11th APCTP-BLTP JINR-PINP NRC KI-SPbSU Joint Workshop
"Modern problems in nuclear and elementary particle physics"

July 25, 2017

Search for ^{10}N Resonances with ^{9}C + p Resonant Scattering

W. Kim

KYUNGPOOK NATIONAL UNIVERSITY

RI Beams with Polarized Proton Target

I. Proton elastic scattering and spin-orbit potential

II. Knock-out reaction and spin-orbit splitting

III. Proton resonant scattering and single-particle levels

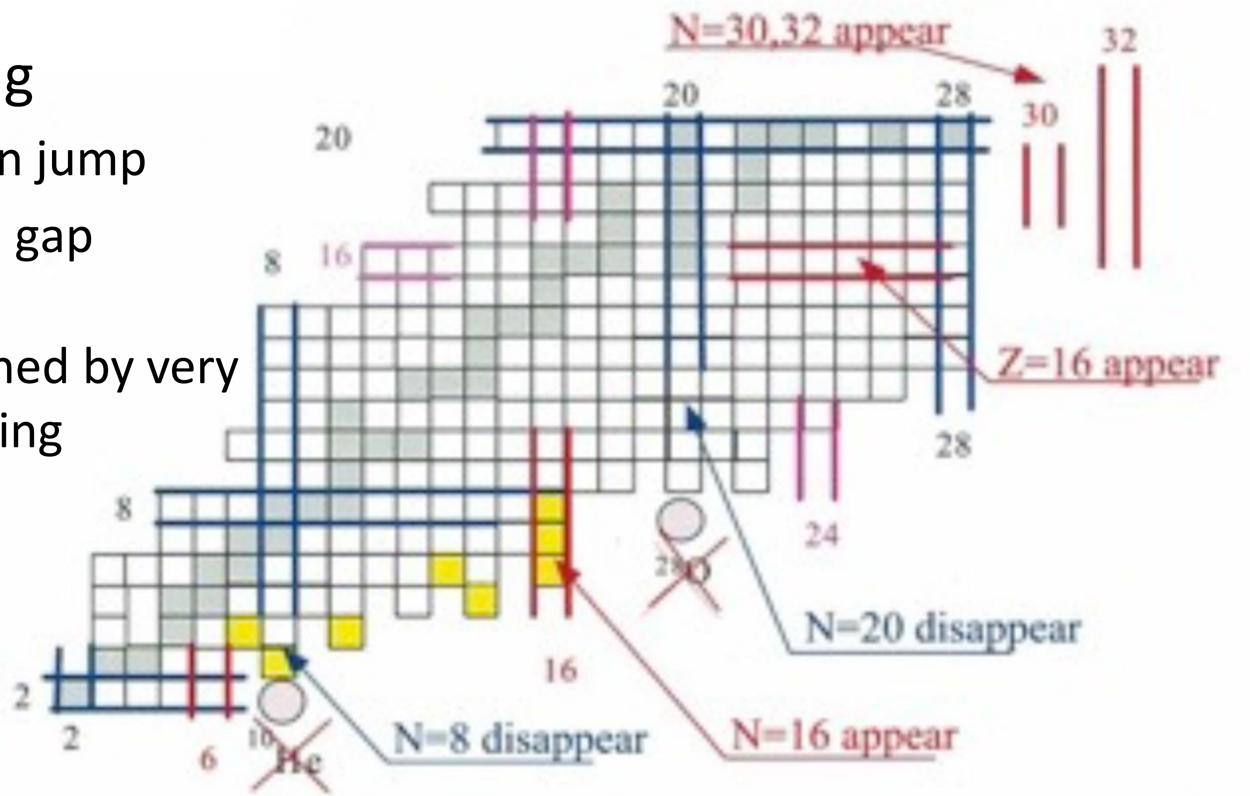
IV. Proton target

Magic Numbers Changing in Unstable Nuclei

Disappearance of conventional magic numbers
Appearance of NEW magic numbers

- Spin-orbit coupling
  - **So strong** that can jump across major shell gap

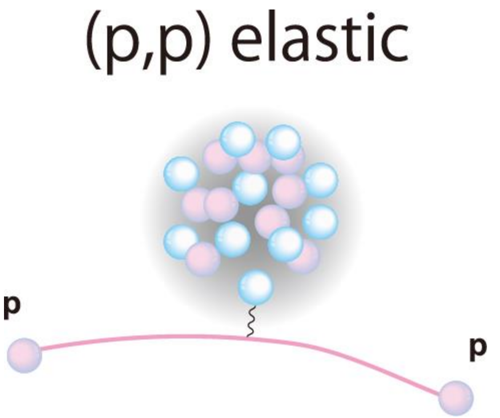
Magic numbers explained by very strong spin-orbit coupling



Role of spin-dependent int. in unstable nuclei is the key!!

I. Proton Elastic Scattering and Spin-Orbit Potential

T. Uesaka, H. Sakai, PRC(R) 82 (2010)



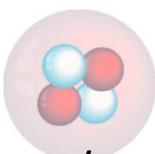
- Vector analyzing powers have been measured for the proton elastic scattering from ^{6,8}He at 71 MeV/A.
- Measured analyzing powers are incompatible with any theoretical predictions.
- Modification of spin-orbit coupling in scattering involving n-rich nucleus: spin-orbit potentials for ^{6,8}He are shallow and extended compared with systematics of stable nuclei.
- Proper description of p-^{4}He scattering should be important for reproduction of p-^{6}He scattering.
- We plan to measure the A_y for p-^{6}He elastic scattering at 200 MeV/A where reaction mechanism is well understood.

p-^{6}He, p-^{8}He Elastic Scattering

- Analyzing power measurement for *p*-^{6,8}He
  - Question:

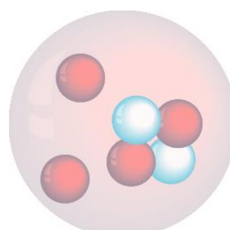
    What is characteristics of spin-orbit potentials?

^{4}He



N/Z = 1

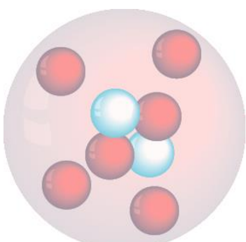
^{6}He



N/Z = 2

α+2n

^{8}He



N/Z = 3

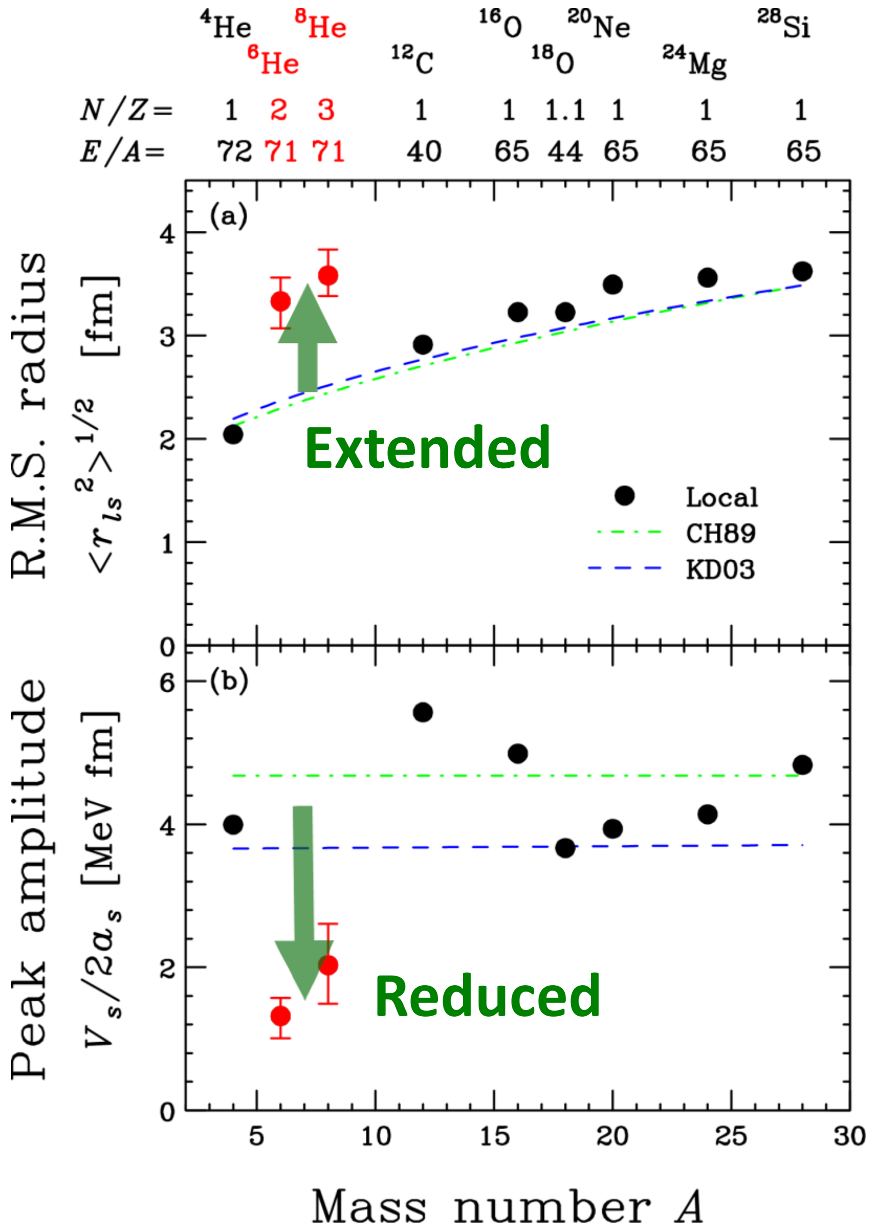
α+4n

Characteristics of $V_{LS}(r)$

- Modification of spin-orbit potential in n-rich nuclei
  - Shape and magnitude
    - R.M.S. radius
    - Peak amplitude

Spin-orbit potential in n-rich helium isotopes:
shallow and extended

(← effect of diffused density distribution?)

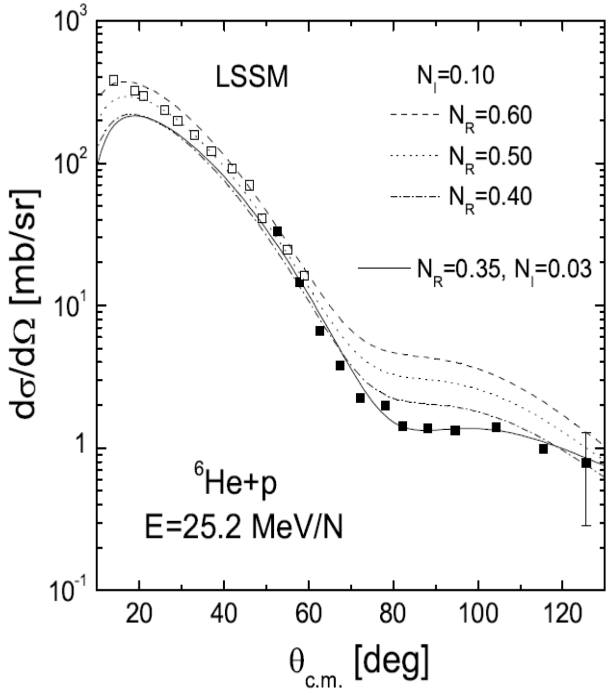


Calculations of ^{6}He+p elastic-scattering cross-sections using folding approach and high-energy approximation for the optical potential

K.V. Lukyanov[1], V.K. Lukyanov[1], E.V. Zemlyanaya[1], A.N. Antonov[2], and M.K. Gaidarov[2,3,a]

[1] Joint Institute for Nulcear Research, Dubna 141980, Russia

Abstract. Calculations of microscopic optical potentials (OPs) are performed to analyze ^{6}He+p elastic-scattering data at a few tens of MeV/nucleon (MeV/N). The role of the spin-orbit terms and of the non-linearity in the calculations of the OPs, as well as effects of their renormalization are studied.



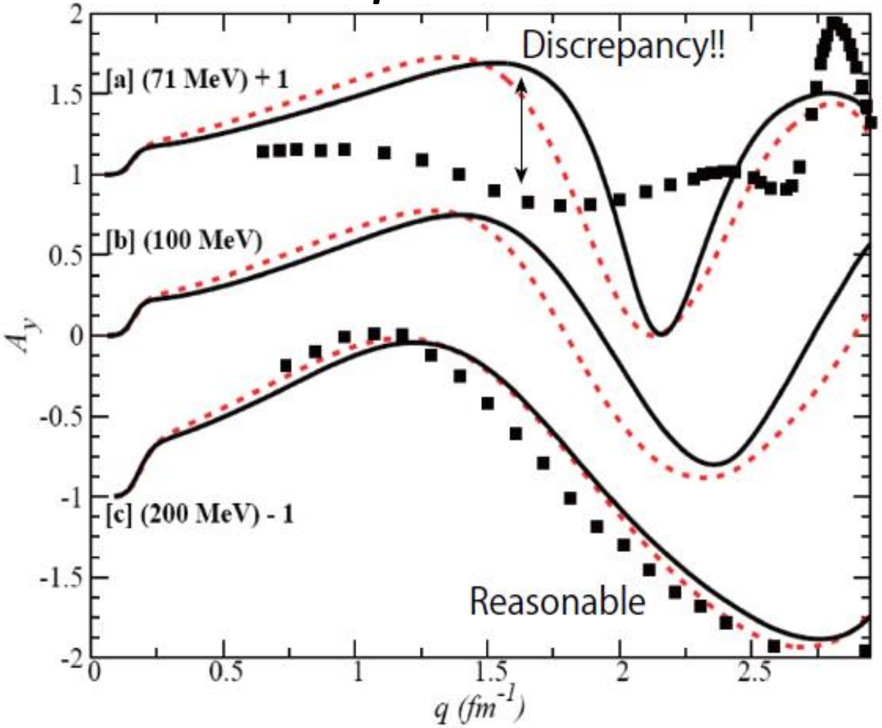
Elastic ^{6}He+p scattering cross-sections for $\mathrm{E} = 25.2\mathrm{MeV/N}$ calculated by using the LSSM density for ^{6}He.

Eur. Phys. J. A 33, 389 (2007)
DOI 10.1140/epja/i2007-10458-6

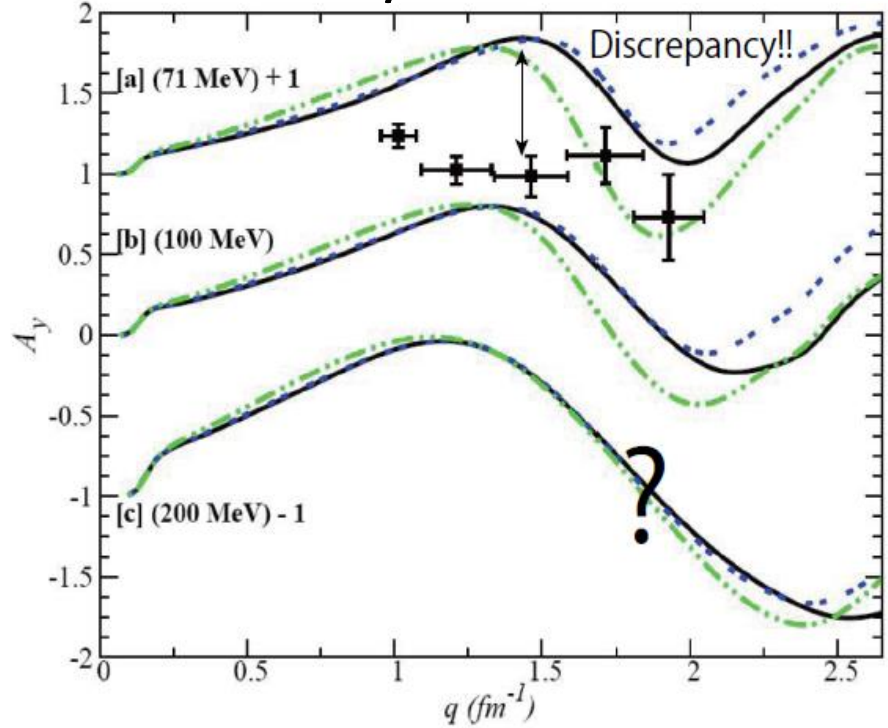
Experimental Data

S. Sakaguchi, et al. PHYS. Rev. C, 84, 024604 (2011)

p-^{4}He



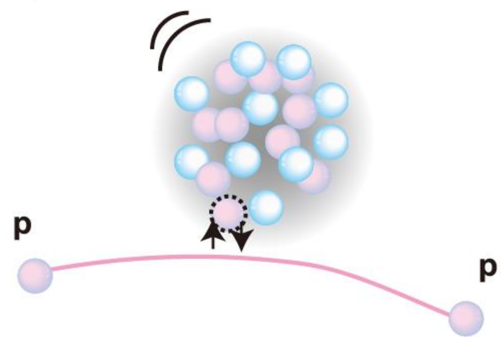
p-^{6}He



Calculations of A_y for proton elastic scattering from ^{4}He and ^{6}He at 71, 100, and 200 MeV/A by the multiple scattering theory with COSMA density.

A_y provides new information which can not be seen in $d\sigma/d\Omega$.

III. Proton Resonant Scattering and Single-Particle Levels



- Proton resonant scattering from ^{9}C at 5.6 MeV/A will be measured with a spin-polarized proton target for RI-beam exp.

- Overlapping resonances will be resolved with the analyzing power data which is completely new information.

- Low-lying level structure of ^{10}N (mass, E_R, Γ, J^{π}) will be revealed.

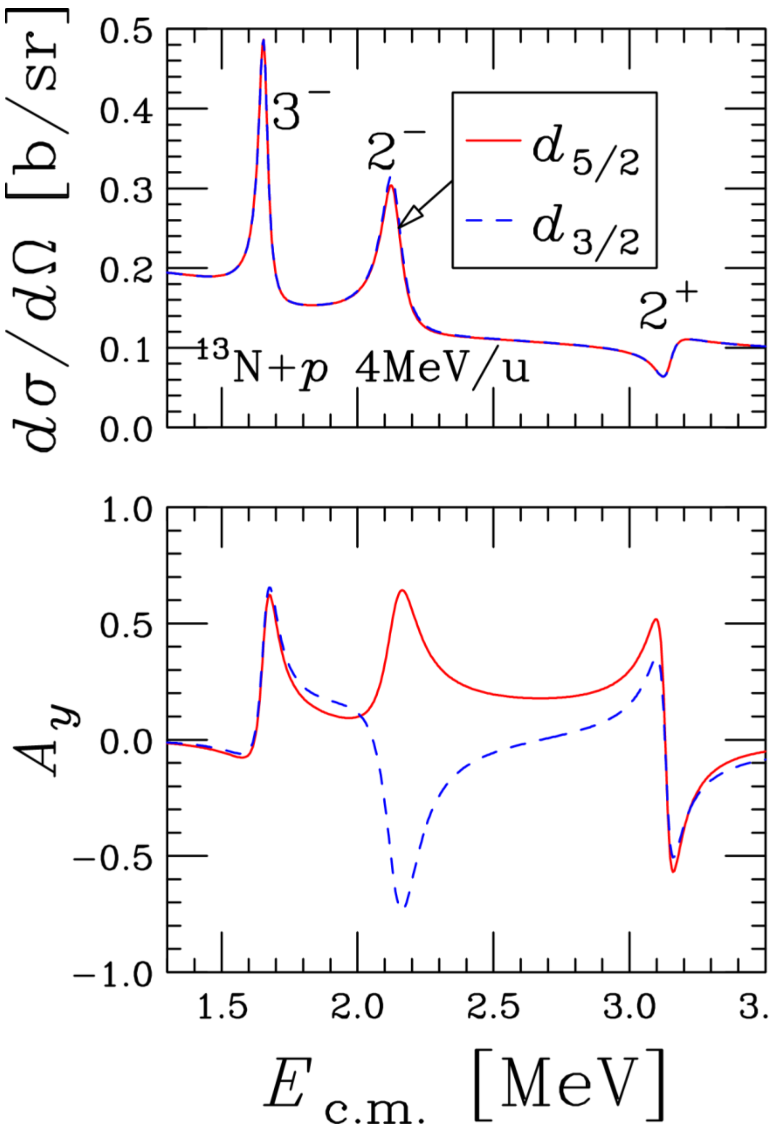
- ^{10}N levels $\rightarrow$ mirror levels in ^{10}Li $\rightarrow$ n-^{9}Li potential
  $\rightarrow$ three-body model for borromean nucleus ^{11}Li.

Pioneer experiment: First measurement of polarization observable in scattering exp. with low-energy RI-beam $\Rightarrow$ New possibilities

Resonant proton scattering

- Roles of spin asymmetry
  - J^{π} determination
    - Projectile w/ non-zero spin
    - Sensitive to configuration mixing
  - Information for extremely wide resonances

- Feasibility demonstration
  - $^{13}N+\vec{p}$ scattering
  - Monte-Carlo simulation P_p = 20%, 10 mg/cm^2, 10^5 pps, 3 days, pure $d_{5/2}$



T. Teranishi, S. Sakaguchi, T. Uesaka, et al., AIP Conf. Proc. 1525, 522 (2013)

Borromean Nucleus

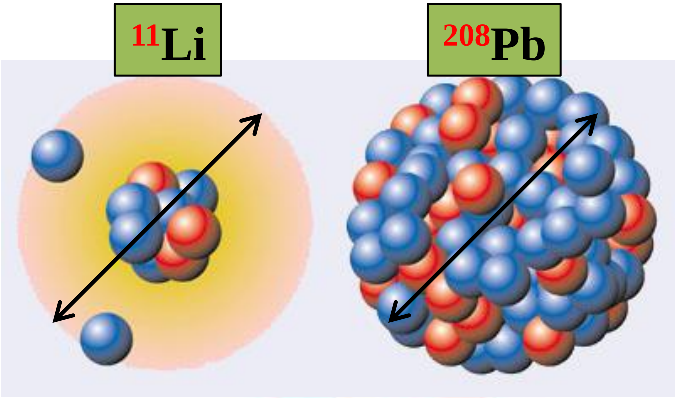
RIKEN, T. Teranishi (Kyuhsu), E. Milman (KNU)

Resonant elastic scattering

$$^{9}C + \vec{p} \rightarrow {}^{10}N \rightarrow {}^{9}C + p$$

with a low-energy ^{9}C beam at 5.6 MeV/u

and a spin-polarized proton target.



Combined information on excitation function

($d\sigma/d\Omega$ (E)) and analyzing power (A_y (E))

→ **Search for broad ^{10}N resonances**

^{10}N (=^{9}C+p) ← mirror → ^{10}Li (=^{9}Li+n): binary subsystem

of borromean nucleus ^{11}Li (= ^{9}Li+n+n)

→ **Understanding of ^{9}Li+n potential for 3-body model**

Borromean ring

Polarization observable as additional information is useful for:

- resolving wide resonances overlapping each other
- J^{π} assignment especially when the beam nucleus has non-zero spin

The present situation (very broad ^{9}C+p resonances & I (^{9}C) = 3/2) will be a good place for testing the new experimental technique.

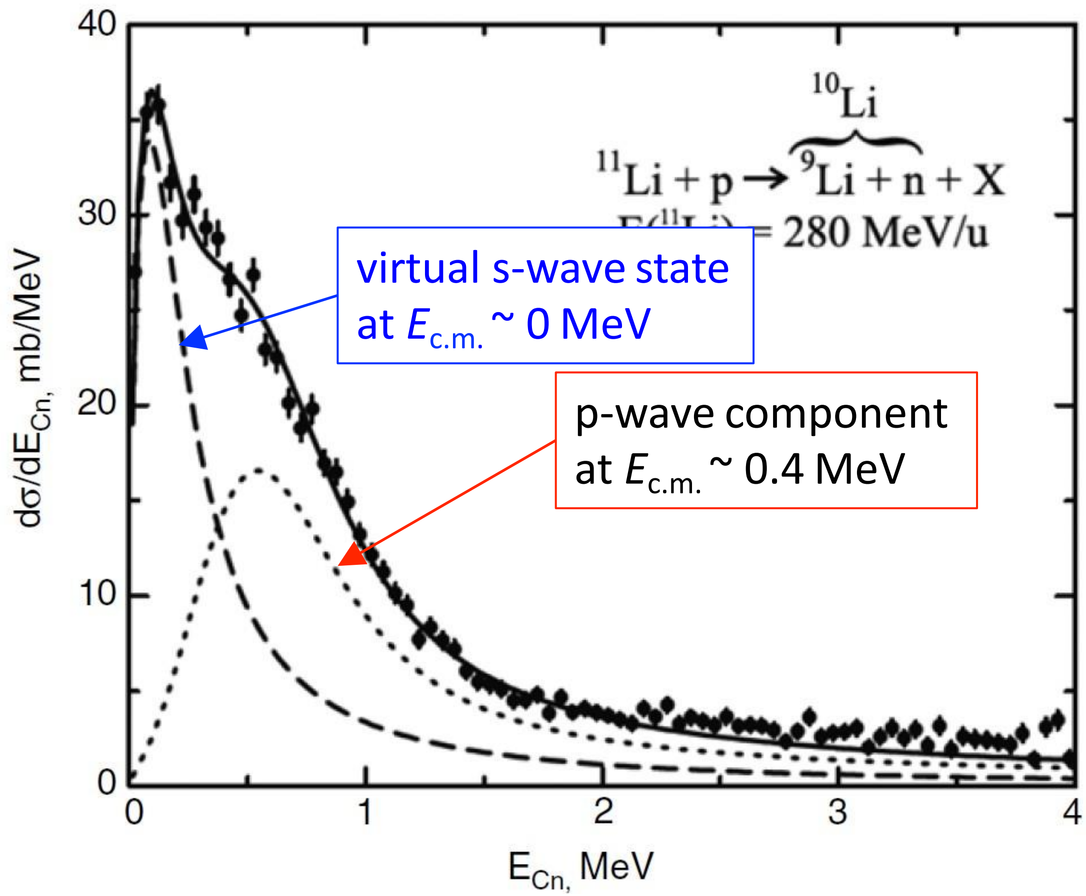
Limited information on ^{10}Li

J^{π} (^{9}Li) = 3/2^{-}

^{9}Li+n (s1/2) à J^{π} = 1^{-} or 2^{-}

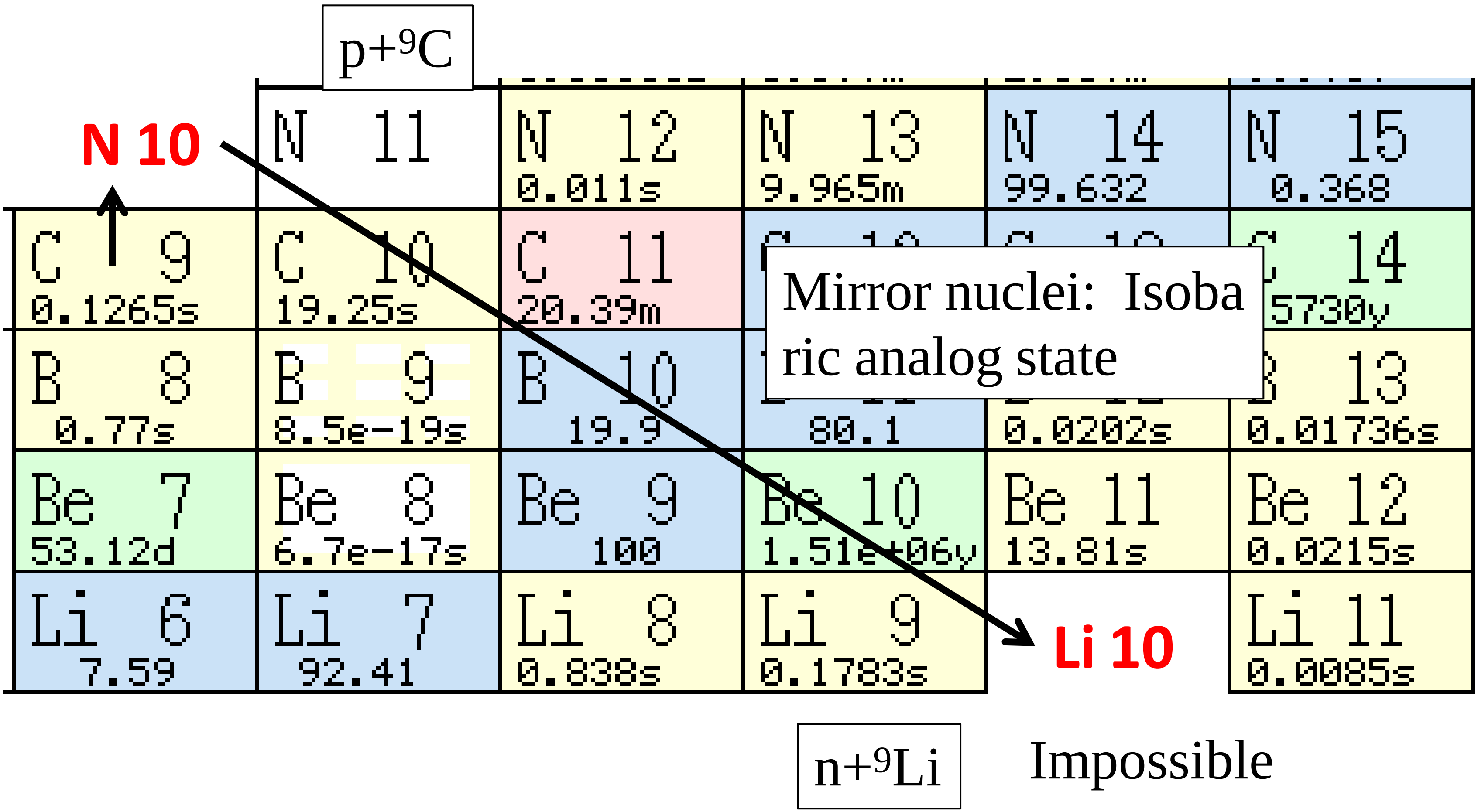
^{9}Li+n (p1/2) à J^{π} = 1^{+} or 2^{+}

Four low-lying components
J^{π} = 2^{-}, 1^{-}, 1^{+} & 2^{+},
but only two observed.
No clear J^{π} assignment.



Yu. Aksyutina et al., PLB666(2008)430

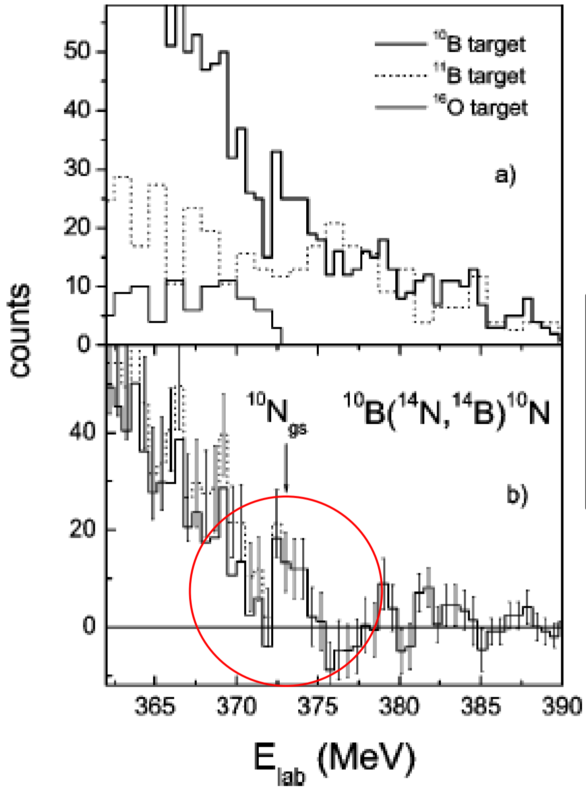
^{9}C+p as a new approach



^{10}Li (=^{9}Li+n) ß mirror à ^{10}N (=^{9}C+p)

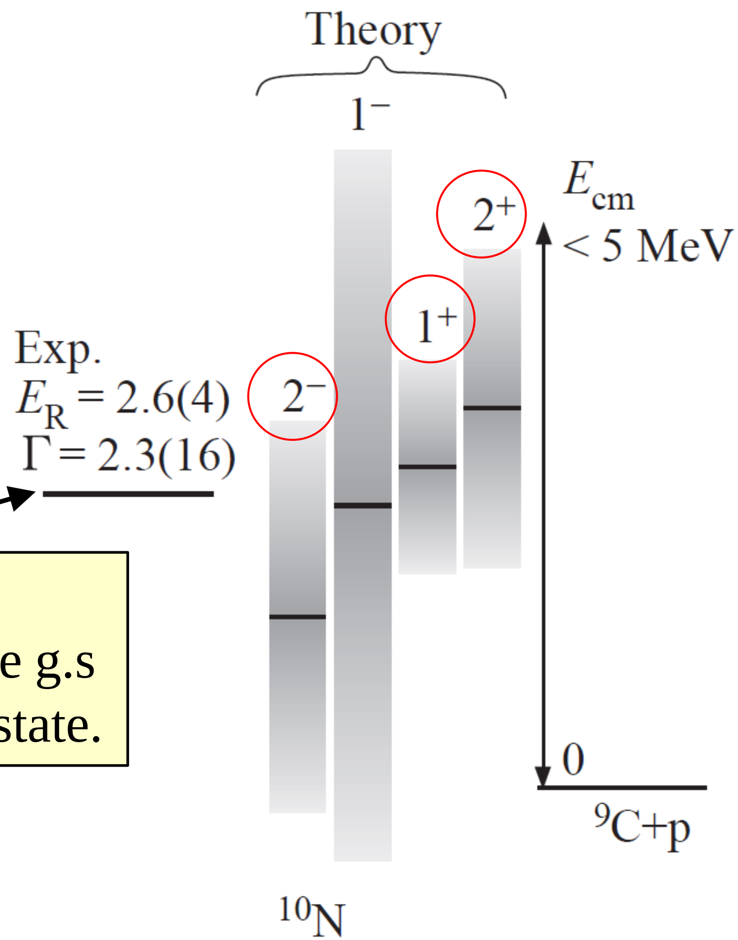
^{10}N (^9C+p) Resonances

Almost unknown experimentally.
Only one observation with small statistics.
No J^π assignment.



A. Lepine-Szily et al., PRC(65)054318.

The observed state
may **not** be the s-wave g.s
but a p-wave excited state.



Theoretical prediction of 2^-(s), 1^+(p) & 2^+(p):
S. Aoyama, K. Kato, K. Ikeda, PLB414(1997)13.

Search for **very broad ^{10}N resonances** in ^9C+p scattering

Outline of Experiment

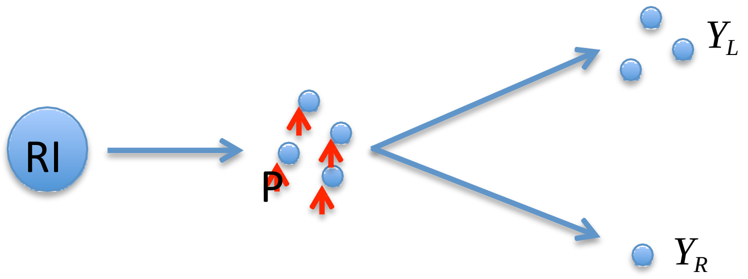
- Resonant elastic scattering $^{9}\mathrm{C} + p \longrightarrow {}^{10}\mathrm{N} \longrightarrow {}^{9}\mathrm{C} + p$
  with a low-energy ^{9}C beam at 5.6 MeV/u
  and a spin-polarized proton target.

- Measurement of excitation function and analyzing power

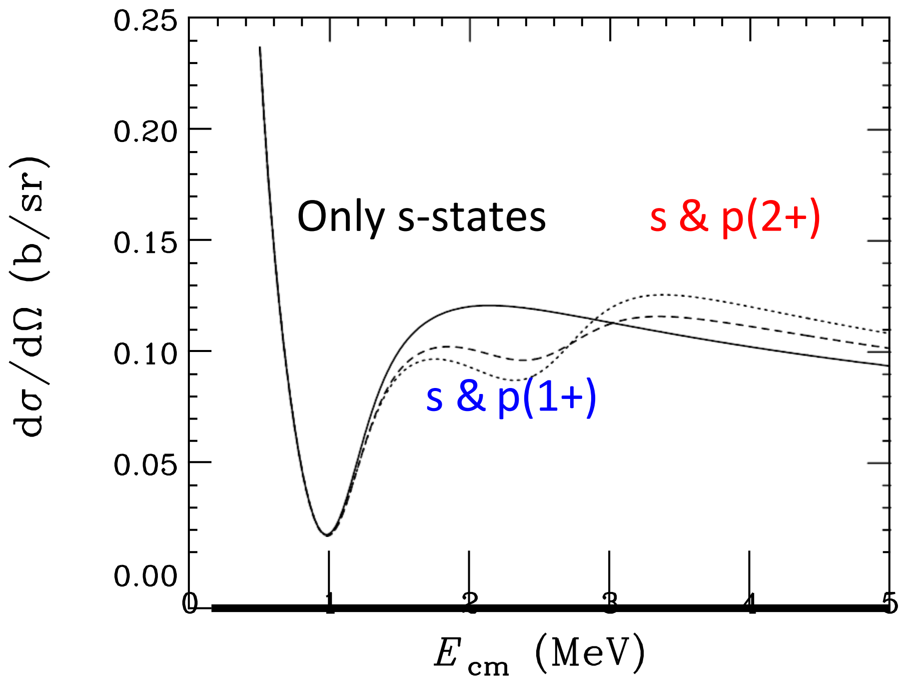
- Investigation of low-lying resonances of ^{10}N
  - Ø Mass of ^{10}N
  - Ø Information on n-^{9}Li

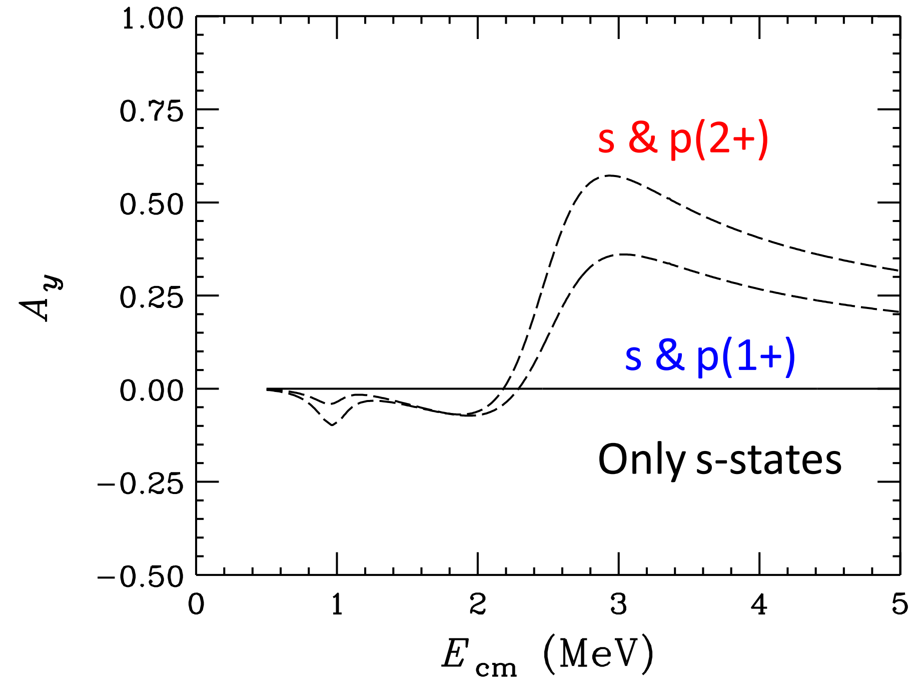
Do we need analyzing power (A_y)?

$$A_y = \frac{1}{P_y}\frac{Y_L - Y_R}{Y_L + Y_R}$$



Polarized target -> A_y measurement

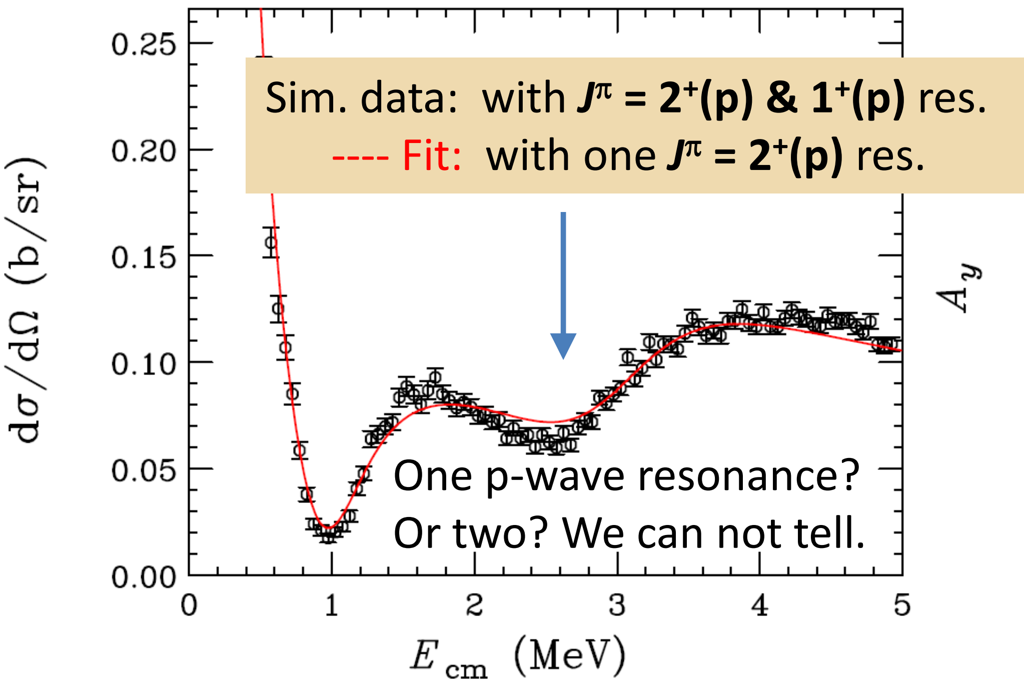


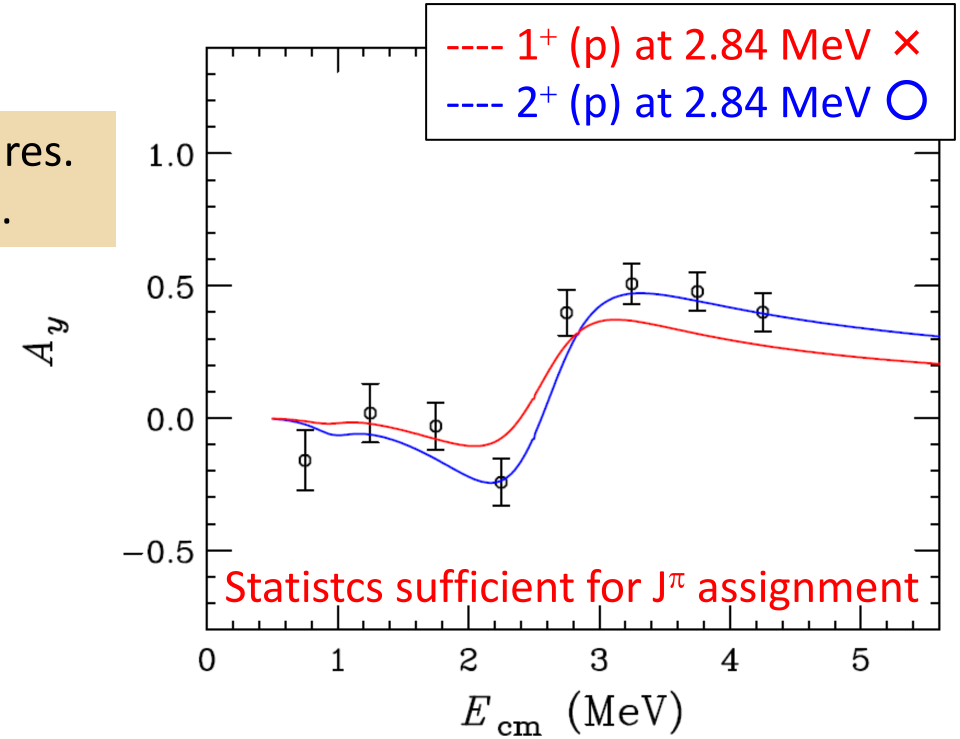


- Clearer J^π assignment
- Effective to solve broad resonances

R-matrix calculations

Is A_y really necessary?





One p-wave 2^+ resonance → $A_y \sim$ **0.6**

Two p-wave resonances (2^+ & 1^+) → $A_y \sim$ **1.0 (almost doubled)**

due to constructive contributions from 2^+ & 1^+

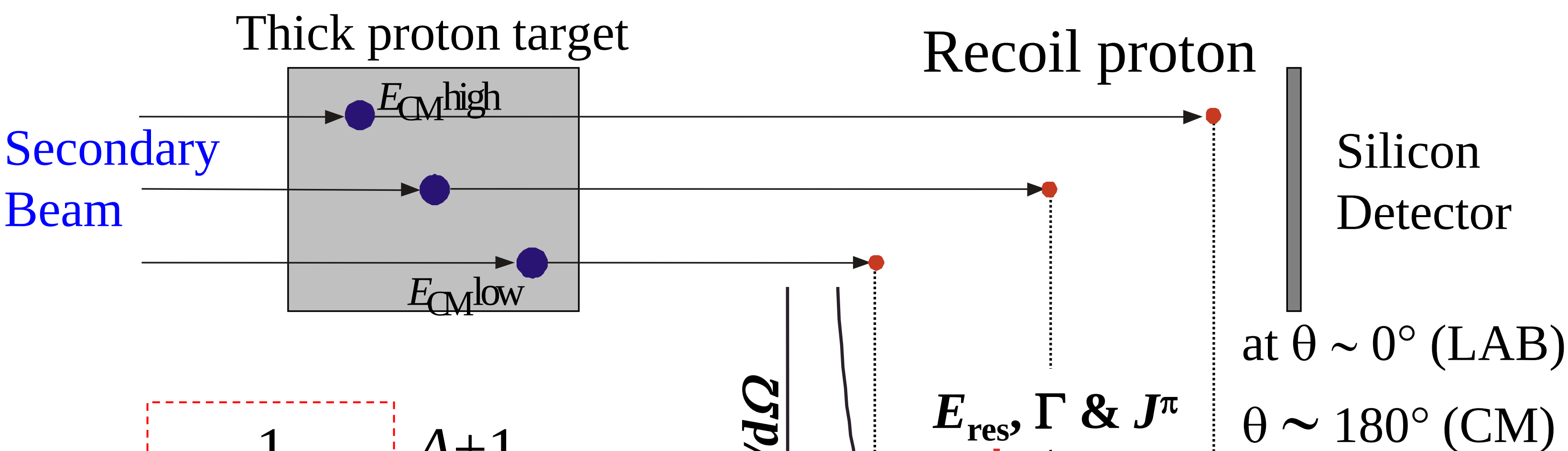
Yes, necessary.

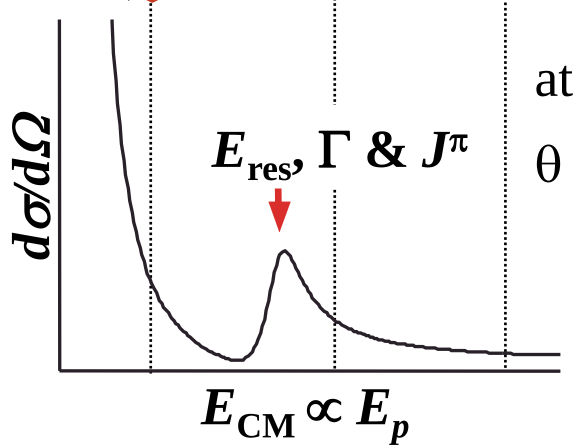
Thick Target Method in Inverse Kinematics Method

– Energy loss of beam in target

  ⇒ Excitation function with single incident energy

— A resonance can be observed as an interference pattern of potential & resonance scattering.





$$E_{CM} = \boxed{\frac{1}{4\cos^2\theta_p}}\,\frac{A+1}{A}\,E_p$$

→ **Good resolution** of E_{CM}

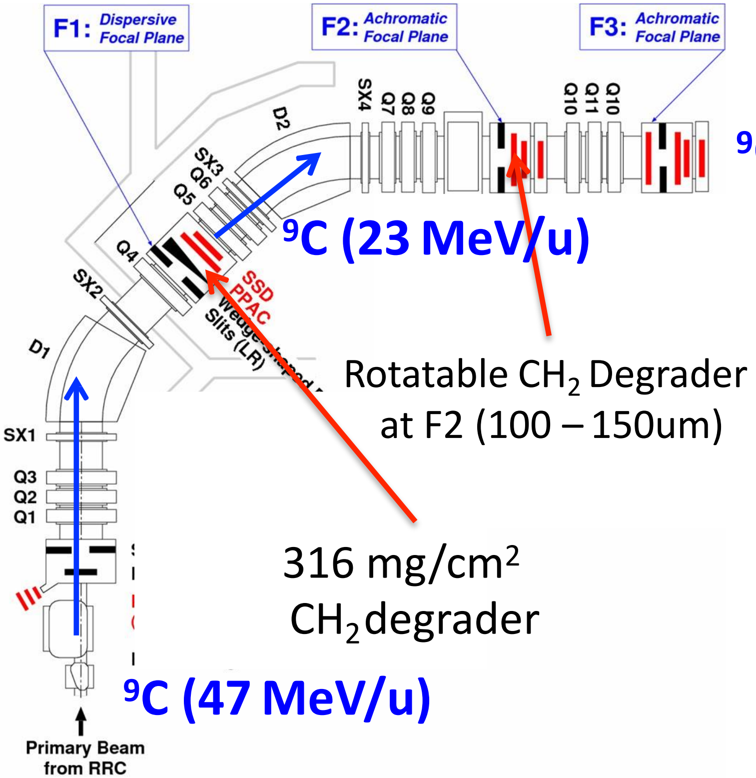
Test Experiment (September, 2015)

Goals:

- Production of low-E ^{9}C beam at RIPS, RIKEN
  - Use CH_2 degrader to improve beam intensity

- Measure excitation function with CH_2 target (50X50mm)
  - pol. p target for low-E experiment is under development

Experimental Setup (RIPS)



^{12}C (70 MeV/u)

Pr. Target 3.5 -4 mm Be

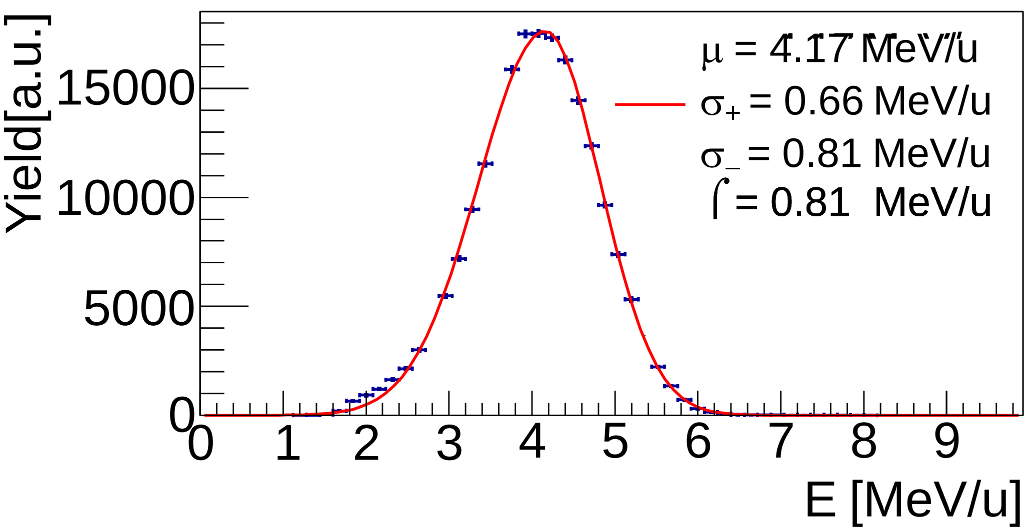
- Improve transmission from F1 to F2
- Suppress multiple scattering effects in the thick degrader
  - Smaller angular spread reduces positional spread at downstream
- **Use lighter material for degraders such as CH_2**

Result of Beam Production

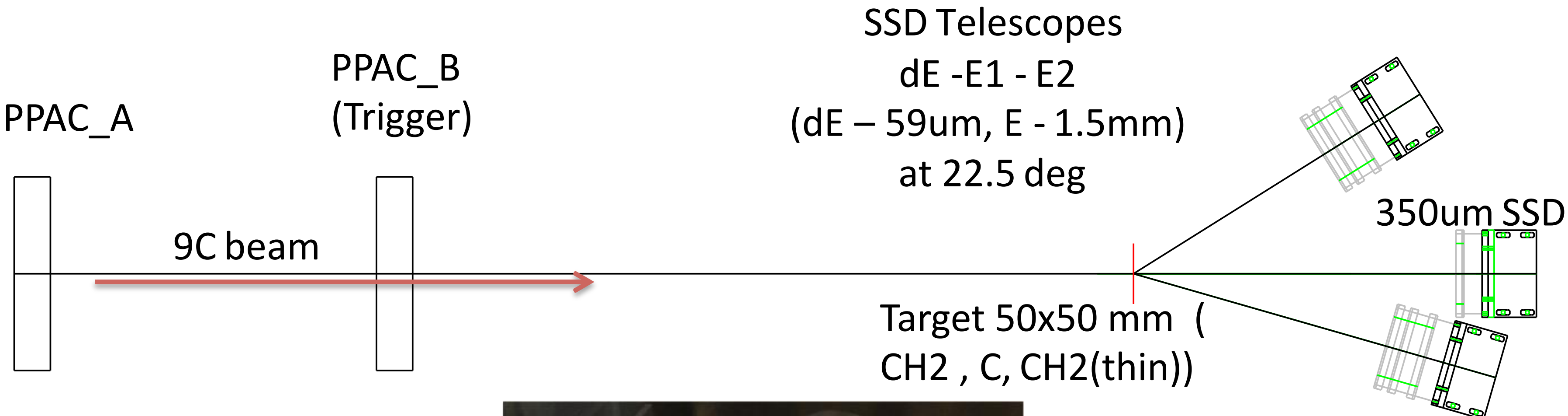
- Purity of ^{9}C beam is 15%
- ^{9}C Intensity at F3 was 25 kps

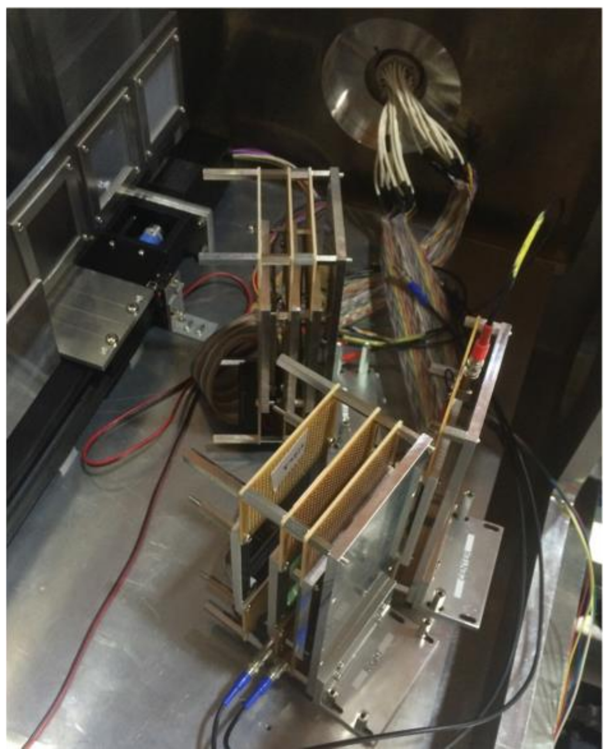
- Beam intensity **1.8 times** higher with CH_2 degrader at F2
    - Compared with standard Al degrader

9C beam energy on target



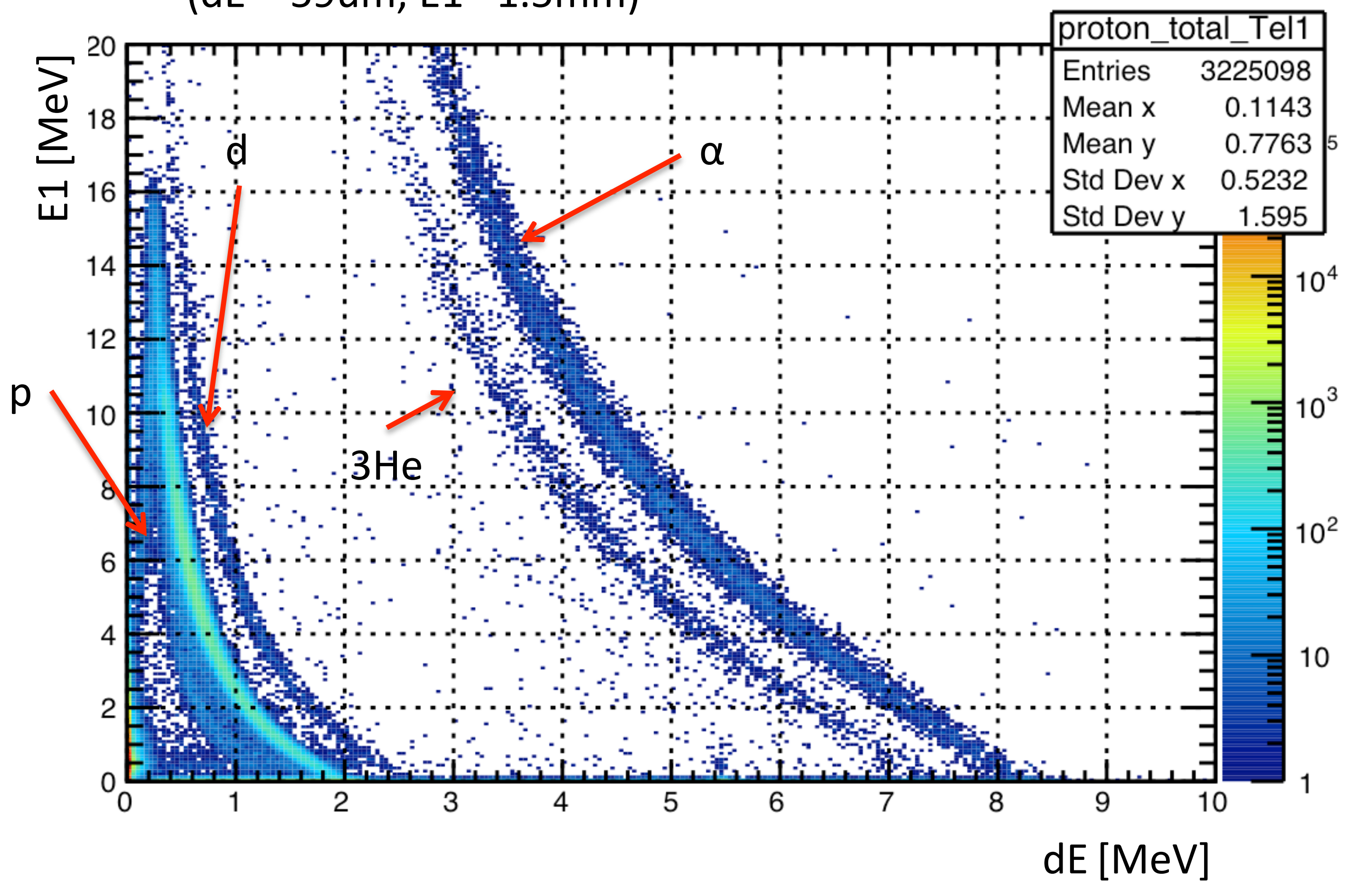
Experimental Setup





Recoil Particle Identification

SSD Telescope dE -E1
(dE – 59um, E1 - 1.5mm)

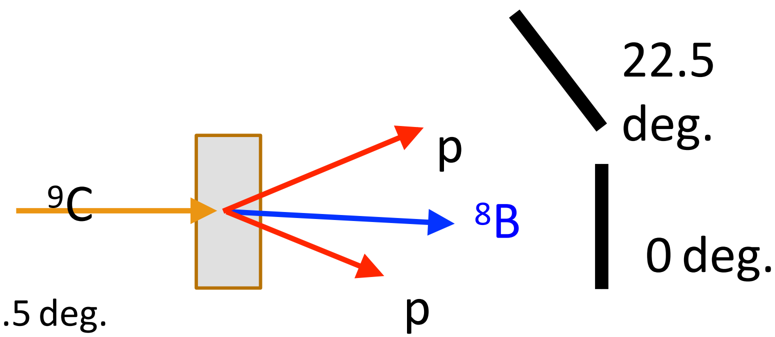


Background Reduction

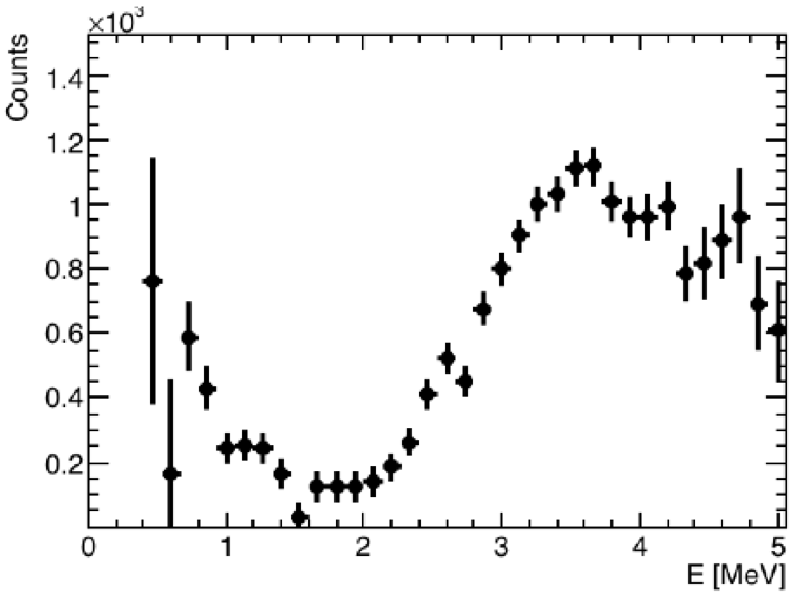
- Reactions of beam particles with C in the target
  - C target data was taken for B.G. subtraction

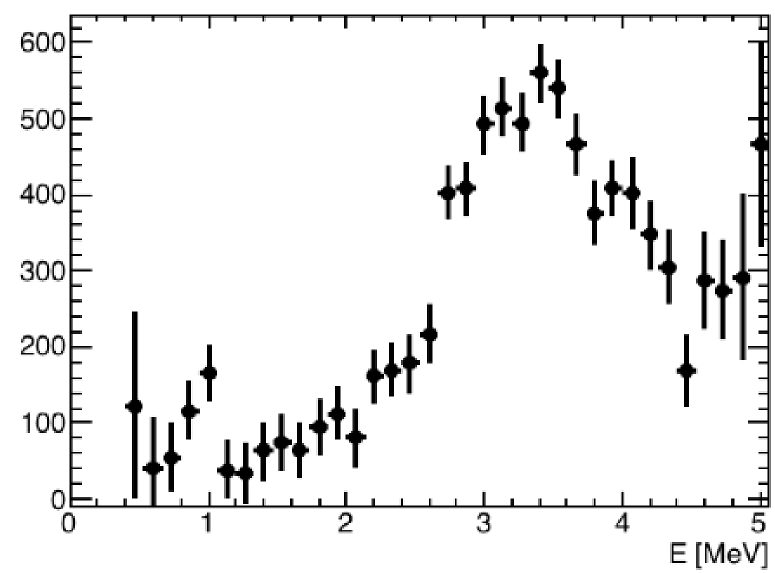
- Beta-delayed events
- Beta decay of stopped 9C in the target: 9C -> 9B* + β^+
  - 9B* -> 8Be + p , 9B* -> 5Li + α
  - B.G. spectrum was evaluated by selecting events with different timing

- Inelastic scattering events
  - ${}^{9}\mathrm{C}+p \longrightarrow {}^{8}\mathrm{B}+2p$
  - Thin CH_2 target run
    - Heavy ions / protons ware detected at 0 / 22.5 deg.
    - Analysis of inelastic data is still in progress



The Spectra on Tel.1 (left) and Tel.2 (right) after Efficiency Corrections



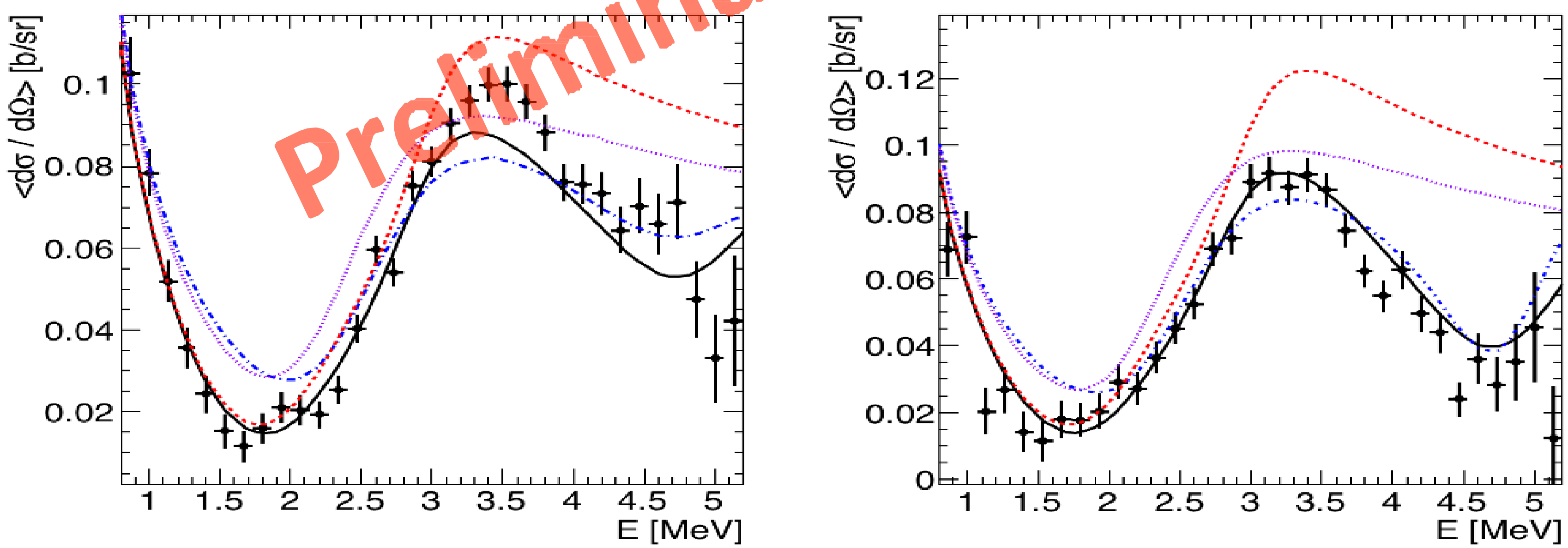


R-matrix Fit Parameters (Preliminary)

J^{π}	l	E_{ex} (MeV)	Γ (MeV)
2-	0	2.6	2.5
1-	0	2.9	1.1
1+	1	5.1	1.8
2+	1	5.1	1.6

- J^{π} set to 2^{-}
- 1^{-} resonance at 2.9MeV with a Γ of 2.5MeV
- R-matrix calculation with 2– (s-wave) and 1+, 2+ (p-waves)
- The best fit achieved with2– , 1–(s-waves) and 1+, 2+ (p-waves)

Preliminary



The excitation function measured by Tel.1 (left) and Tel.2(right) with R- matrix calculations.

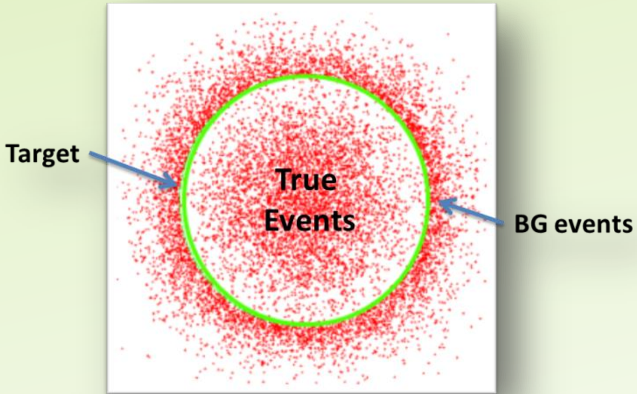
IV. Proton Target

Polarization enhancement and development of enlarged polarized proton target

- Enlarged the Target Size

Target diameter:

  - Was 14 mm
    - Loss of statistics
    - Increase in background events
  - Upgraded to 24 mm
    (RI beam: 20~30 mm)



Simulated RI-beam profile on 14 mm target

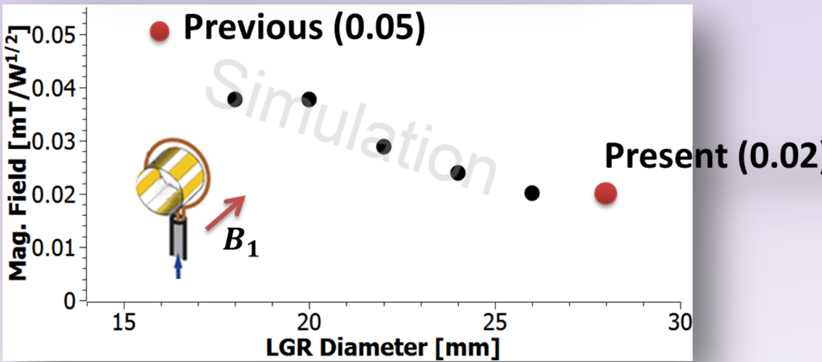
- Modifying the LGR size

LGR diameter: from 16 mm to 28 mm

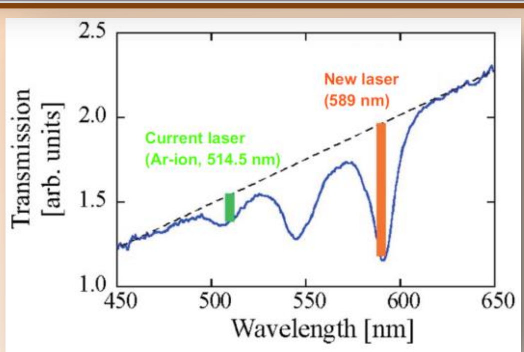
  - B_1 : 2.5 times weaker
  - P_{MW} : 6 times needed

Copper plate thickness: from 4.4 μm to 18~35 μm

  - Increase in field amplitude?

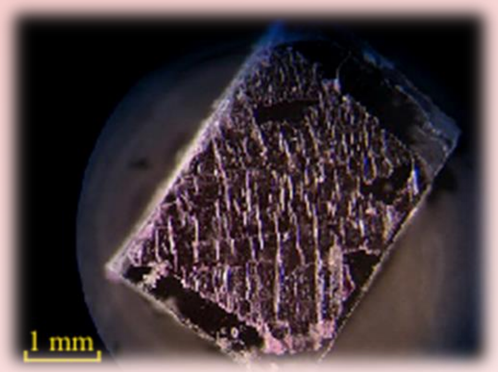


- Enhancing polarization with the new laser
  - ☐ Optimum λ: 589 nm
  - ☐ Higher power: 10 W
    (50 times higher)



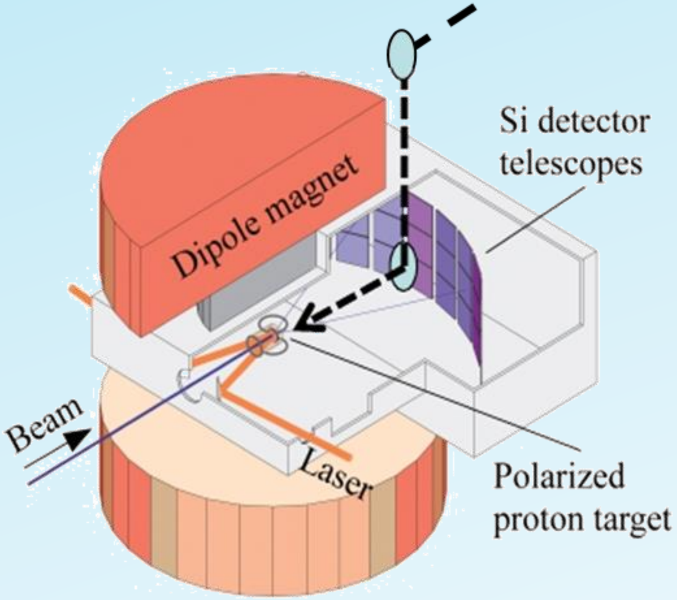
Towards low-E exp. with polarized protons

- **Polarized target requirements:**
  - Cooling gas -> Vacuum environment
  - Target thickness: 1mm -> 0.1 mm
  - Need to change the molecular axis by rotating it 90 deg to make the crystal less fragile



\- *Estimated polarization is ~13%*

- **Intercepting laser from SSD**
  - Thin foil?
  - Veto during laser irradiation?
  - Laser injection from 0 deg.?



Summary

- Proton resonant scattering from ^{9}C at 5.6 MeV/u with a spin-polarized proton target was proposed
- Low-lying level structure of ^{10}N (mass, E_R, Γ, J^{π}) will be revealed by analyzing power and excitation function
- Test experiment with unpolarized target was performed
  - Low energy 4 MeV/u 9C beam was produced at RIPS
  - Use of CH2 degrader increases beam intensity by factor of 1.8 (compare to standard Al degrader)
  - Data analysis is still in progress

Collaboration

Kyushu University
T. Teranishi
Y. Akiyama
T. Fukuta
D. Sakae
S. Sakaguchi
R. Kaku
Y. Norimatsu

CNS, Univ. of Tokyo
K. Abe
S. Hayakawa
N. Imai
D. Kahl
N. Kitamura
Y. Sakaguchi
H. Yamaguchi

RIKEN Nishina Center
T. Uesaka
H. Ueno
T. Kaneko
K. Yamada
D. Beaumel
Y. Ichikawa
K. Tateishi
M. Sasano
D. Kim

Kyungpook National Univ.
E. Milman
S. Chebotaryov
W. Kim

Ewha women Univ.
D.H. Kim

Oak Ridge National Laboratory
A. Galindo-Uribarri
E. Romero-Romero

JAEA
S. Hwang

Backups

Beta-delayed events

Beta decay of stopped 9C in the target:

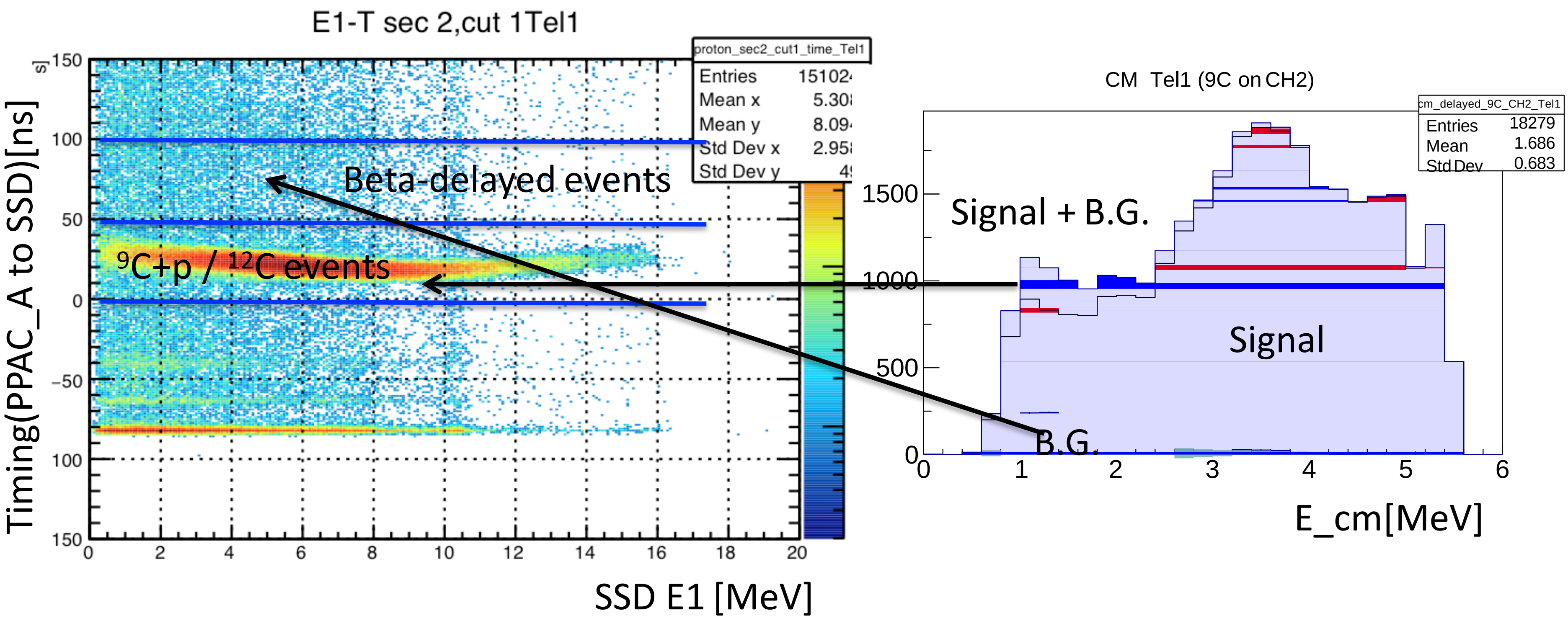
9C -> 9B* + β^+

9B* -> 5Li + α 9B* -> 8Be + p

α + α + p

Beta-delayed proton spectrum was evaluated by selecting events with different timing

Beta-delayed proton spectra were evaluated for C and CH2 targets.

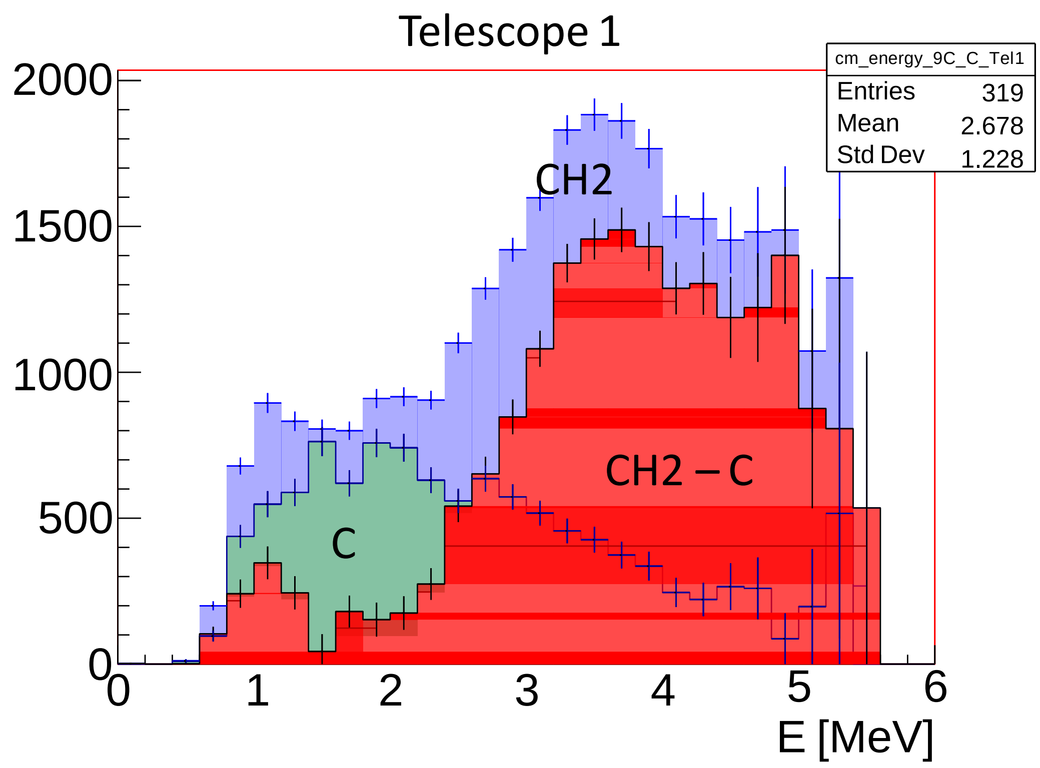


Delayed proton B.G. was successfully extracted

C background

Reactions of beam particles with C in the target

C target data was taken for B.G. subtraction



Angular spread due to multiple scattering

Angular spread

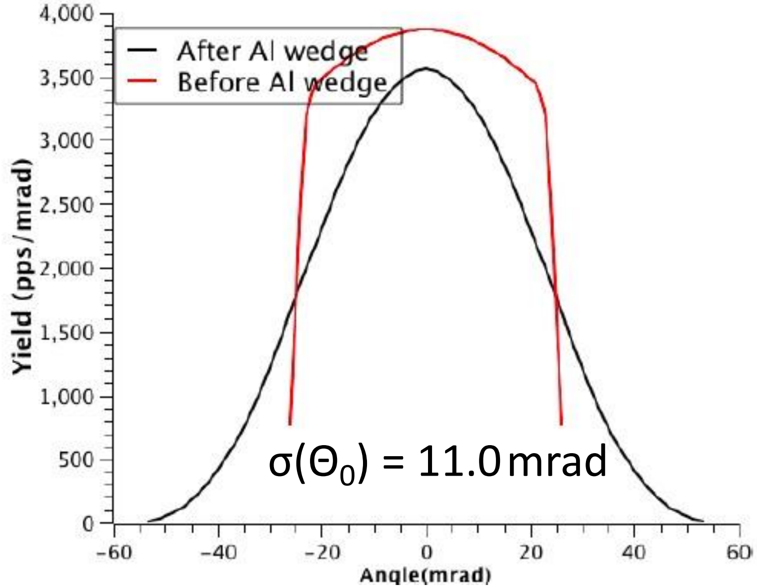
$$\theta_0 = \frac{13.6}{\beta c p} z \sqrt{x/X_0}\,[1 + 0.038 \ln(x/X_0)]$$

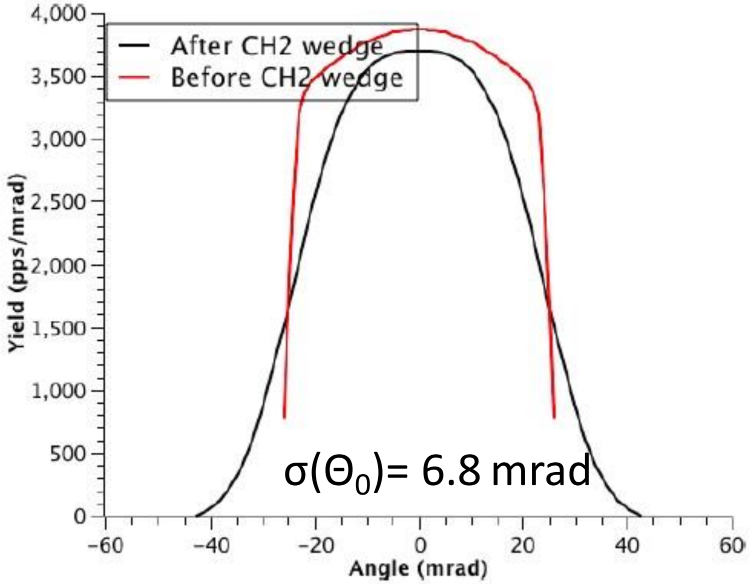
Radiation length

$$X_0 = \frac{716.4A}{Z(Z+1)\ln(287/\sqrt{Z})}.$$

Use lighter material for degraders such as CH_2 or Be

LISE++ simulation

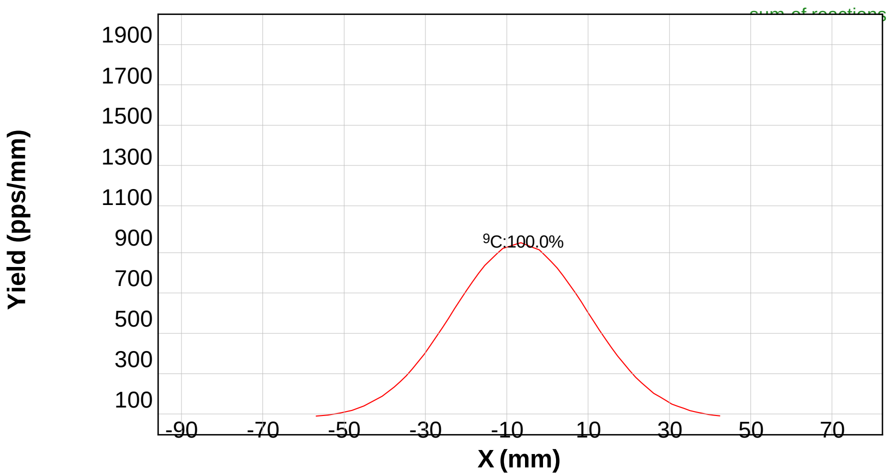




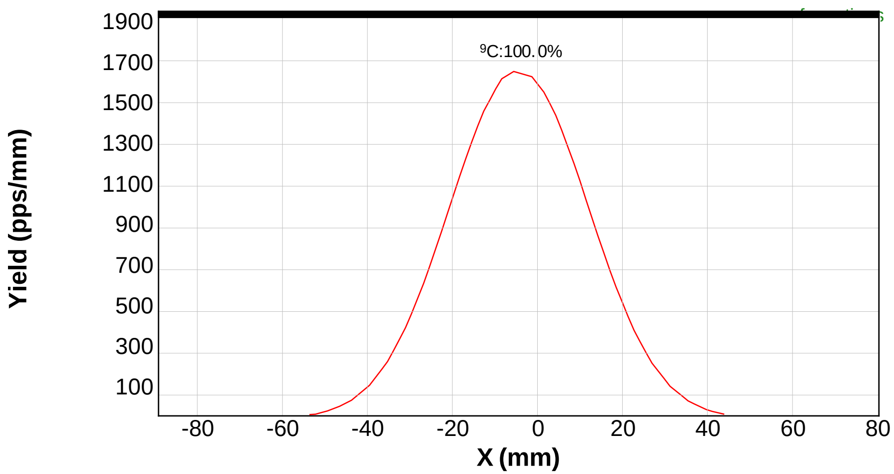
Smaller angular spread reduces positional spread at downstream

^{9}C beam intensity at F3 (LISE++ sim.)

~40k pps w/ Al-wedge at F3

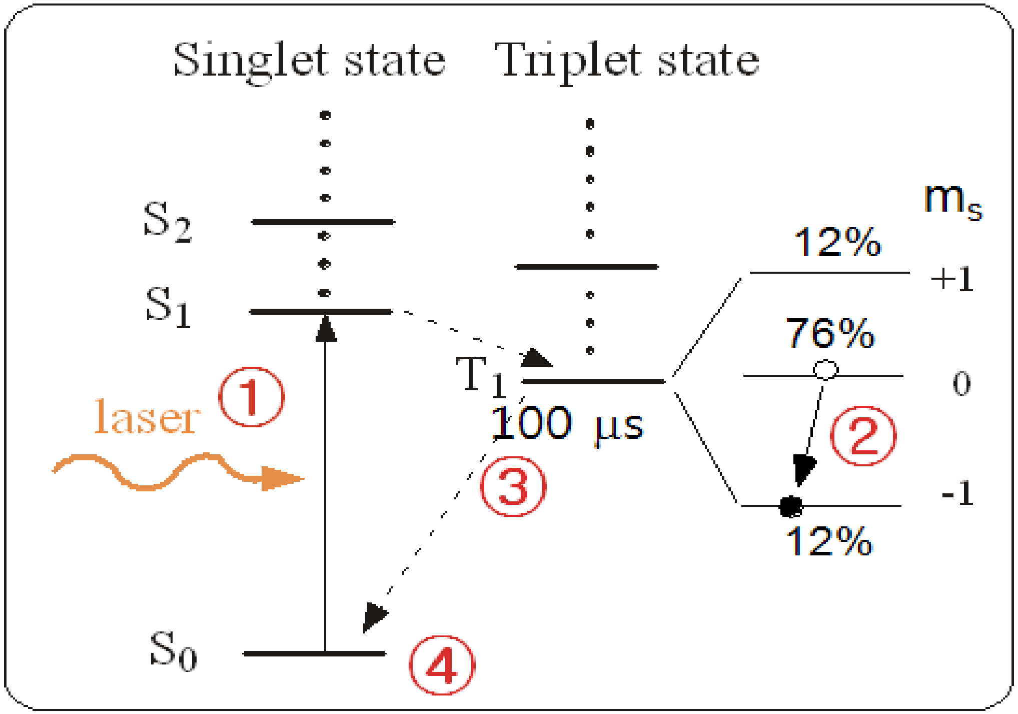


~80k pps w/ CH_2-wedge at F3



Gain factor of two is expected with CH2 degrader.

Research Development Procedures:
Solid Polarized Proton Target Using Optical Pumping



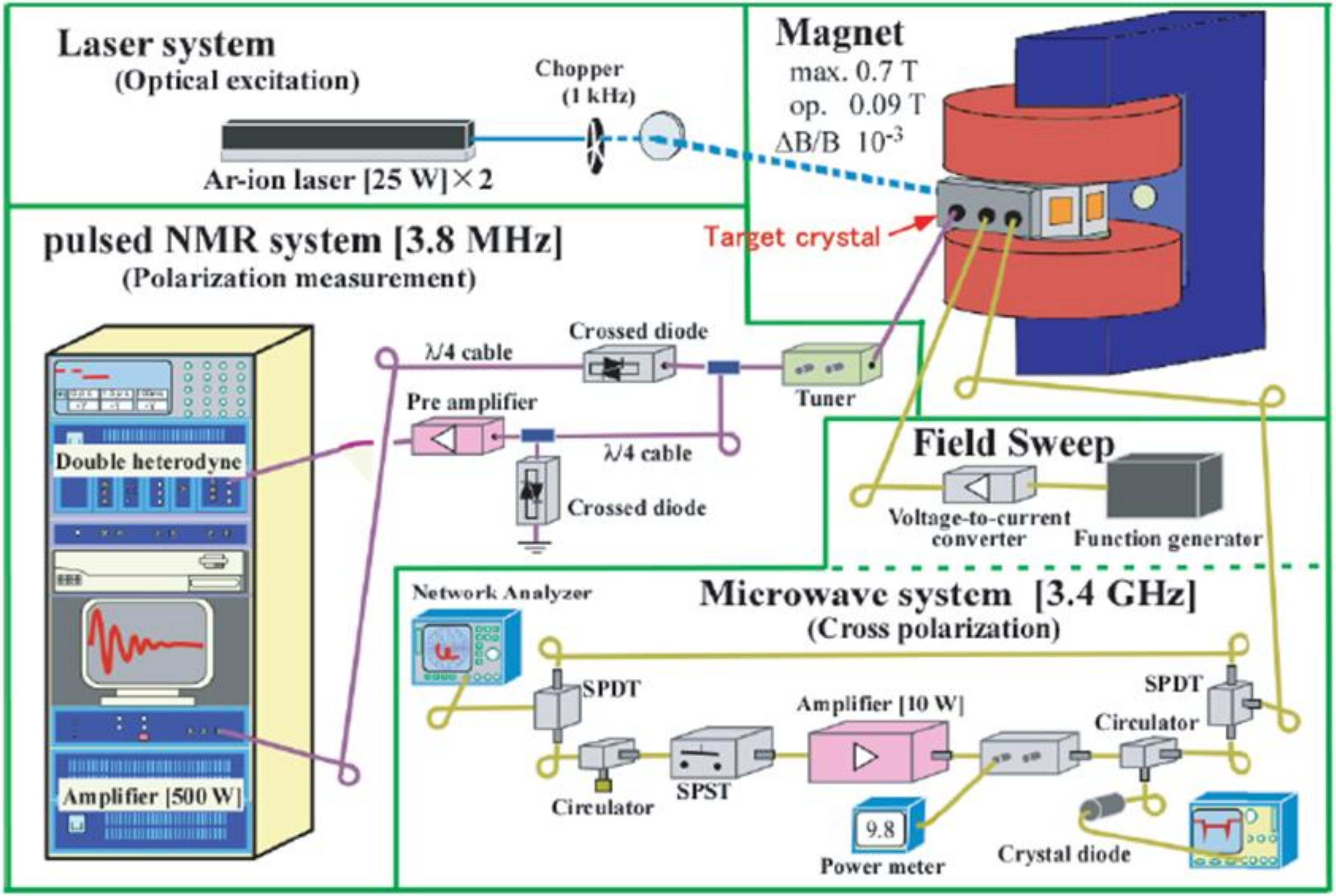
Solid pentacene target excitation model

1. Optical pumping excitation, electron population
2. Polarization transfer
3. Decay to ground state
4. Due to dipole interaction, polarization diffuses to the protons within the molecules

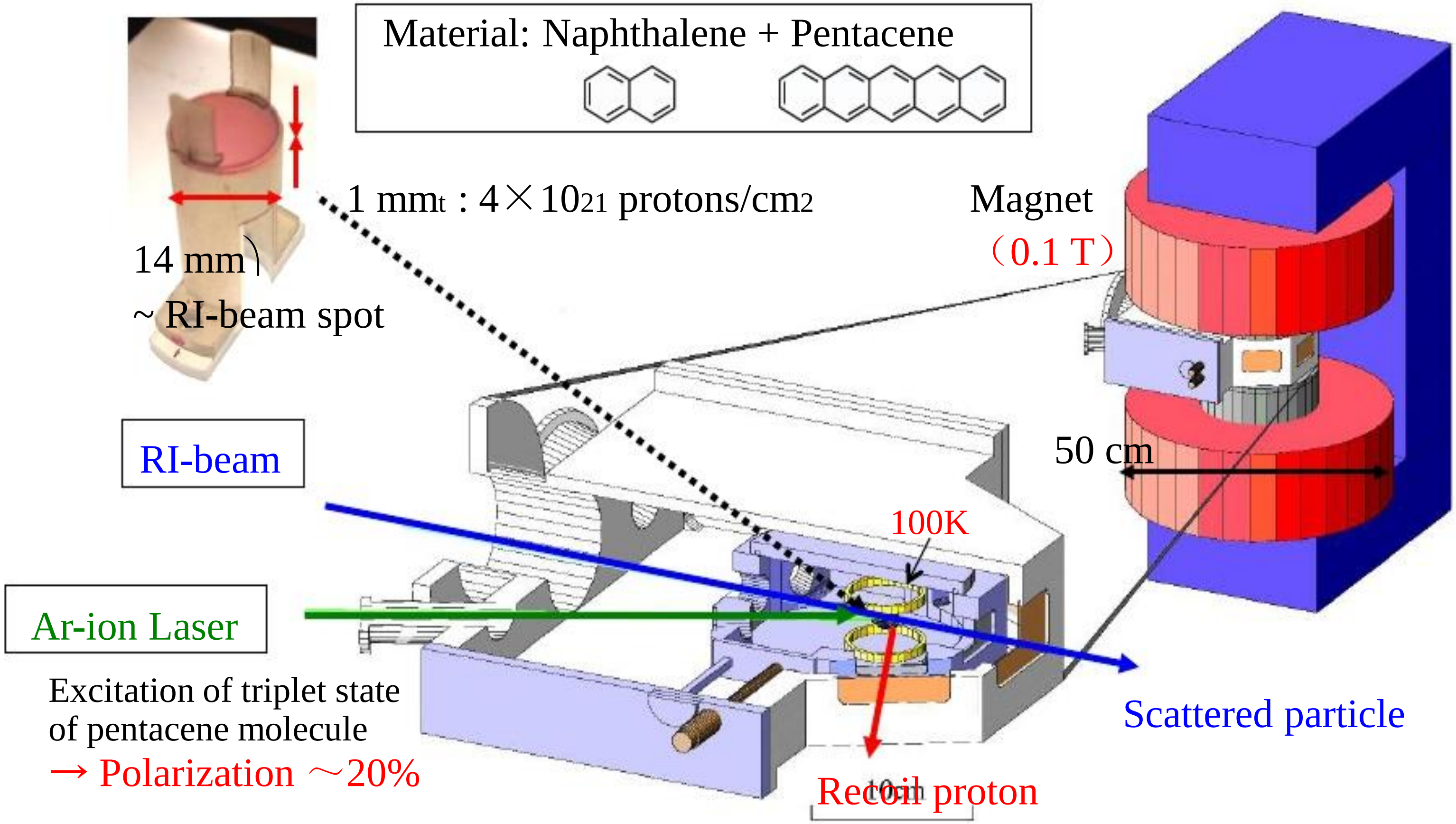
$$\left|\frac{\langle T_3|\mathcal{H}_{SO}|S_1\rangle}{E_{T_3}-E_{S_1}}\right|^2$$

Due to spin orbit coupling: singlet→triplet

Solid Polarized Proton Target for RI Experiments



Solid polarized proton target @RIKEN/CNS



T. Wakui et al., NIM A 550 (2005) 521.
T. Uesaka et al., NIM A 526 (2004) 186.