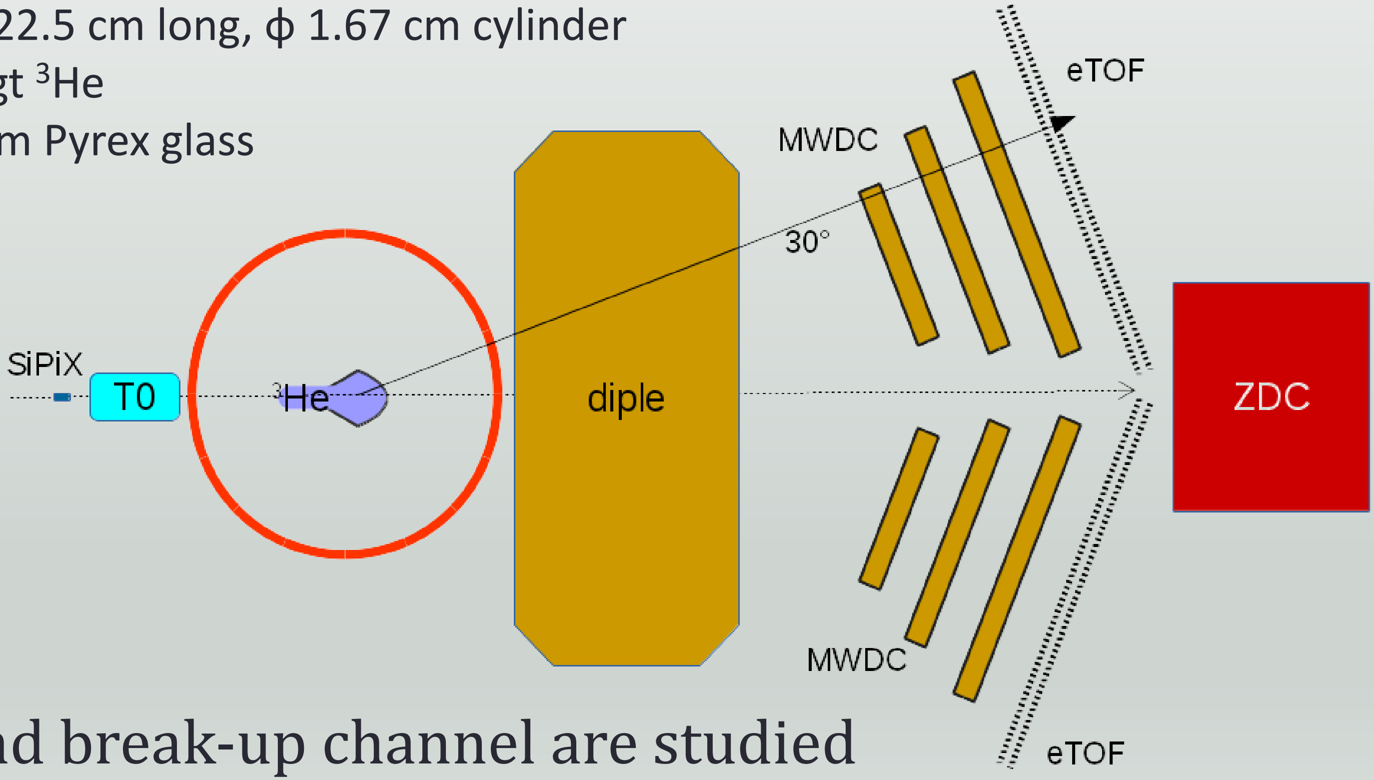


Planned measurement in CEE

- Put the ^{3}He target between T0 detector and the diple

Target parameters:

- Coil radii: 50 cm
- Cell geometry: 22.5 cm long, ϕ 1.67 cm cylinder
- Density: 4 amagt ^{3}He
- Window: 0.2 mm Pyrex glass

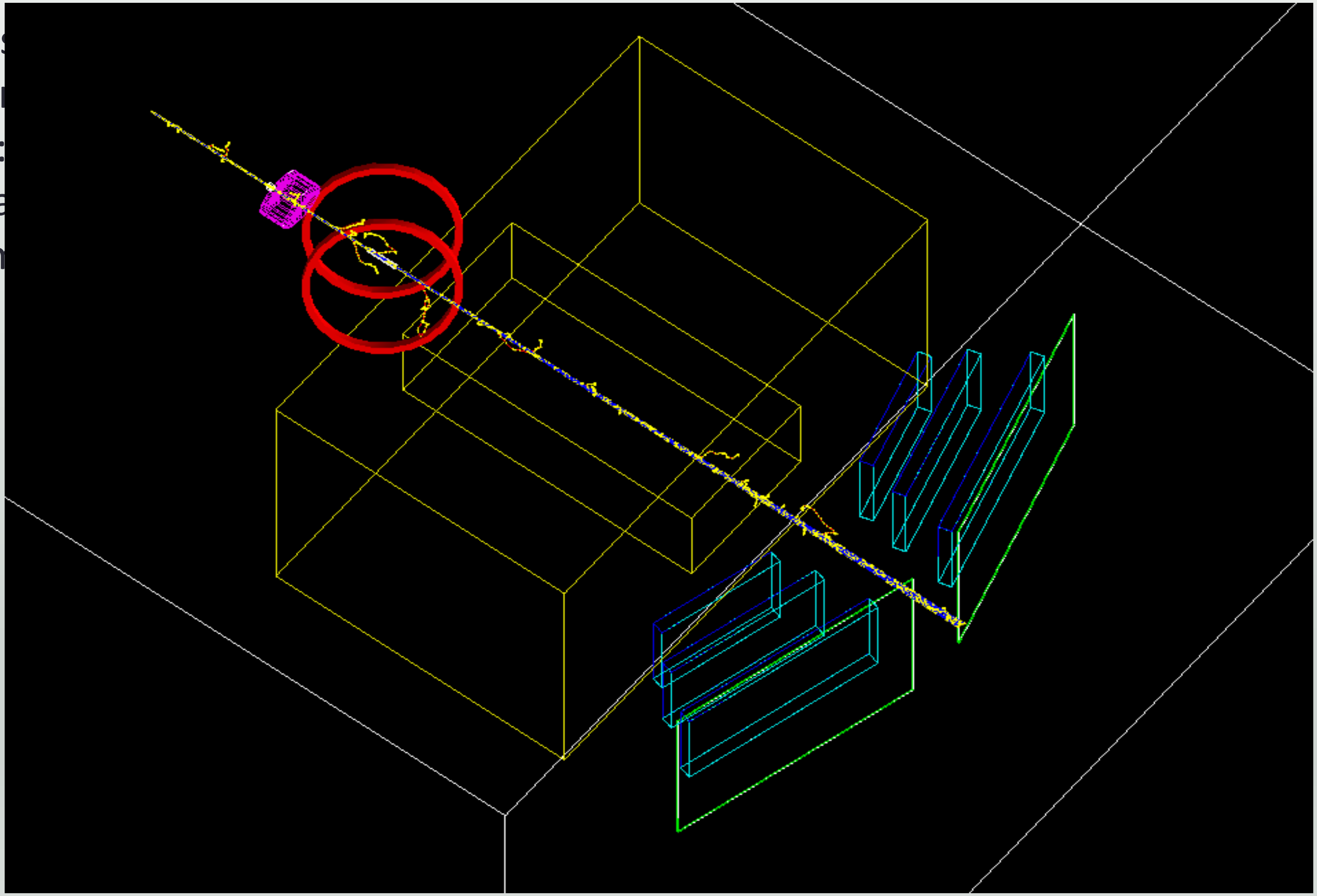


- Both elastic and break-up channel are studied

Planned measurement in CEE

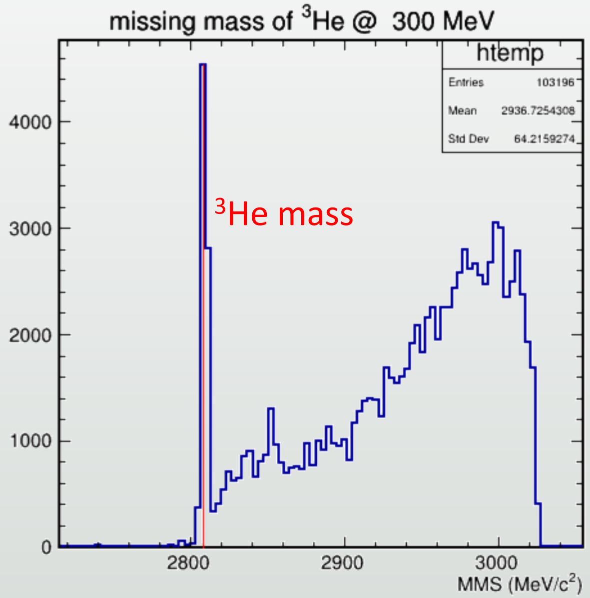
- Put the 3He target between T0 detector and the diple

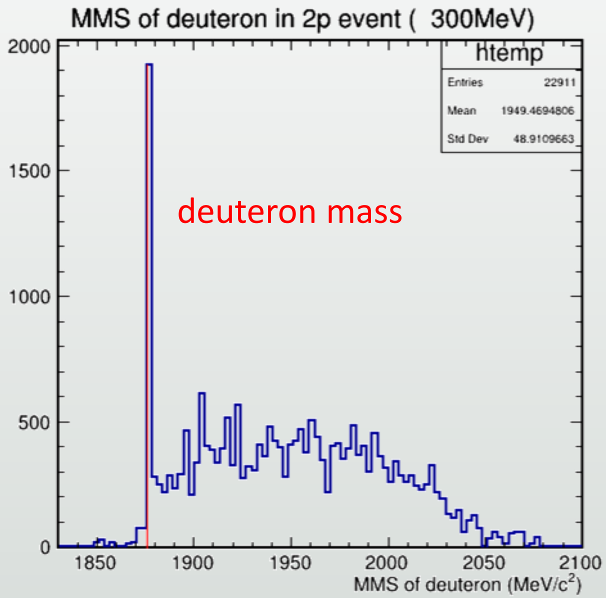
Target parameter
- Coil radii: 50 c
- Cell geometry:
- Density: 4 ama
- Window: 0.2 n



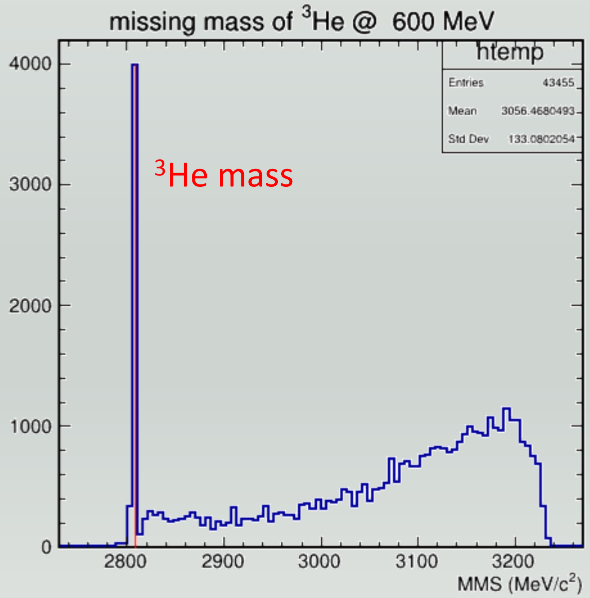
Missing mass spectrum in different channels

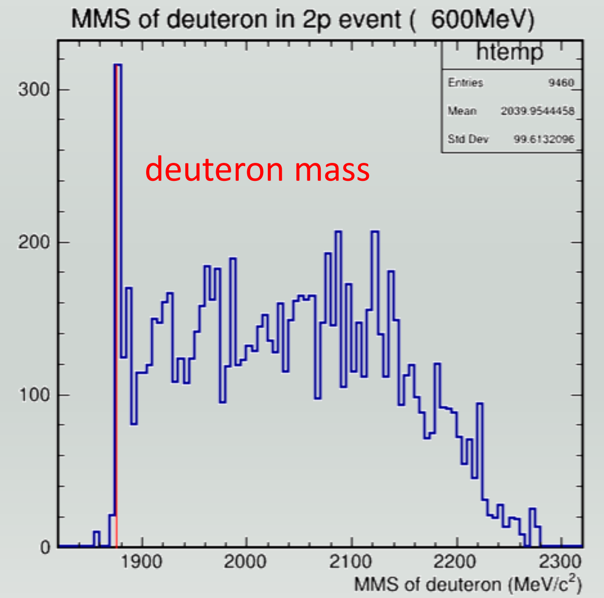
300 MeV



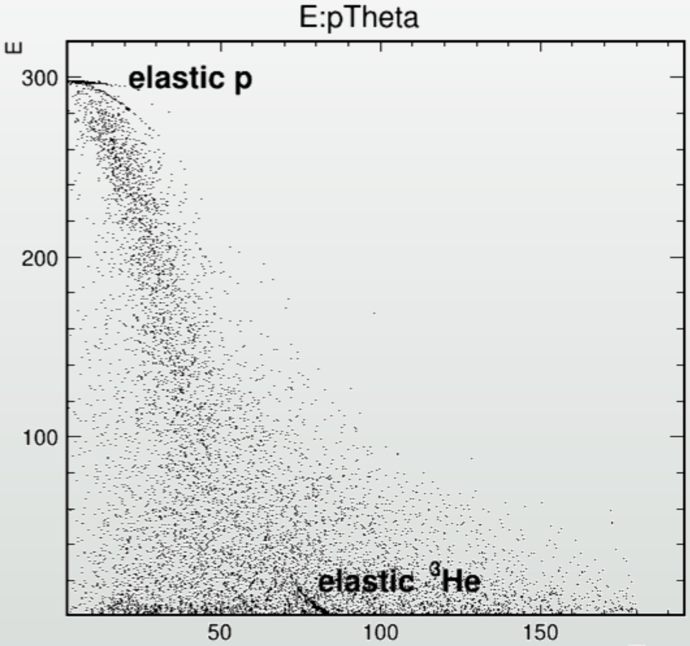


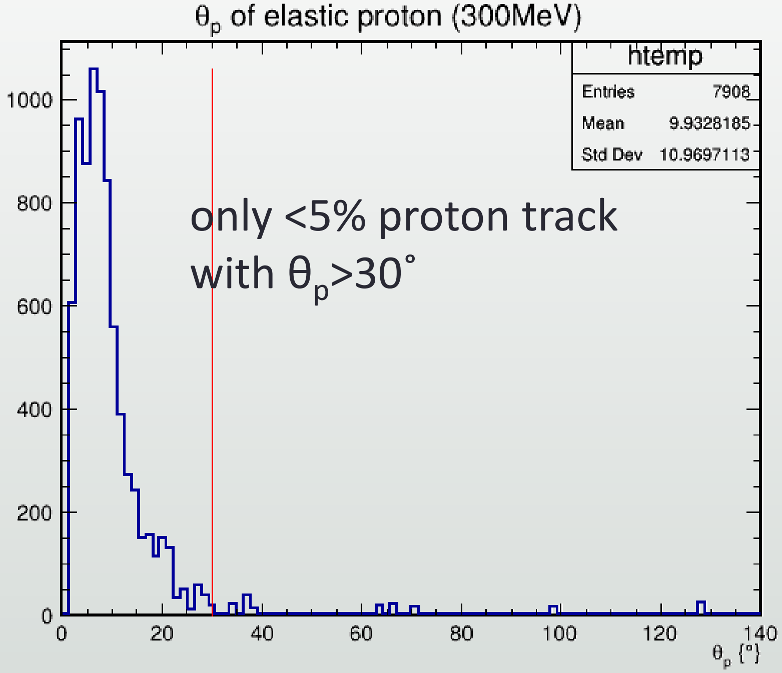
600 MeV



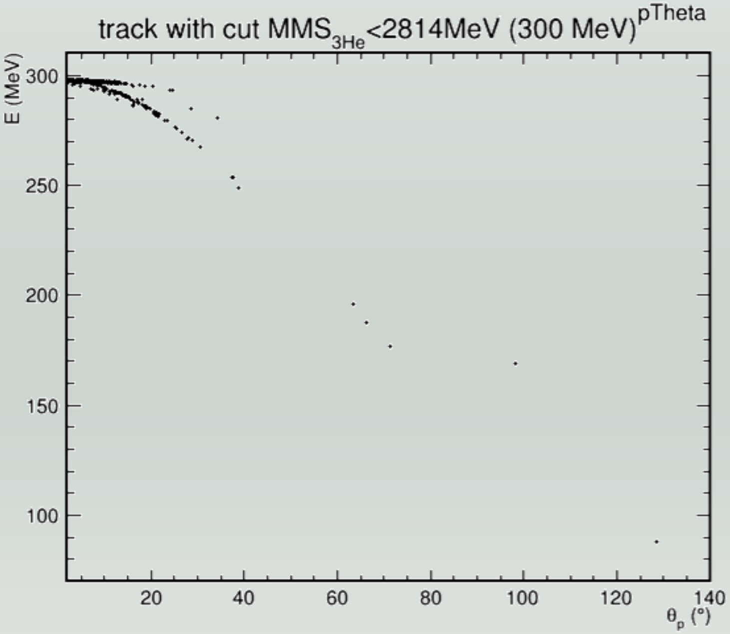


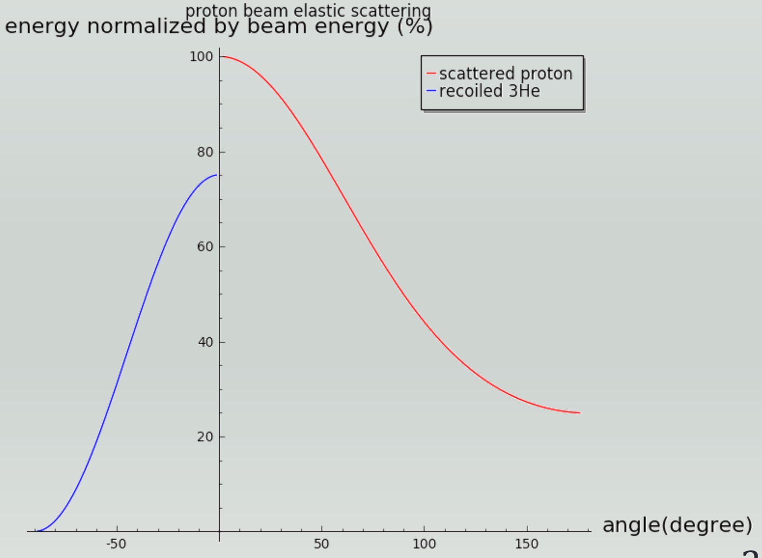
Proton track in Elastic events(E_{beam}=300MeV)


E:pTheta


θ_p of elastic proton (300MeV)

only <5% proton track with θ_p>30˚

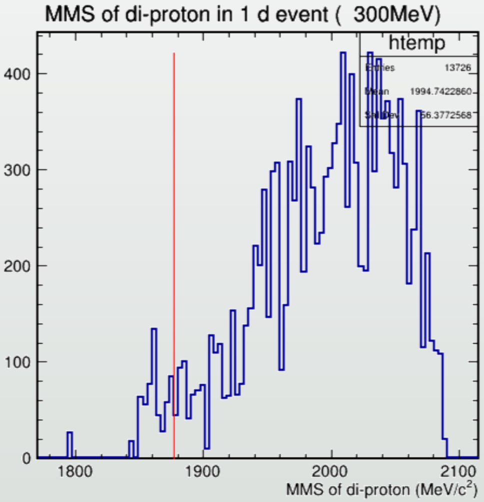

track with cut MMS_{3He}<2814MeV (300 MeV)

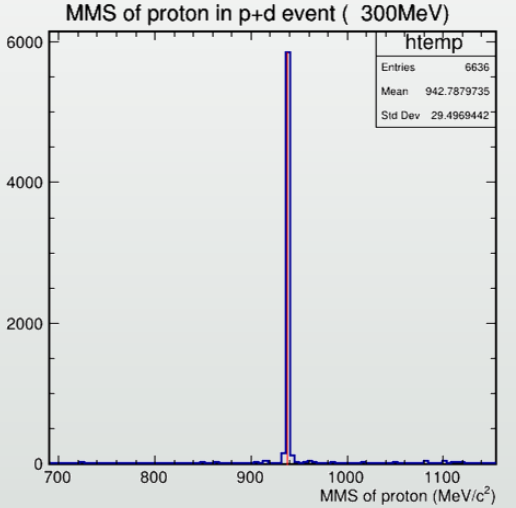

proton beam elastic scattering

energy normalized by beam energy (%)

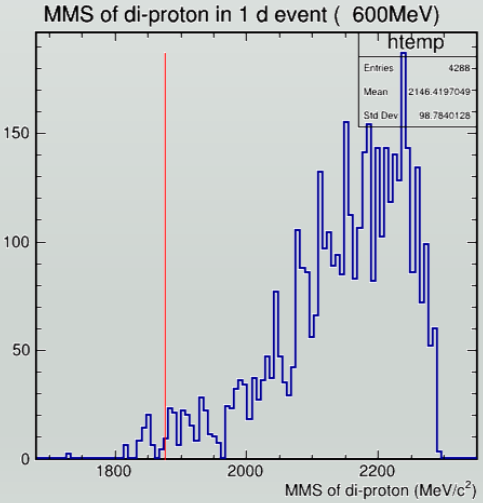
Other types of events in break-up channel

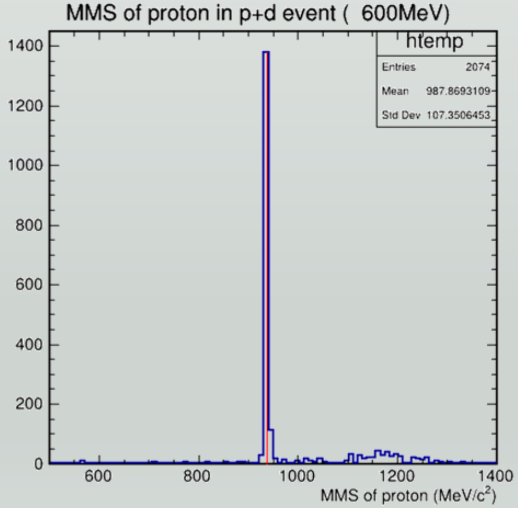
300 MeV





600 MeV

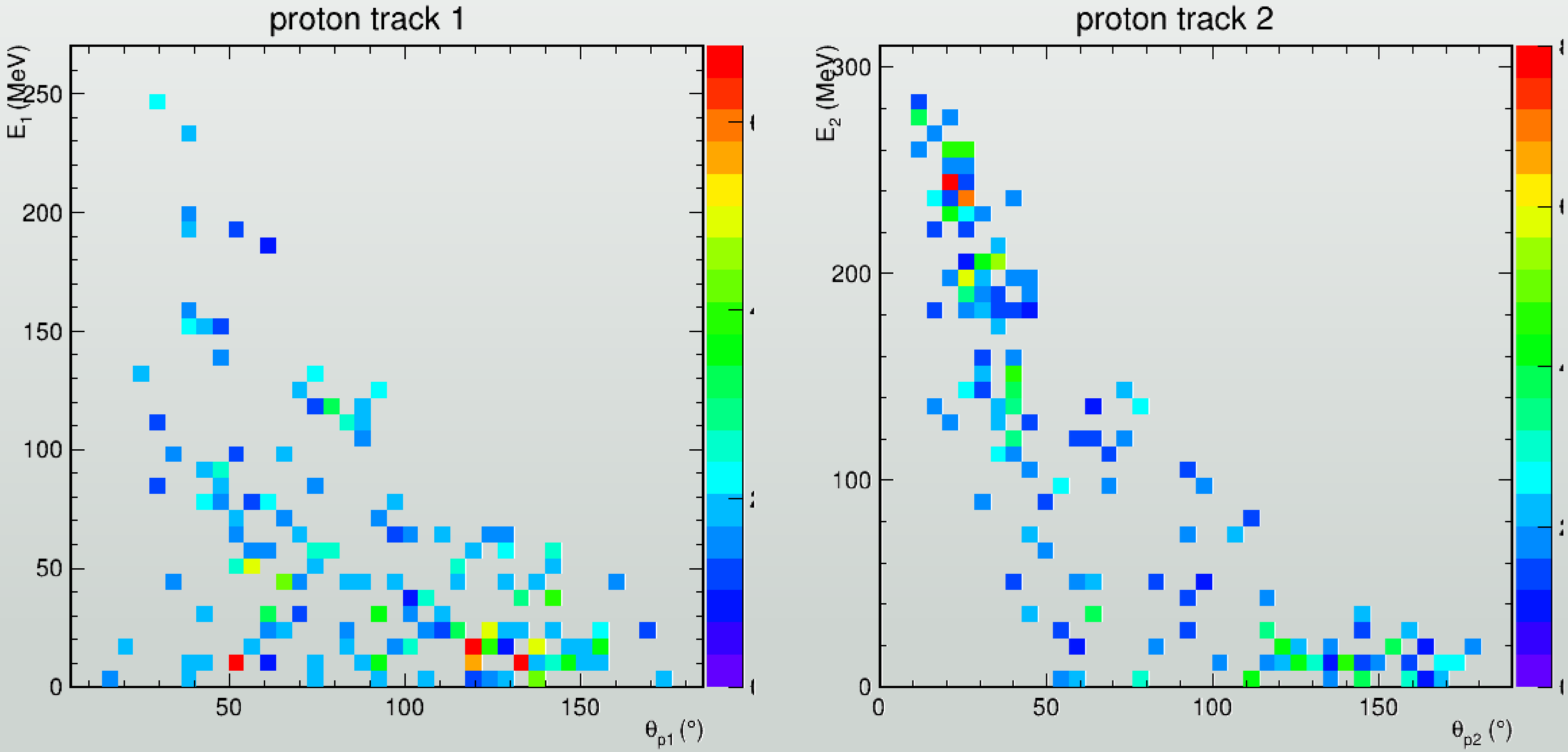




Single deuteron

p + *d*

Proton tracks in Break-up events (E_{beam}=300MeV)



Simulation summary

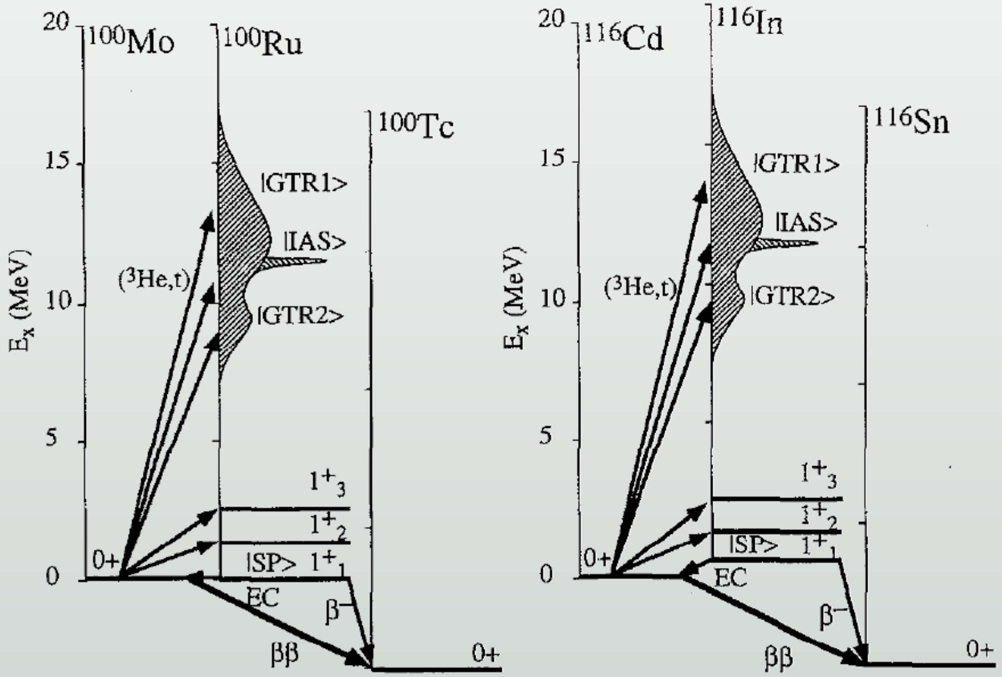
- For elastic channel: most tracks can be covered wthin the acceptance of CEE spectrometer

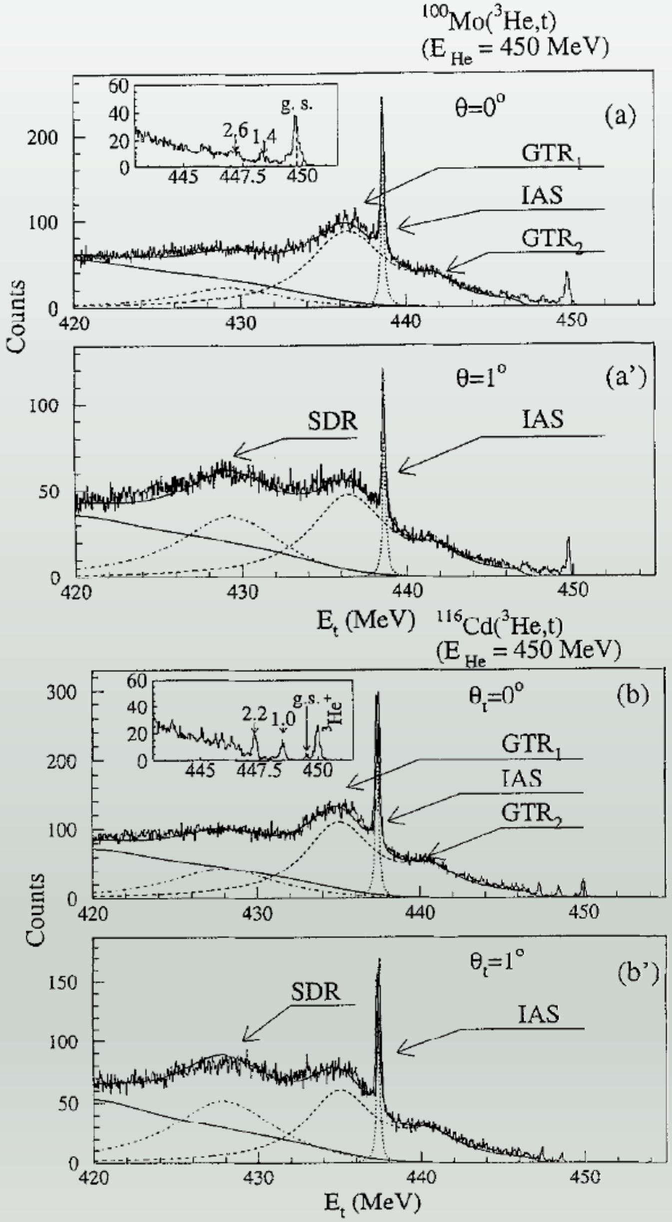
- For break-up channel ($p + {}^3He \rightarrow p + p + d$):
  - p+p and p+*d* events can be identified, while single *d* event cannot
  - Large angle detection is necessary

Polarized charge exchange reaction with inverse kinematics

GT transition in charge exchange reaction

H. Akimune et al. PLB 394 (1997) 23-28

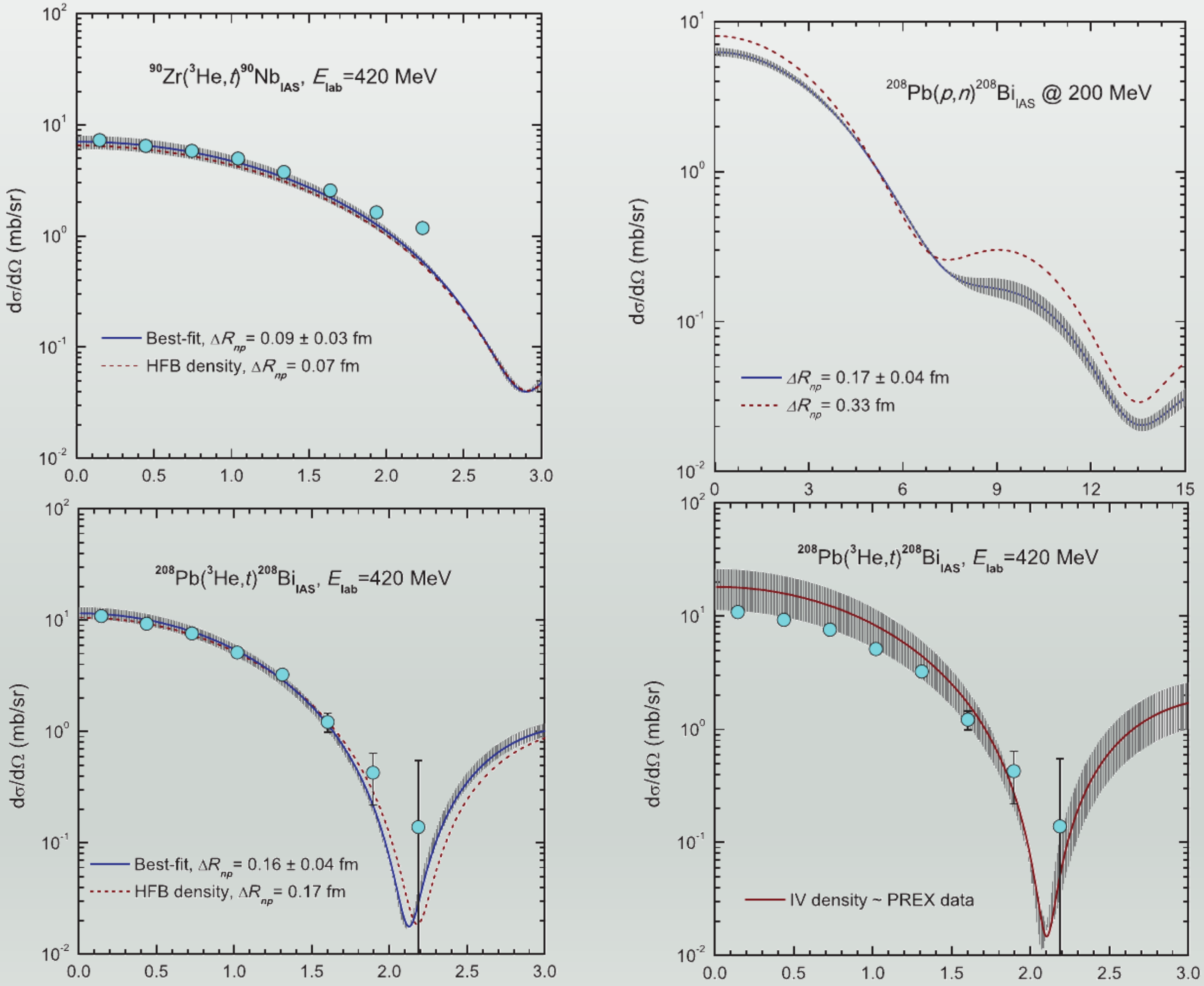




- Measures strength of GT transition in β decay
- Access to the matrix element of 2νββ decay
- Gain information of electron capture process in core collapse of supernova

ΔR_{np} measured in (^{3}He, t)

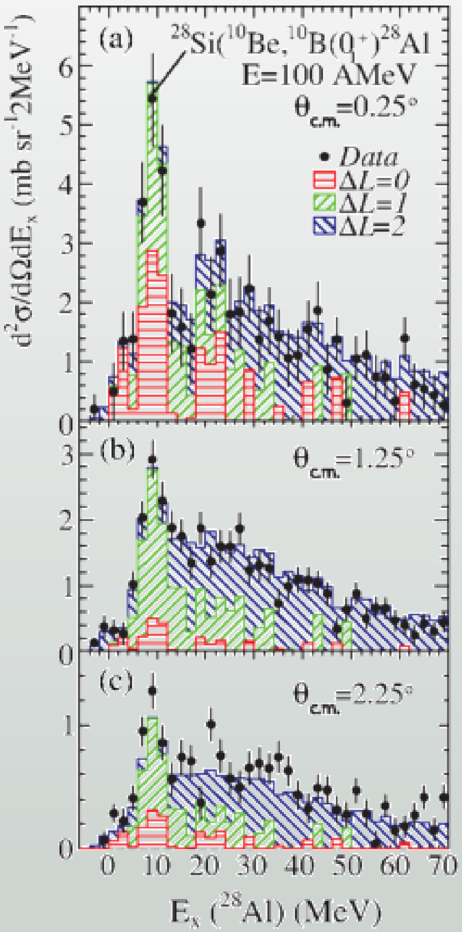
Compared with (p, n), (^{3}He, t) is more sensitive to the surface of nuclei

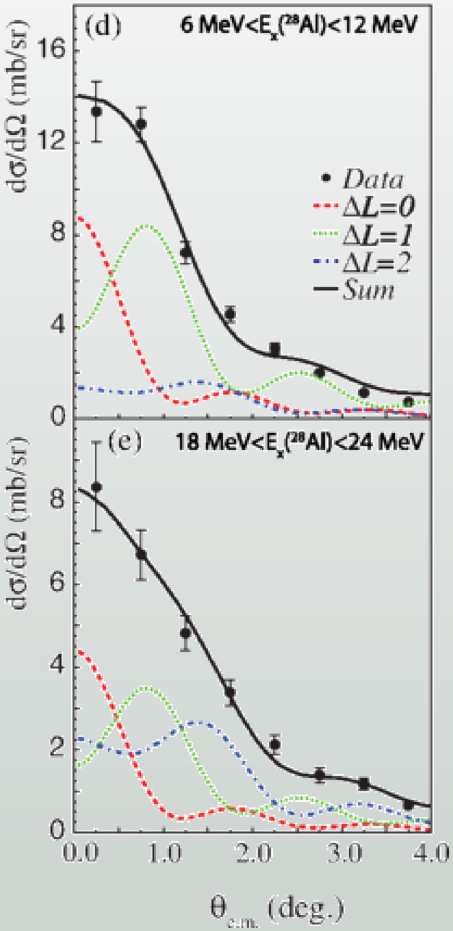


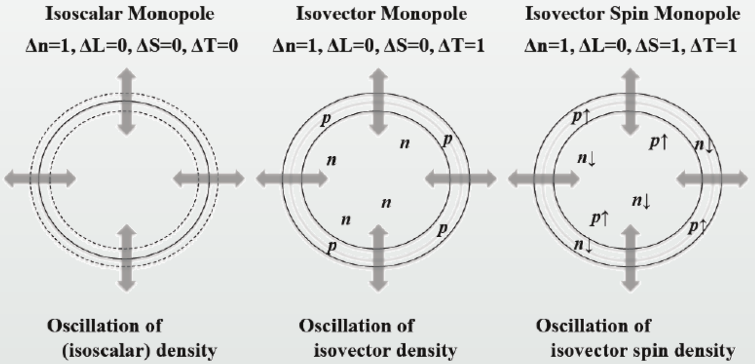
$$\Delta R_{np} = \langle r_n^2 \rangle^{1/2} - \langle r_p^2 \rangle^{1/2}$$

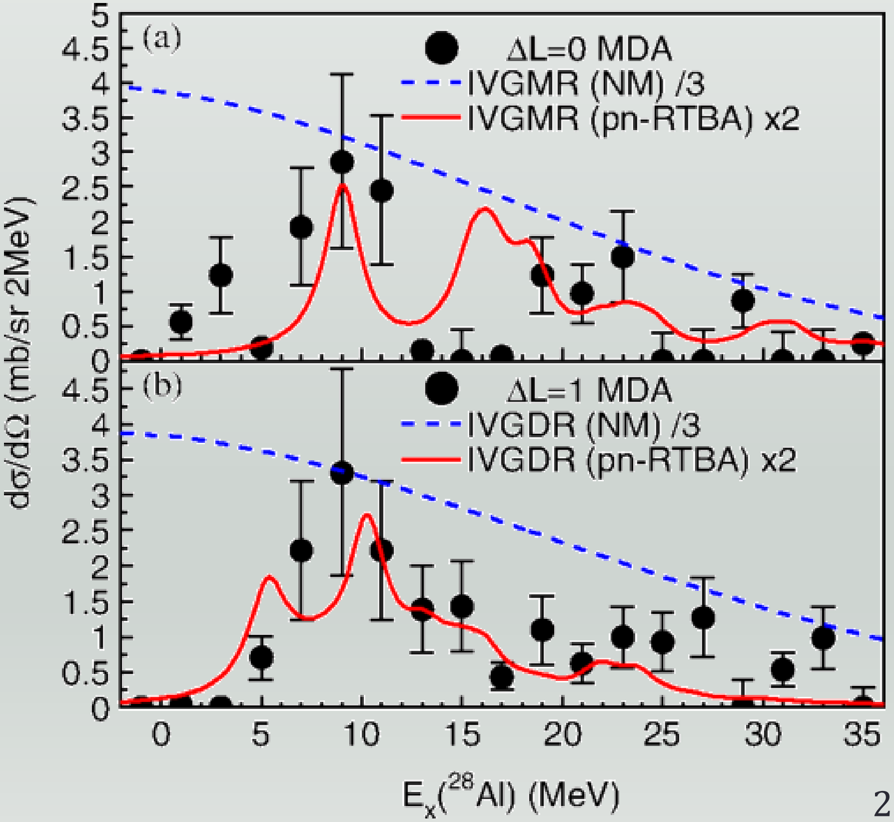
PRC 89, 024317 (2014)

Isovector multipole giant resonance







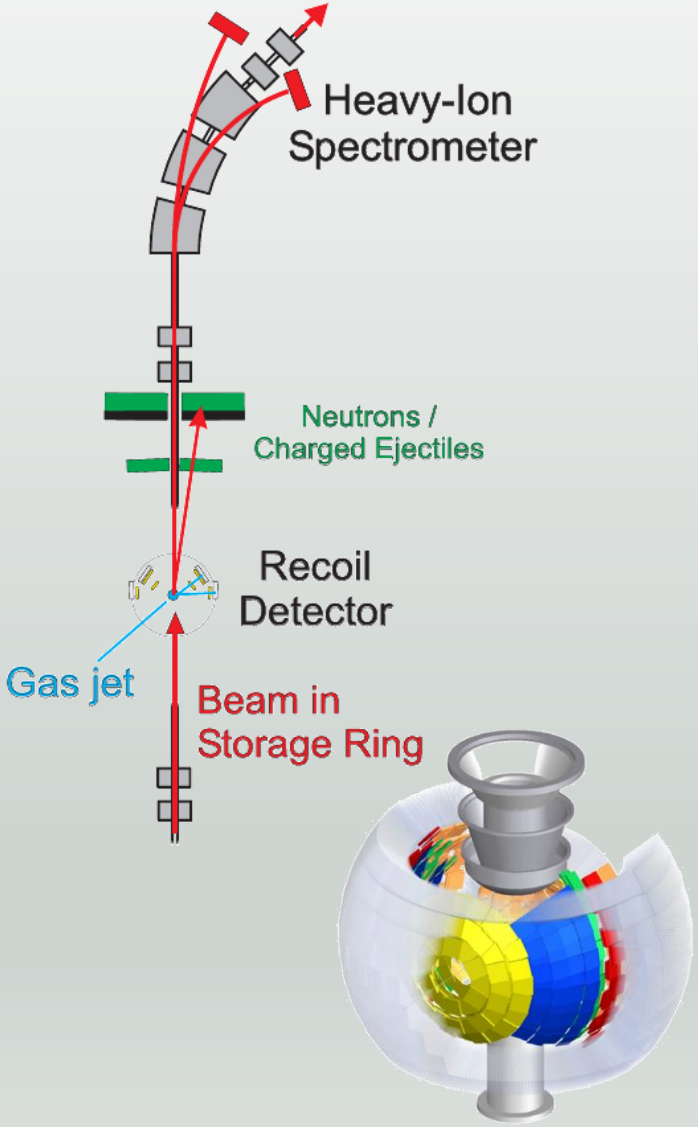


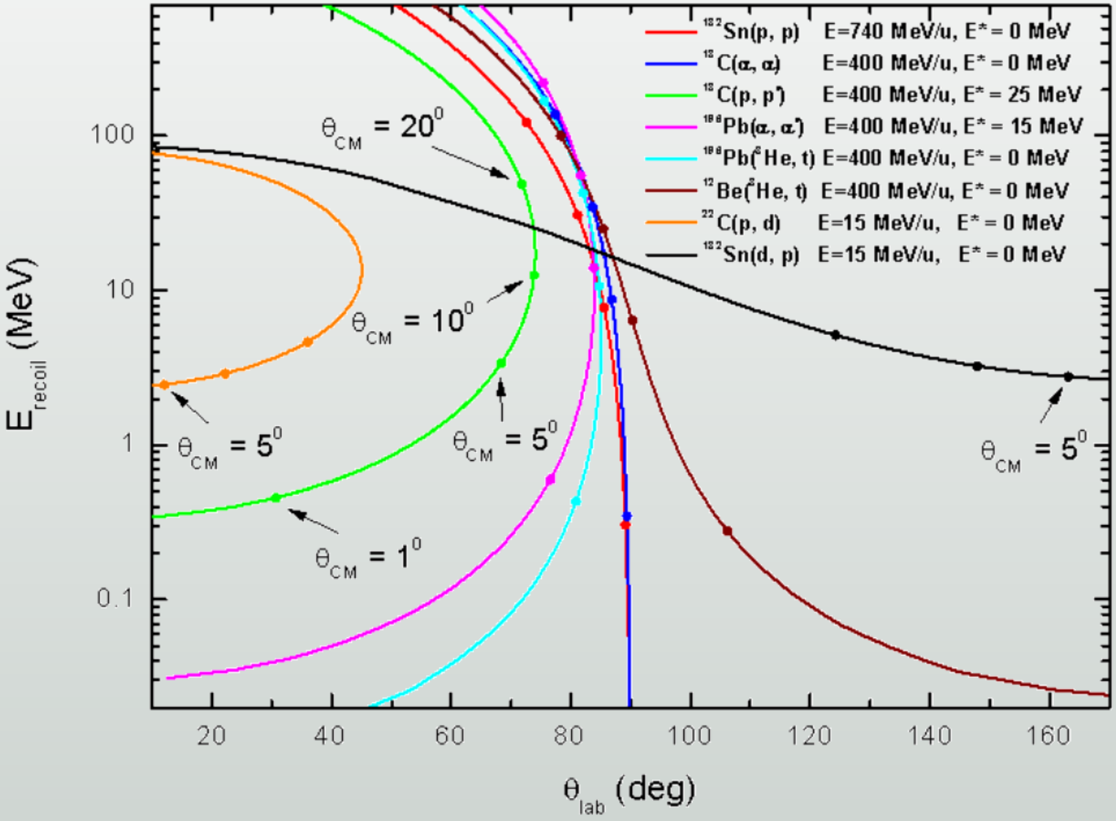
M. Scott et al

Phys. Rev. Lett. 118, 172501 – April 28 2017

Inverse kinematics

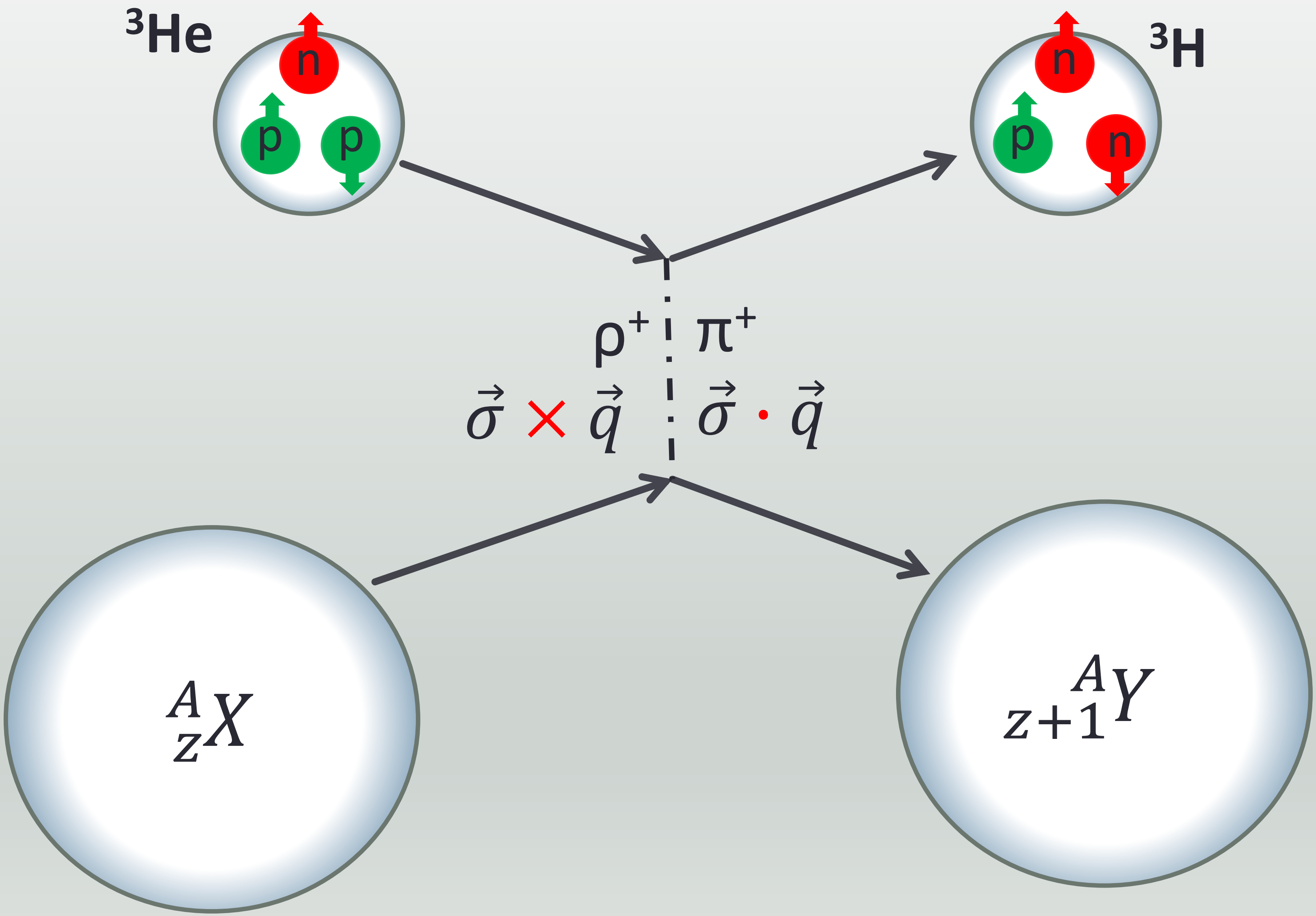
EXL project in NUSTAR collaboration, GSI



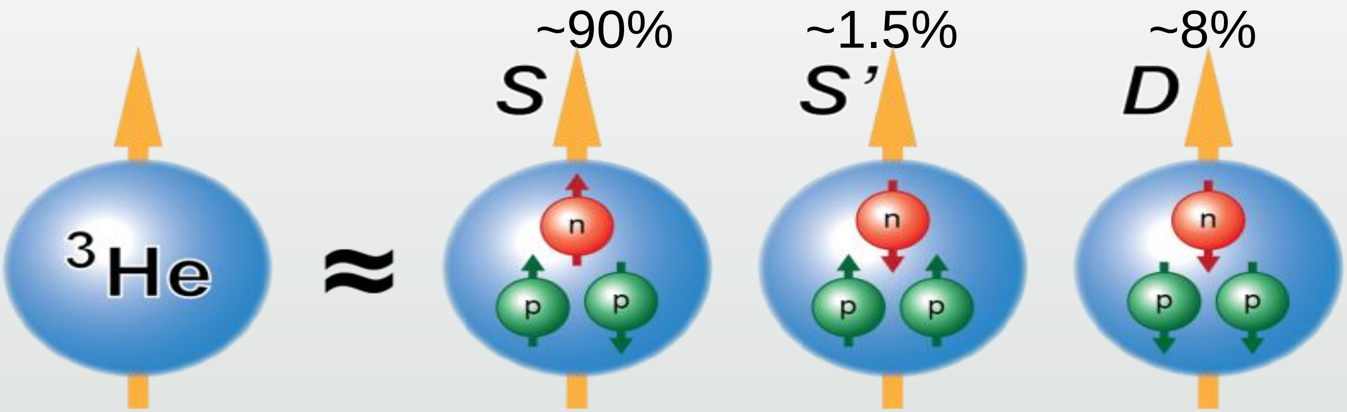


- small momentum transfer
- detection of low energy recoil particles
- high luminosities
- windowless ^{1,2}H, ^{3,4}He, etc. targets.

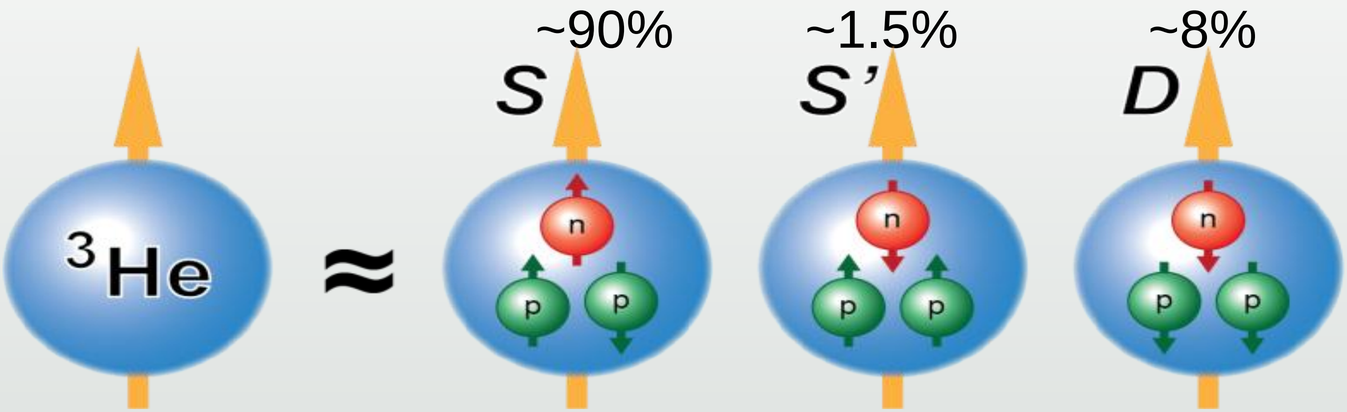
Meson exchange in $^3\mathrm{He}\uparrow({}_{Z}A, {}_{Z+1}A)t$

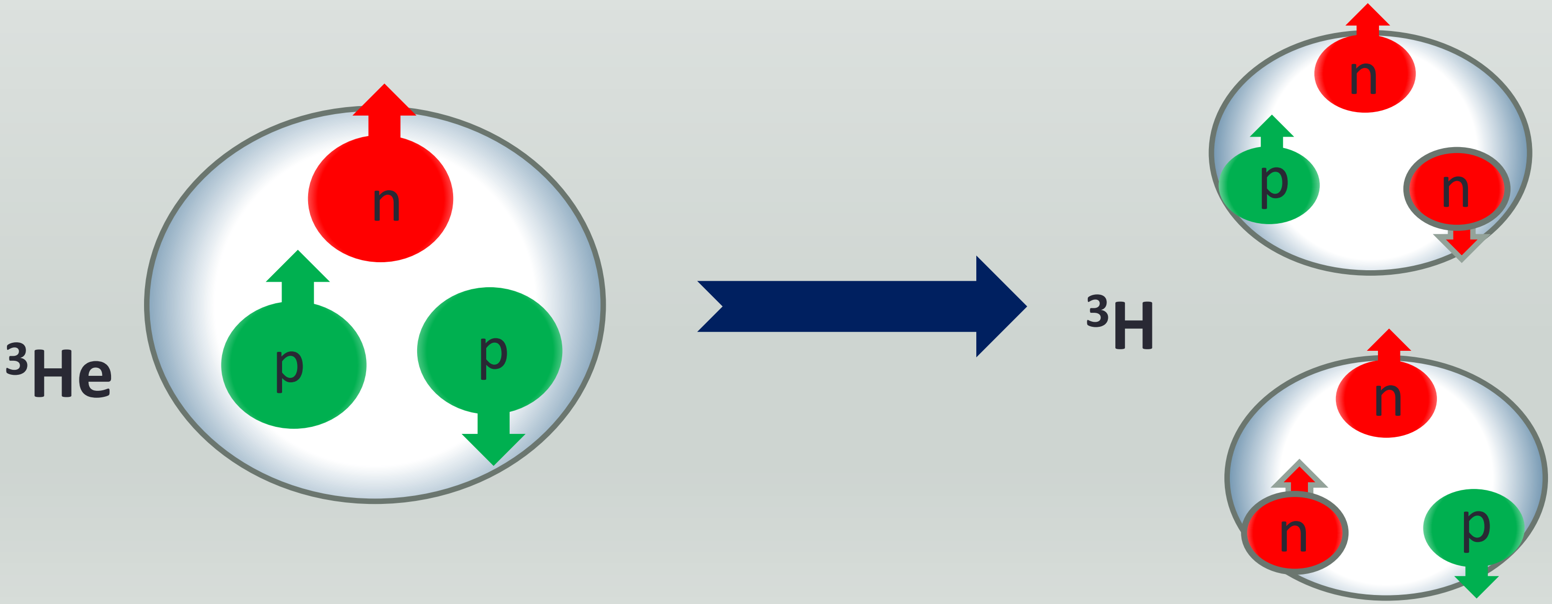


charge exchange reaction: $^{3}\mathrm{He}\uparrow({}_{z}X,\ {}_{z+1}Y)t$

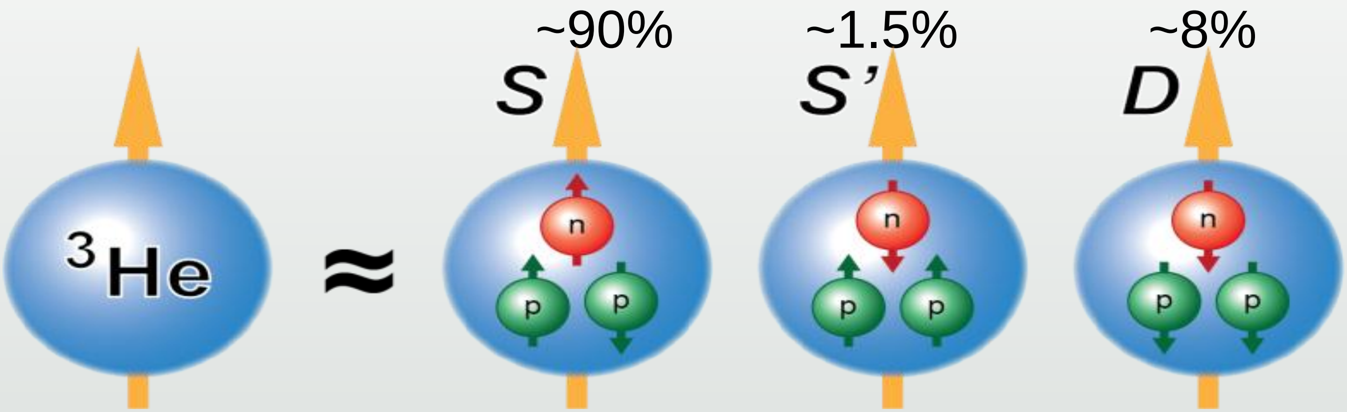


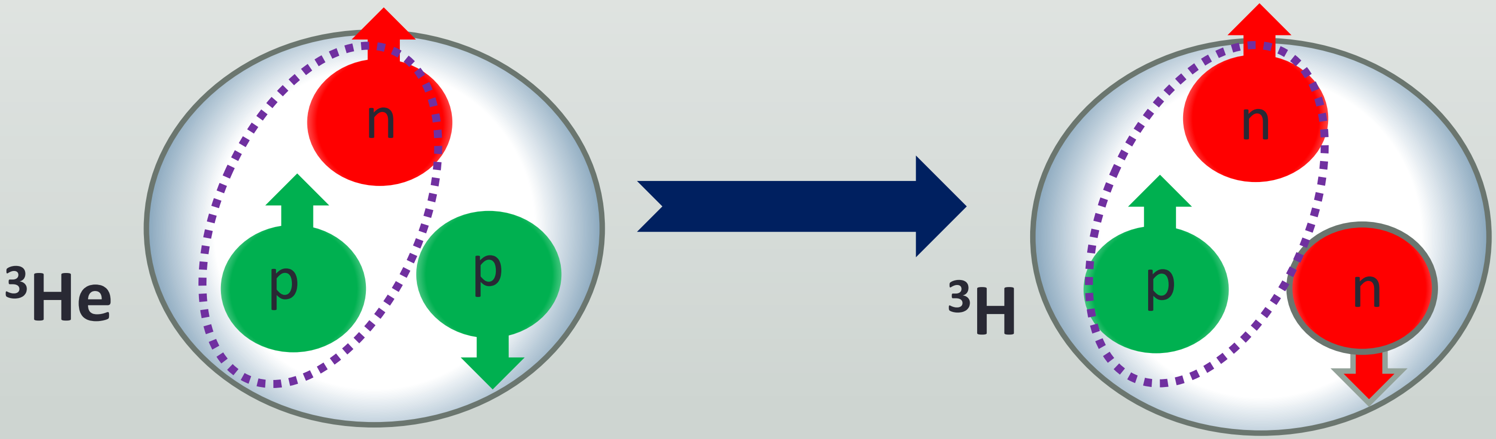
charge exchange reaction: $^{3}\mathrm{He}\uparrow({}_{z}X, {}_{z+1}Y)t$



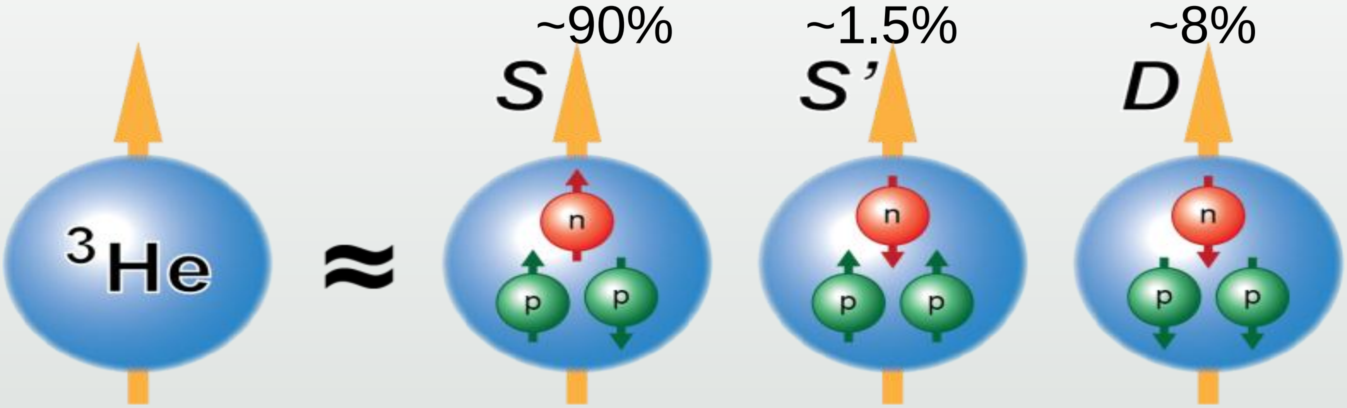


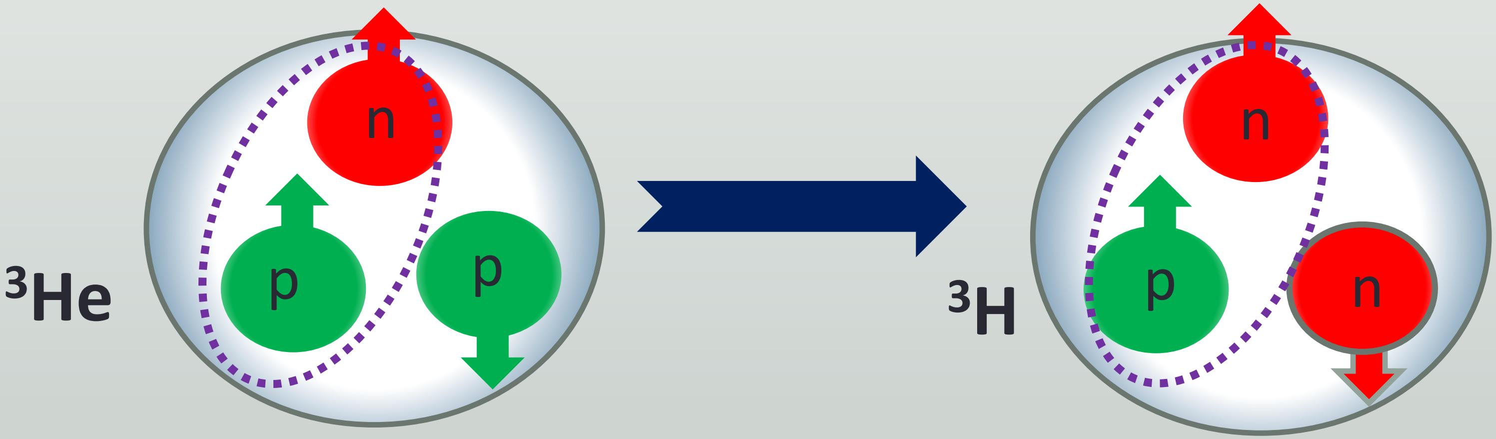
charge exchange reaction: $^{3}\mathrm{He}\uparrow({}_{z}X,\ {}_{z+1}Y)t$





charge exchange reaction: ^{3}He↑($_z$X, $_{z+1}$Y)t

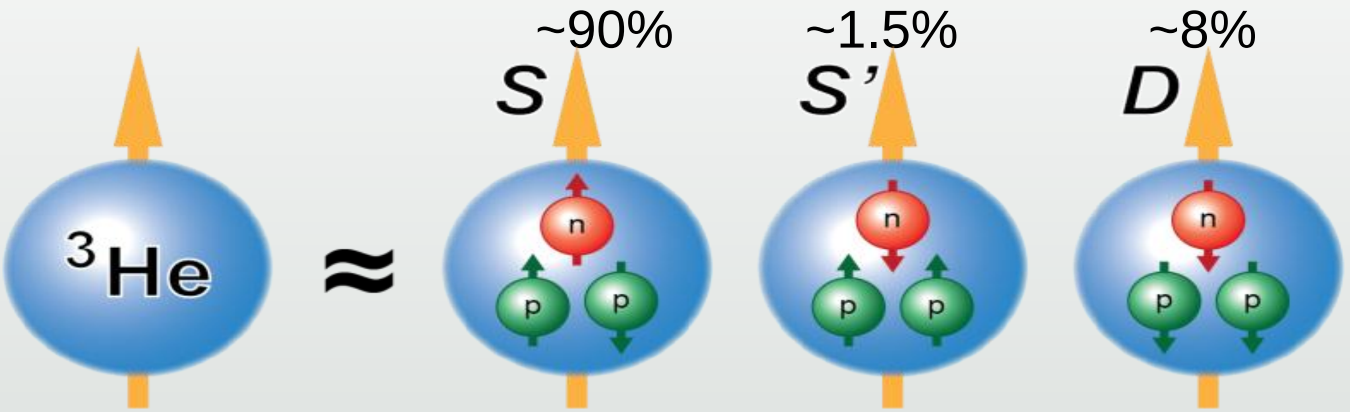


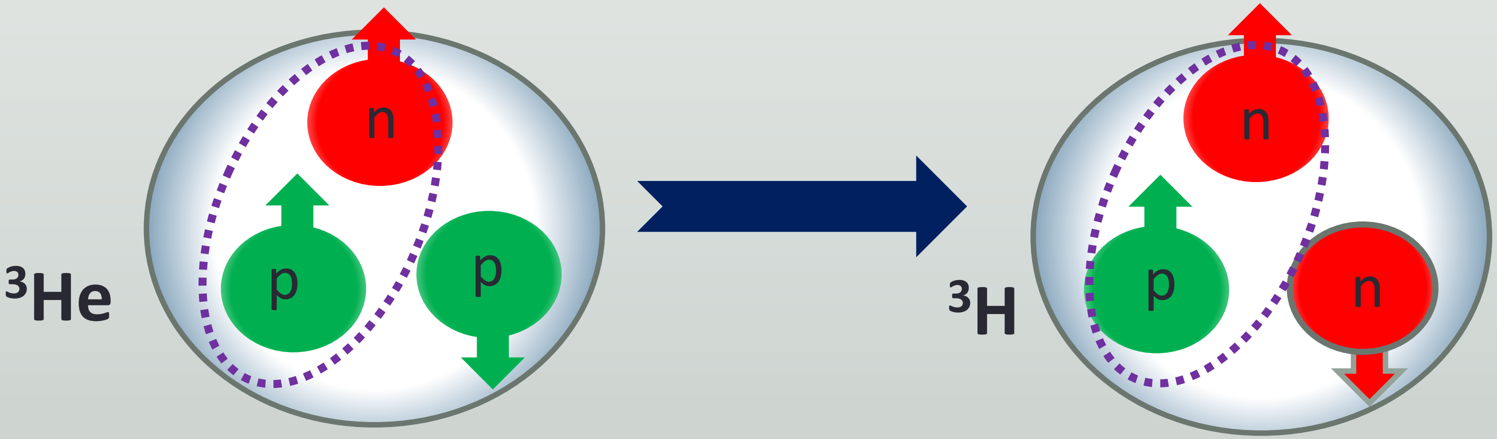


Unpolarized case:

$$
\begin{aligned}
O^p_{ij} = {} & [1, \sigma_i\cdot\sigma_j, S_{ij}, \mathbf{L}\cdot\mathbf{S}, \mathbf{L}^2, \mathbf{L}^2(\sigma_i\cdot\sigma_j), (\mathbf{L}\cdot\mathbf{S})^2] \\
& + [\boxed{1,} \sigma_i\cdot\sigma_j, S_{ij}, \mathbf{L}\cdot\mathbf{S}, \mathbf{L}^2, \mathbf{L}^2(\sigma_i\cdot\sigma_j), (\mathbf{L}\cdot\mathbf{S})^2] \otimes \tau_i\cdot\tau_j \\
& + [1, \sigma_i\cdot\sigma_j, S_{ij}, \mathbf{L}\cdot\mathbf{S}] \otimes T_{ij} \\
& + [1, \sigma_i\cdot\sigma_j, S_{ij}, \mathbf{L}\cdot\mathbf{S}] \otimes (\tau_i+\tau_j)_z
\end{aligned}
$$

charge exchange reaction: $^3\mathrm{He}\uparrow({}_{z}X, {}_{z+1}Y)t$





Polarized case:

$$\begin{aligned} O^p_{ij} = {} & [1, \sigma_i \cdot \sigma_j, S_{ij}, \mathbf{L}\cdot\mathbf{S}, \mathbf{L}^2, \mathbf{L}^2(\sigma_i \cdot \sigma_j), (\mathbf{L}\cdot\mathbf{S})^2] \\ & + [1, \boxed{\sigma_i \cdot \sigma_j}, S_{ij}, \mathbf{L}\cdot\mathbf{S}, \mathbf{L}^2, \boxed{\mathbf{L}^2(\sigma_i \cdot \sigma_j)}, (\mathbf{L}\cdot\mathbf{S})^2] \otimes \tau_i \cdot \tau_j \\ & + [1, \sigma_i \cdot \sigma_j, S_{ij}, \mathbf{L}\cdot\mathbf{S}] \otimes T_{ij} \\ & + [1, \sigma_i \cdot \sigma_j, S_{ij}, \mathbf{L}\cdot\mathbf{S}] \otimes (\tau_i + \tau_j)_z \end{aligned}$$

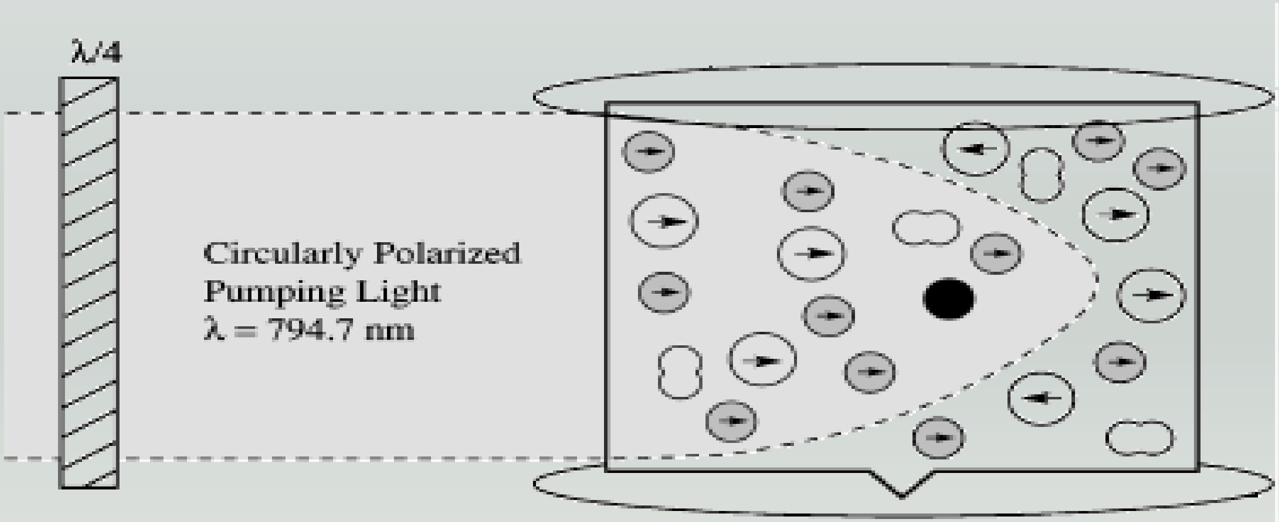
Utilizing Polarizd ^{3}He taget in Lanzhou University

Principle of polarizing ^{3}He

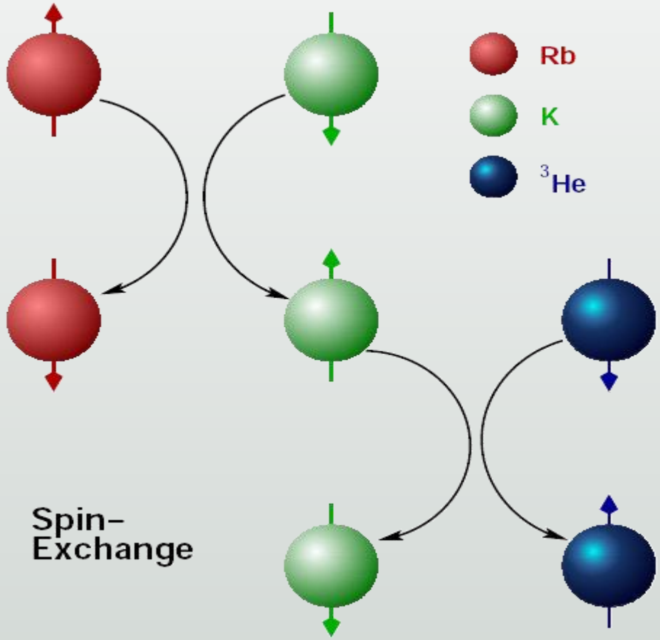
- polarized laser → polarized Alkali atom → polarized ^{3}He

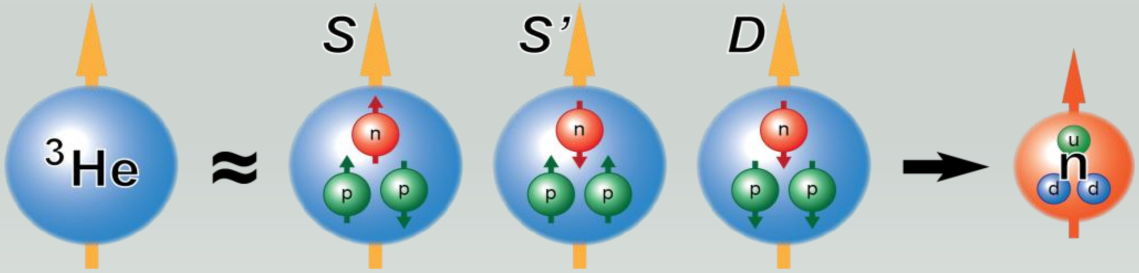
  ↓ optical pumping ↓ spin exchange

- Density of each piece (in cm^{-3})
  - [Rb] ~ 10^{18} at 230 °C
  - [He] ~ $2.69*10^{20}$
  - [N_2] ~ $2.15*10^{18}$



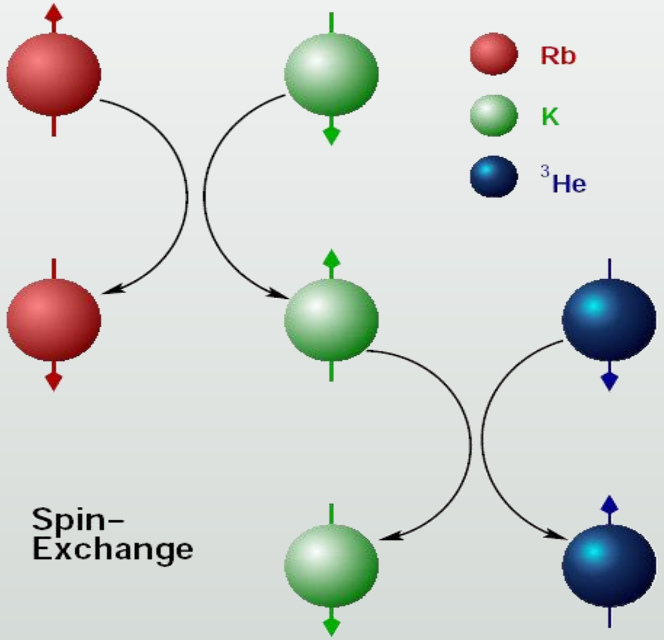
Pumping hybrid alkali





~90% ~1.5% ~8%

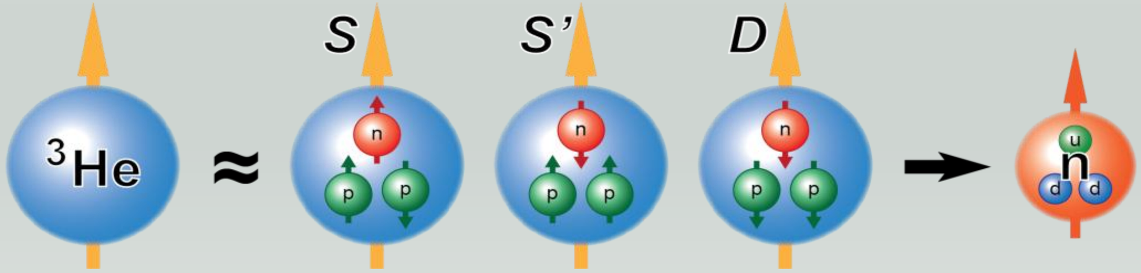
Pumping hybrid alkali



$$P_{\mathrm{He}}(t) = \langle P_{\mathrm{Rb}} \rangle \frac{\gamma_{SE}}{\gamma_{SE}+\Gamma}\left(1 - e^{-(\gamma_{SE}+\Gamma)t}\right)$$

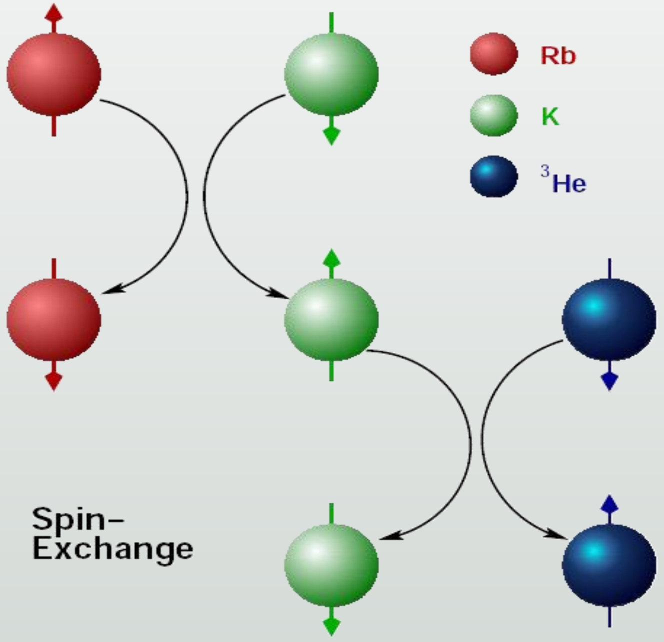
$$\gamma_{SE} = k_{SE}[\mathrm{Rb}]$$

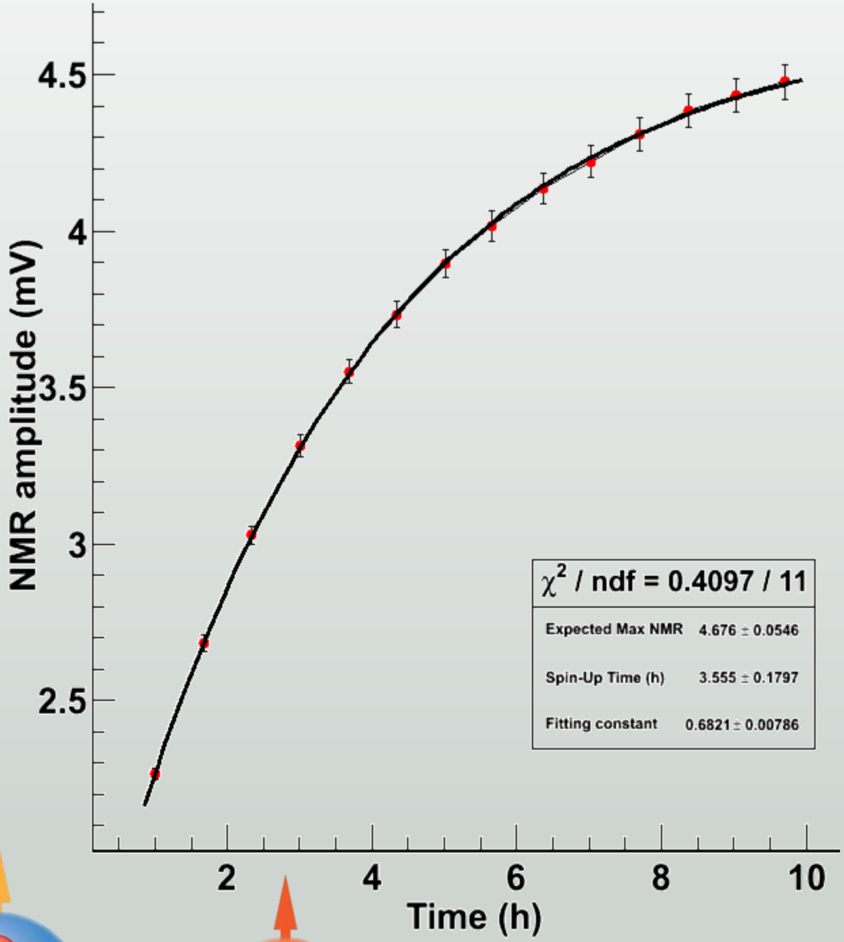
$$k_{SE} = (6.1 \pm 0.2) \times 10^{-20}\ [\mathrm{cm}^3/\mathrm{s}]$$

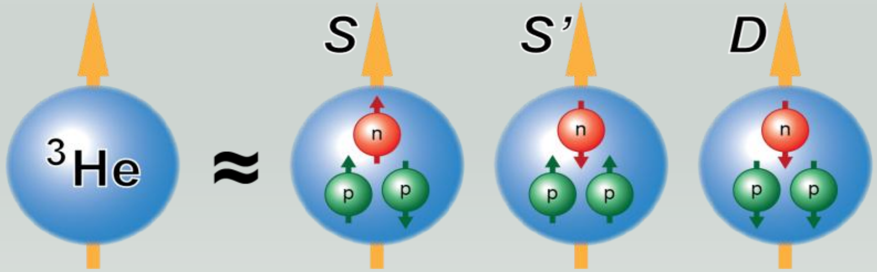


~90% ~1.5% ~8%

Pumping hybrid alkali

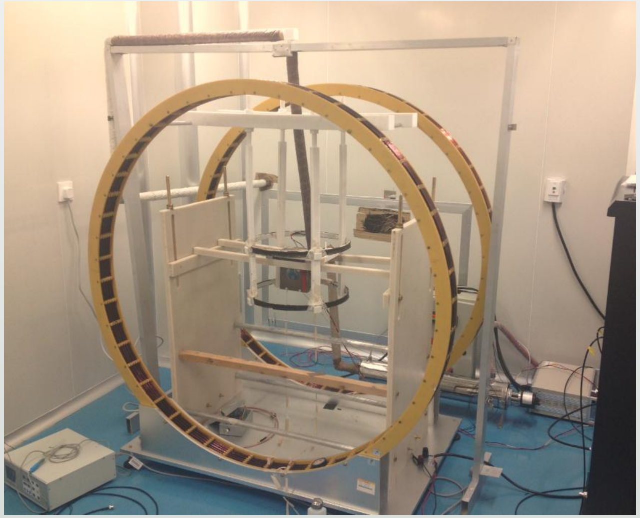


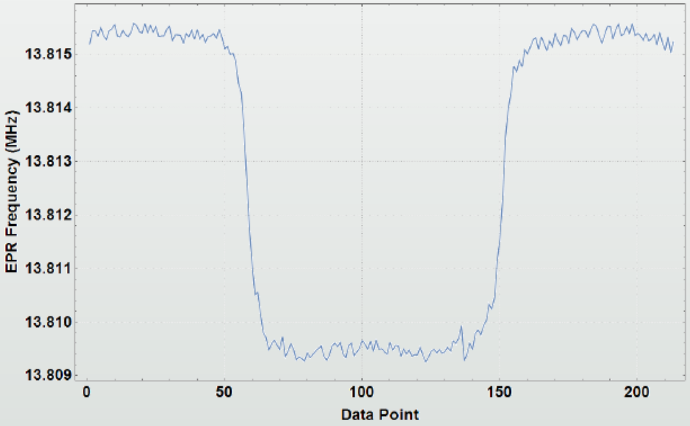




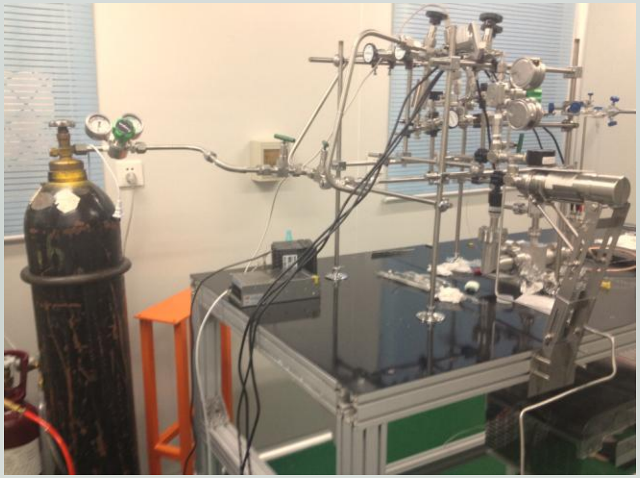
~90% ~1.5% ~8%

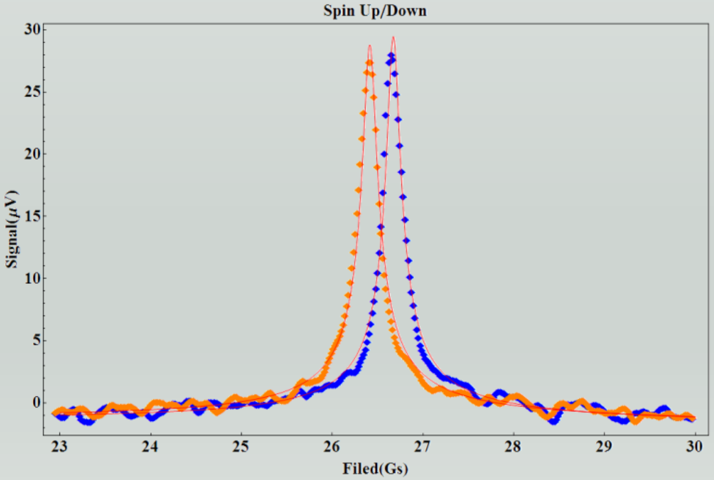
Polarized ^{3}He target build in LZU





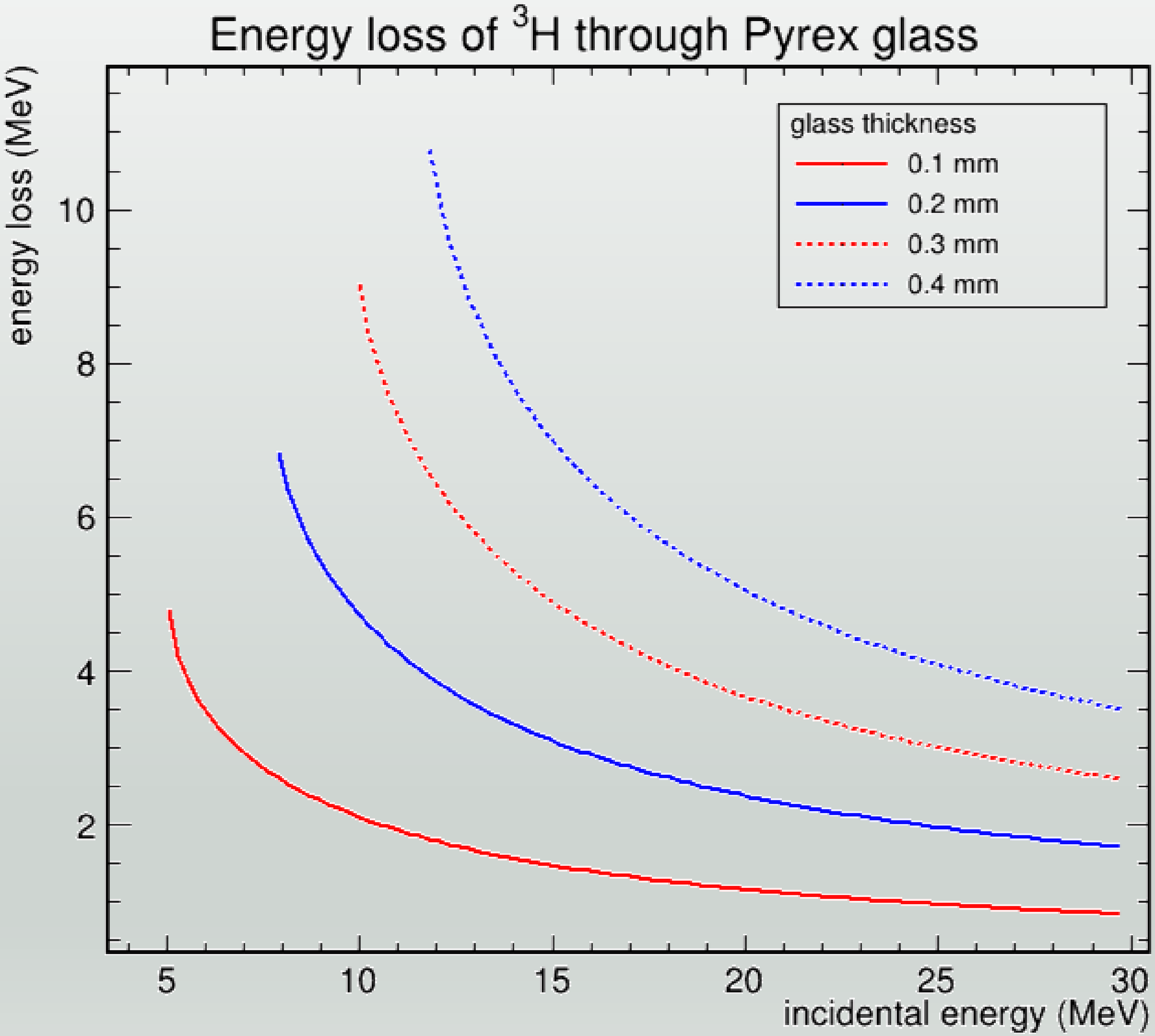
$\varDelta \upsilon = 5.91\ kHz$ $P_{EPR} = 54\%$





- Gas filling system
- Hybrid pumping
- Polarization (~60%)
- 0.9 Amg.
  - plan: ~3 Amg.
- Only 1 chamber
  - Plan: 2 chamber

Eneregy loss in the glass wall



Summary

Polarized target in hadron beam is more like a unique probe rather than an object.

- In few-nucleon system, polarization is important
  - Role of Δ(1232) and Δ(1440*)
  - Tensor force

- In CE process, polarization is crucial
  - Nuclear structure
  - propagation of Δ in nuclear matter
  - Other applications

- For various types of experiments, technical R&D is still challenging

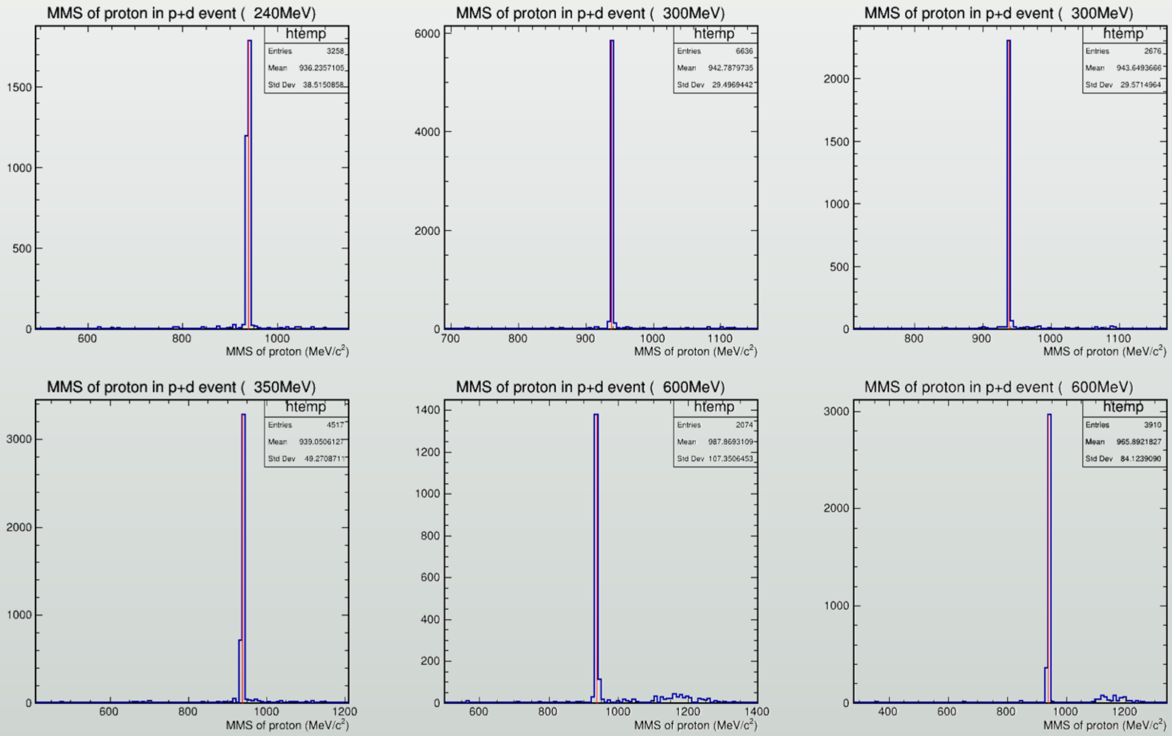
Thank you !

Backup slides

Simulation detail

- Physics model:
  - EM model: G4EmStandardPhysics_option3
  - Hadron physics model: G4HadronPhysicsINCLXX
  - Model for ions: G4IonINCLXXPhysics+G4IonElasticPhysics
- Beam energy: 240MeV~600MeV
- Tracks E_{kine}>1MeV, $\theta > 2^{\circ}$, energy, momentum, position, time…

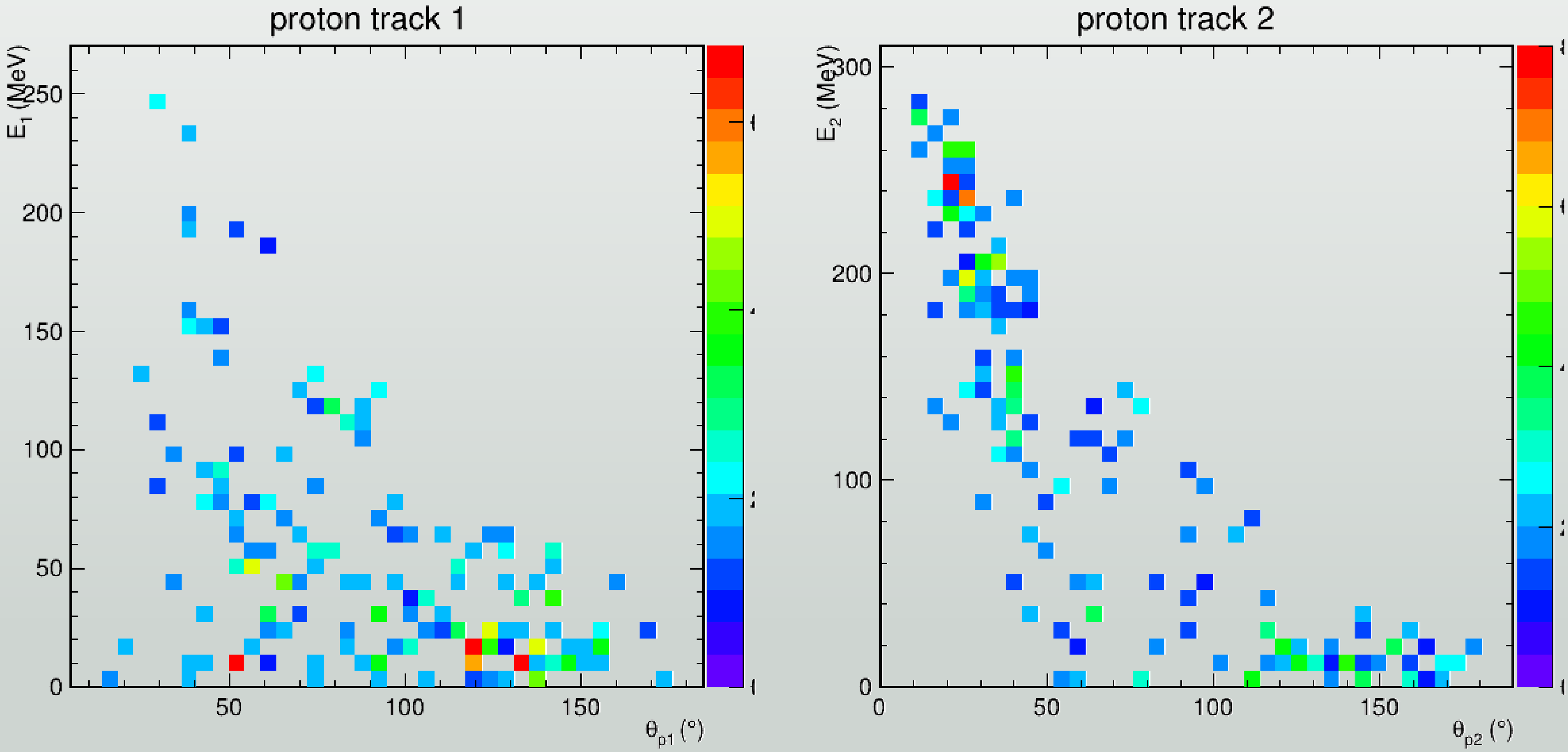
Missing mass of proton in p+d event



Only has ¼ stat. of 2-p event

Red line showing Proton mass

Energy-Angular distribution of proton (300MeV)


proton track 1

proton track 2

Angular correlation of proton (300MeV)