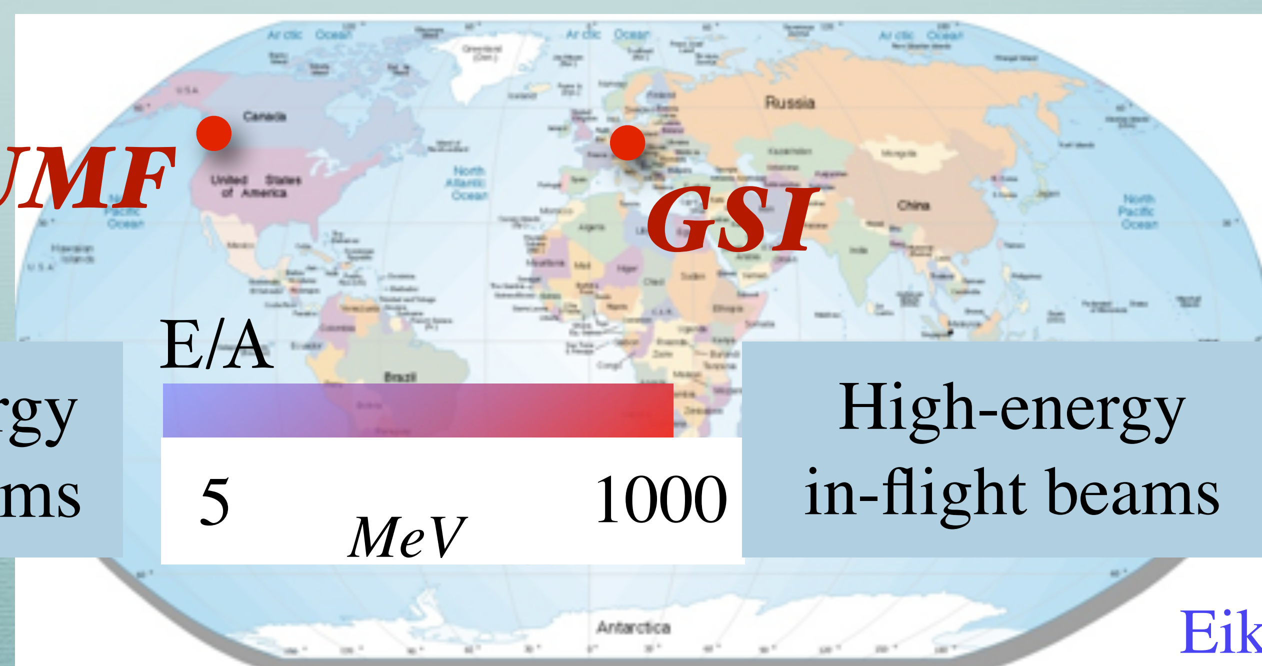
Nuclear structure and nuclear force probed through direct reactions of light rare isotopes

R. Kanungo

Saint Mary's University / TRIUMF



Nuclear Orbitals
Excited States
Elastic Scattering
Born Approximation

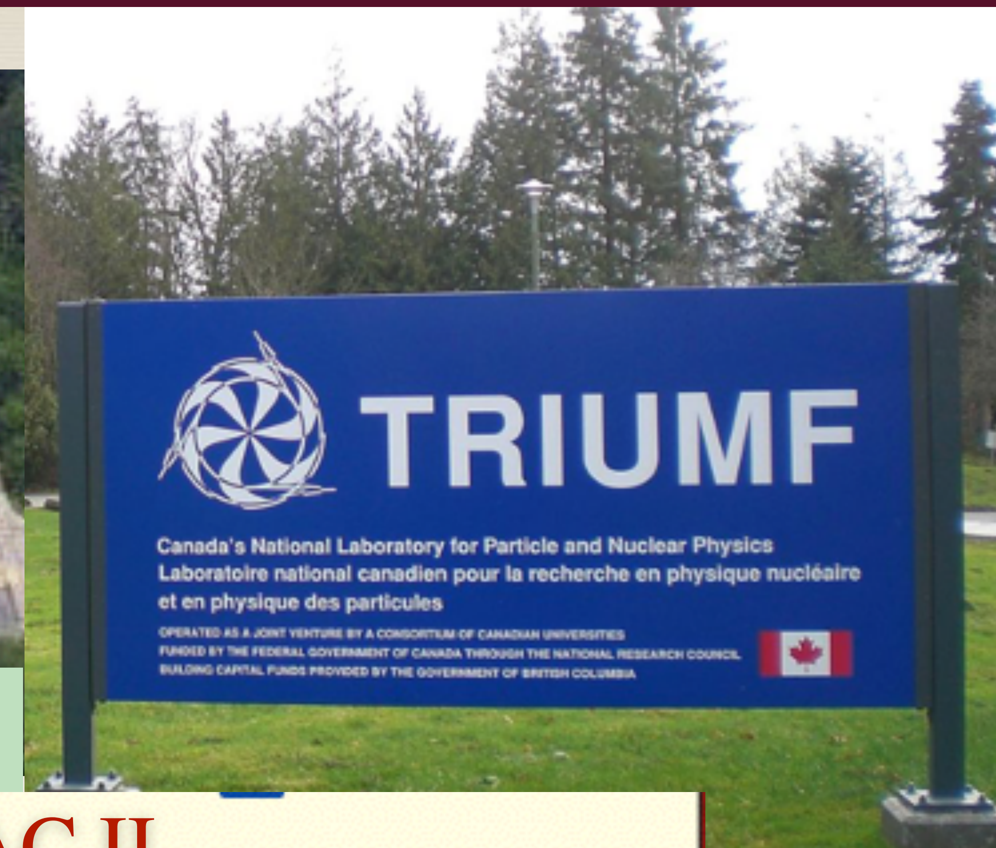
Low-energy
ISOL beams

High-energy
in-flight beams

Nuclear Radii
Nuclear Orbitals
Eikonal Approximation

TRIUMF - ISAC / ARIEL

High Quality, Low-energy re-accelerated RI beams

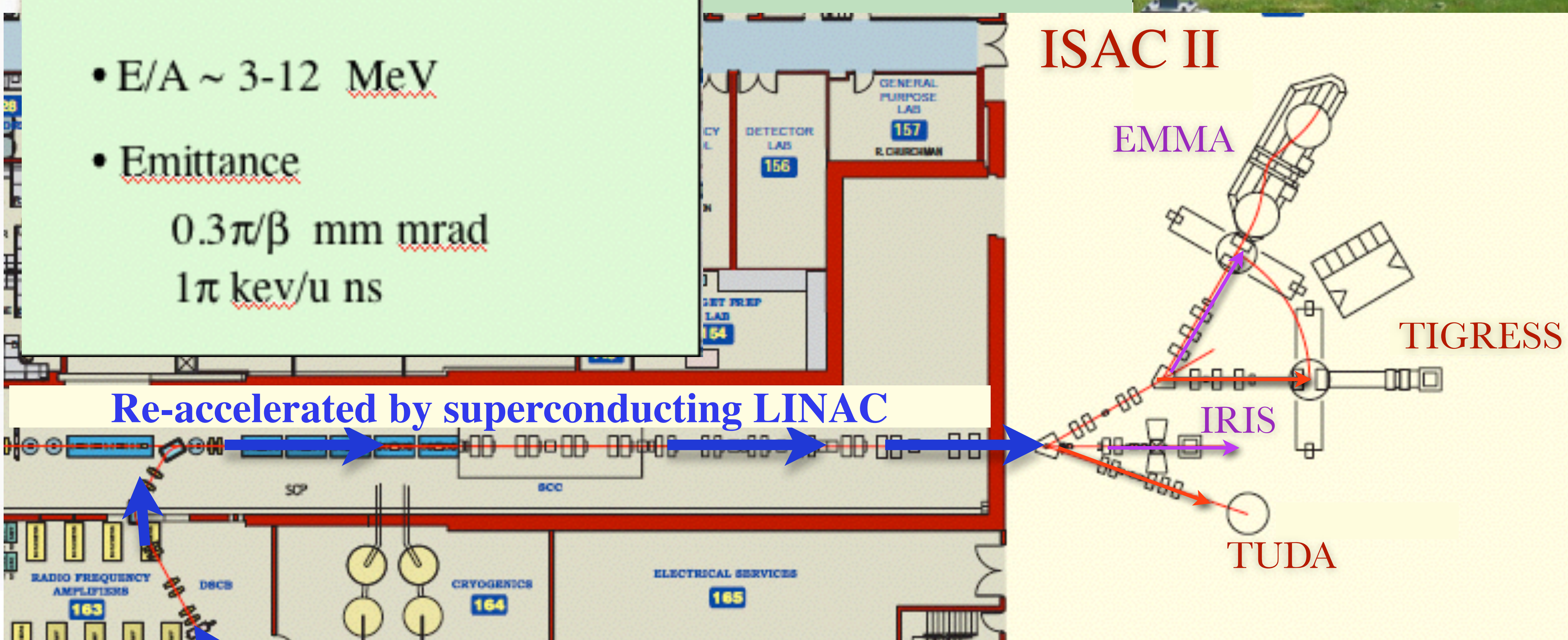


- E/A ~ 3-12 MeV
- Emittance

  0.3π/β mm mrad

  1π kev/u ns

Re-accelerated by superconducting LINAC



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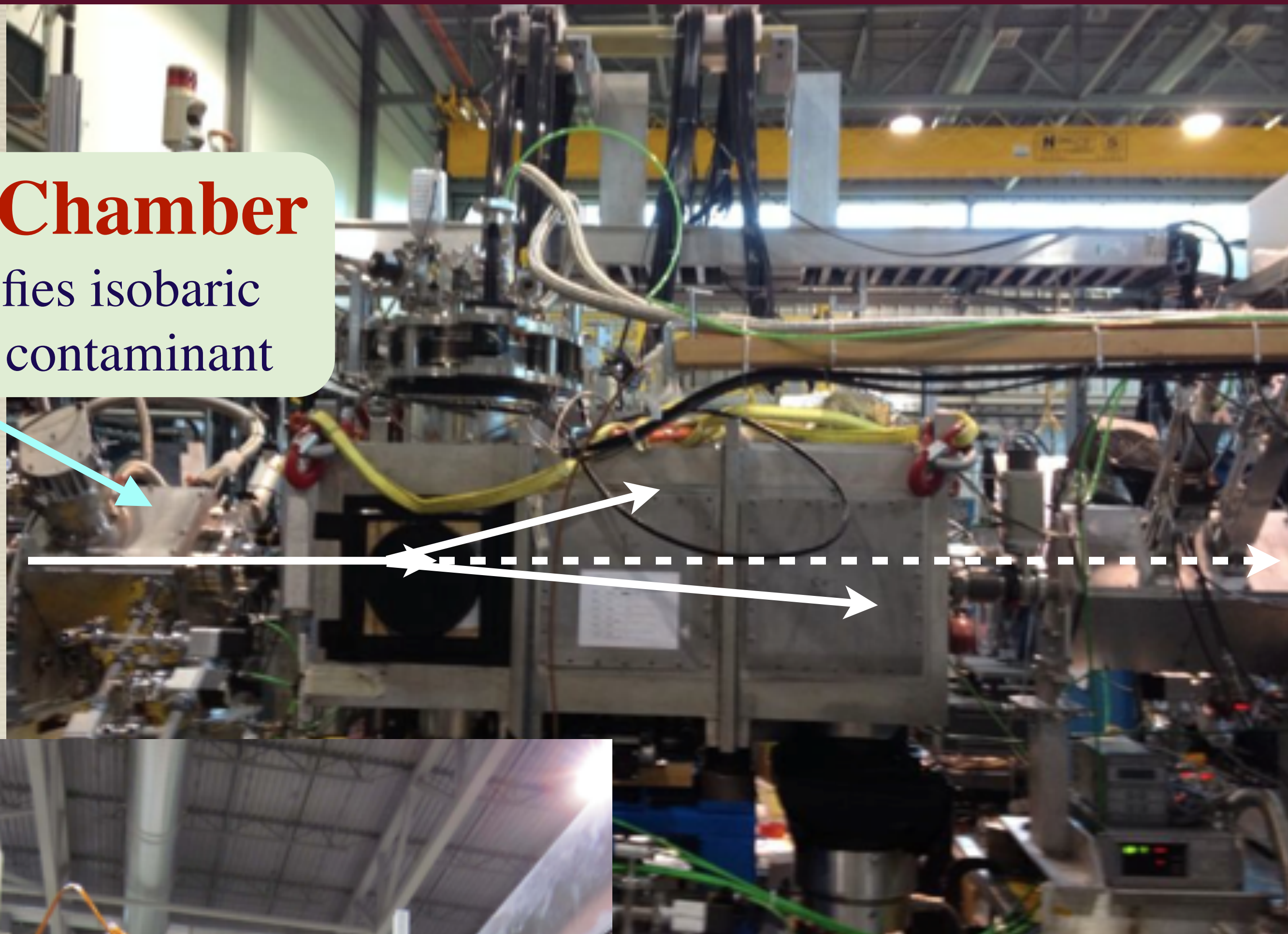
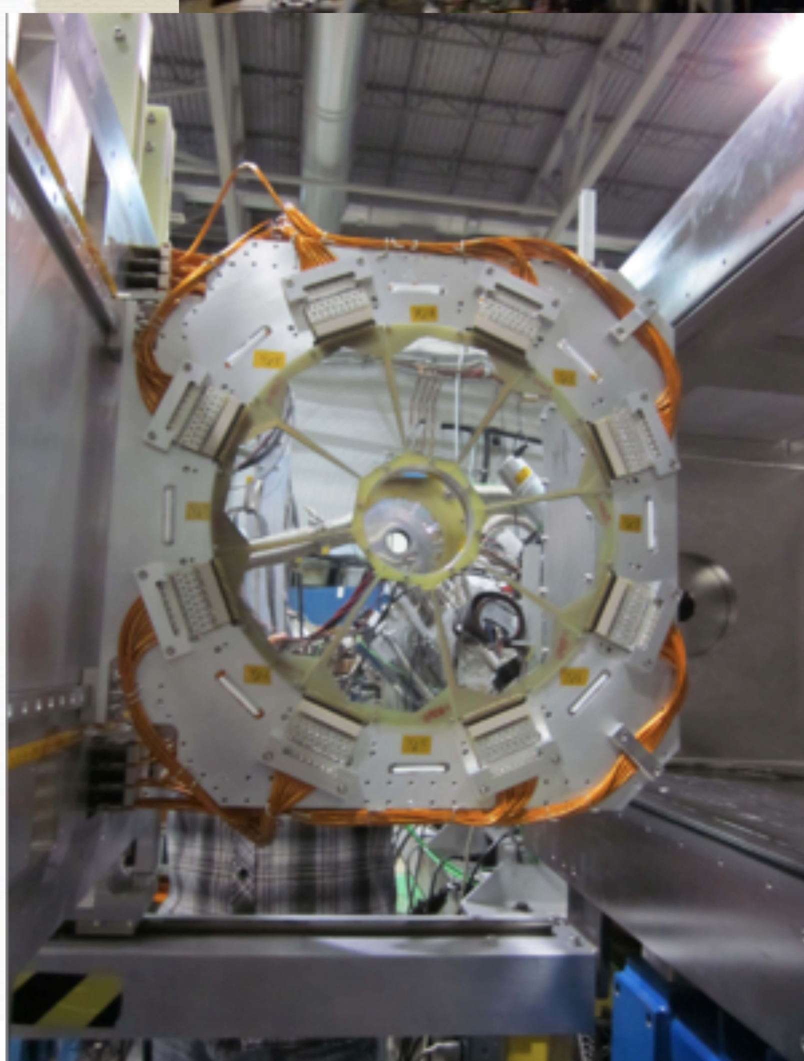
IRIS Reaction spectroscopy station

Ion Chamber

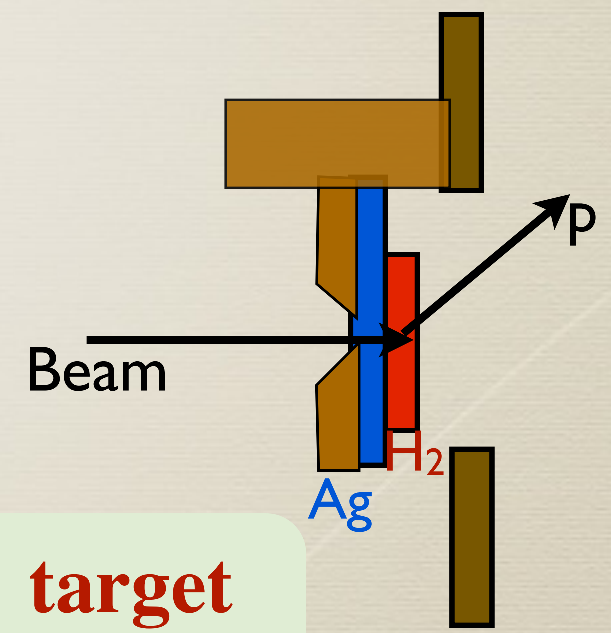
Identifies isobaric beam contaminant





4K

100 μm H_2



Unique Feature

Thin windowless Solid H_2/D_2 target

Higher reaction yield

Negligible background

Program @ IRIS

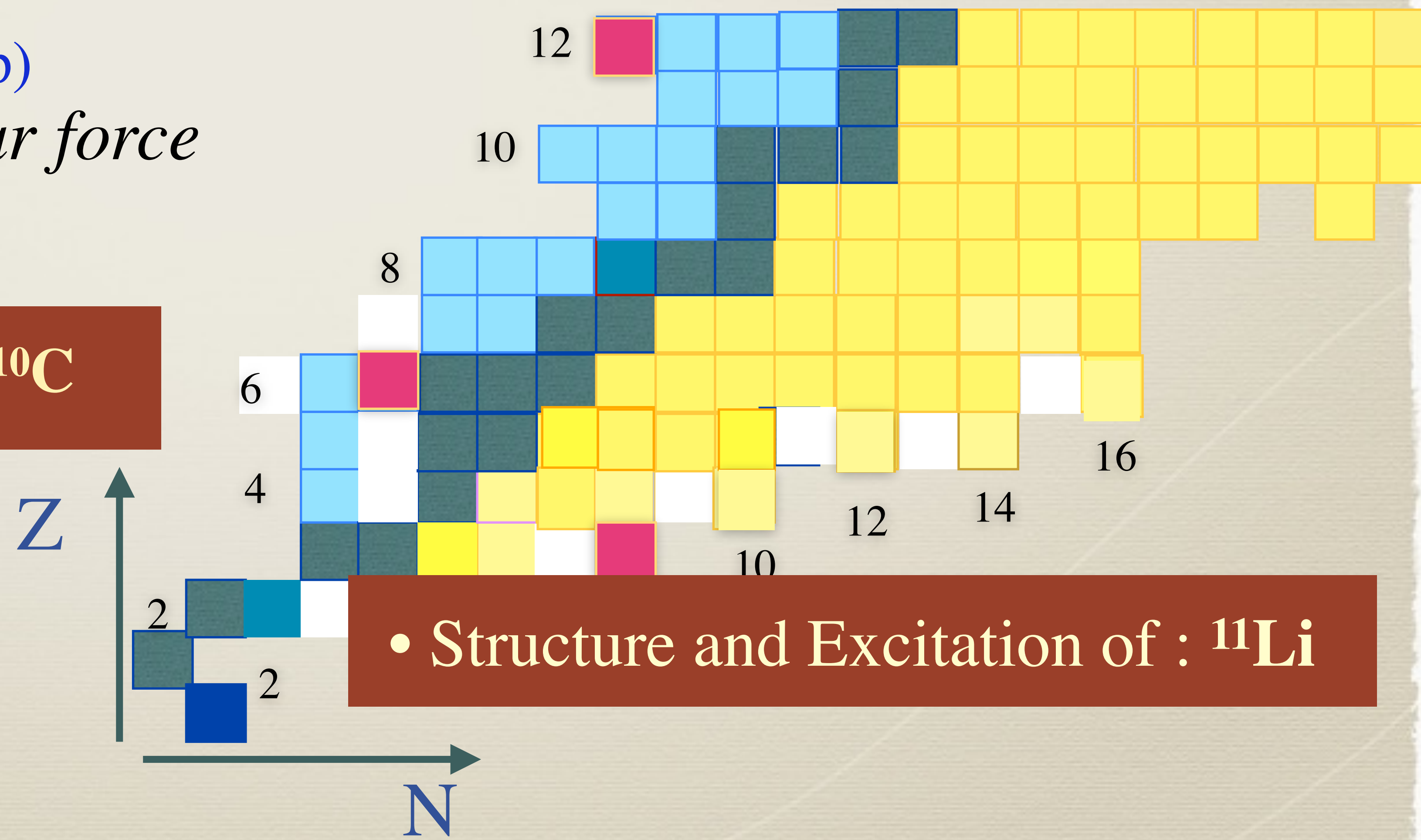
- Transfer Reactions (p,d) , (p,t), (d,p), (d,t)
  Evolution of nuclear shells
  Exploring pairing correlation
  Constraining reactions rates for nucleosynthesis

- Inelastic Scattering (p,p') , (d,d')
  Search for new excited , resonance states

- Elastic Scattering (p,p)
  Constraining the nuclear force

• Resonance in : ^{20}Mg

• Nuclear Force : ^{10}C



• Structure and Excitation of : ^{11}Li

Soft dipole resonance in ^{11}Li

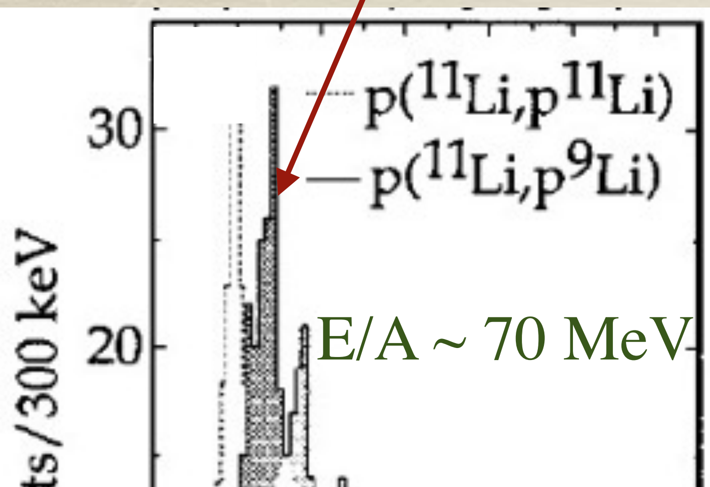
excitation in the neutron continuum

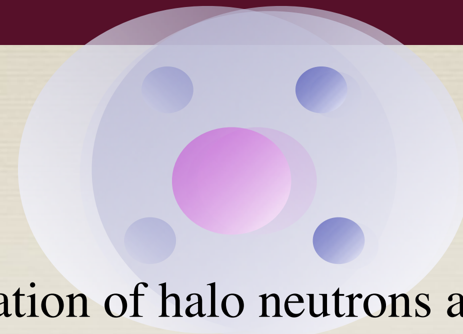
E* = 1.3 ±0.1 MeV,

Γ = 0.75 ± 0.6 MeV

Resolution

FWHM ~ 1.5 MeV

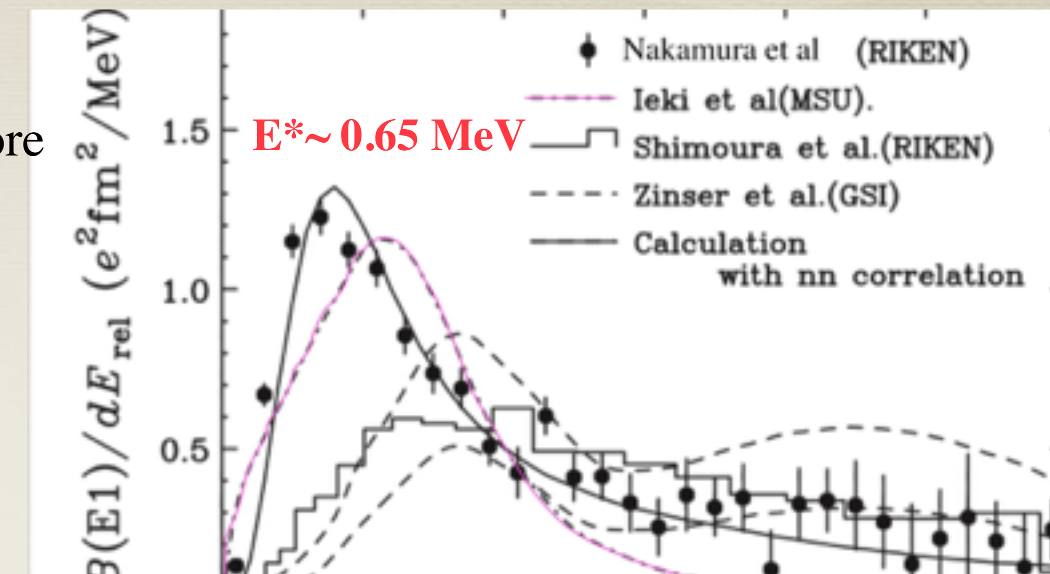




Oscillation of halo neutrons and core

Poor resolution :
Resonance or
enhancement ?

$^{11}Li + ^{208}Pb \rightarrow ^{9}Li + n + n$

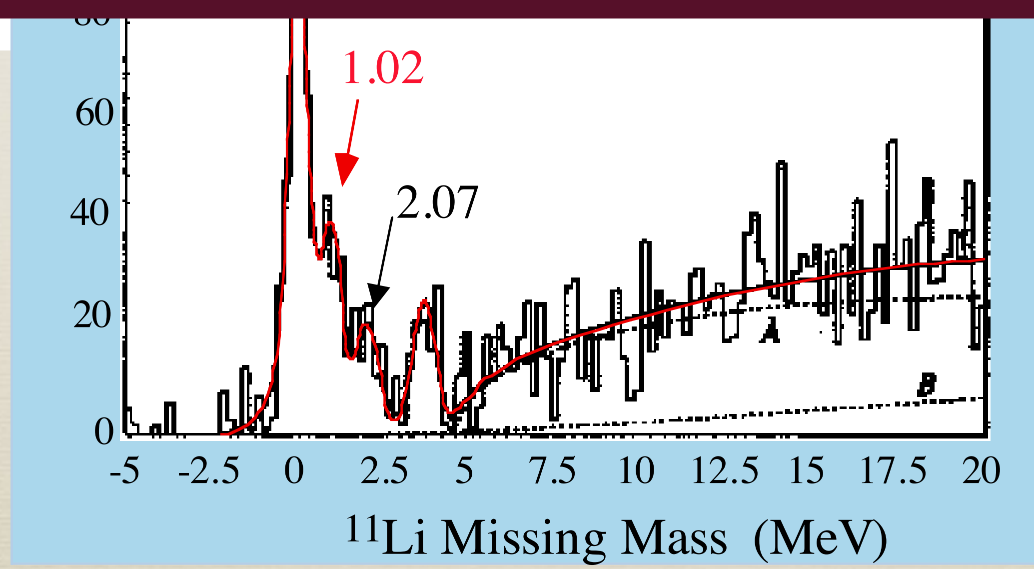


Two decades of various searches did not reach conclusive understanding

Can the neutron-rich surface sustain a low-energy soft dipole resonance ?

Excitation energy

A.A. Korsheninnikov et al, PRC 53('96)R537 ; PRL 78(97)2317

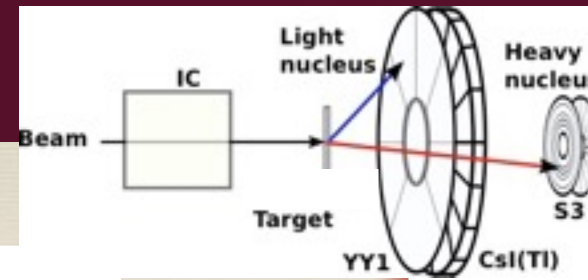


M.G. Gornov et al. PRL 81 (1998) 4325

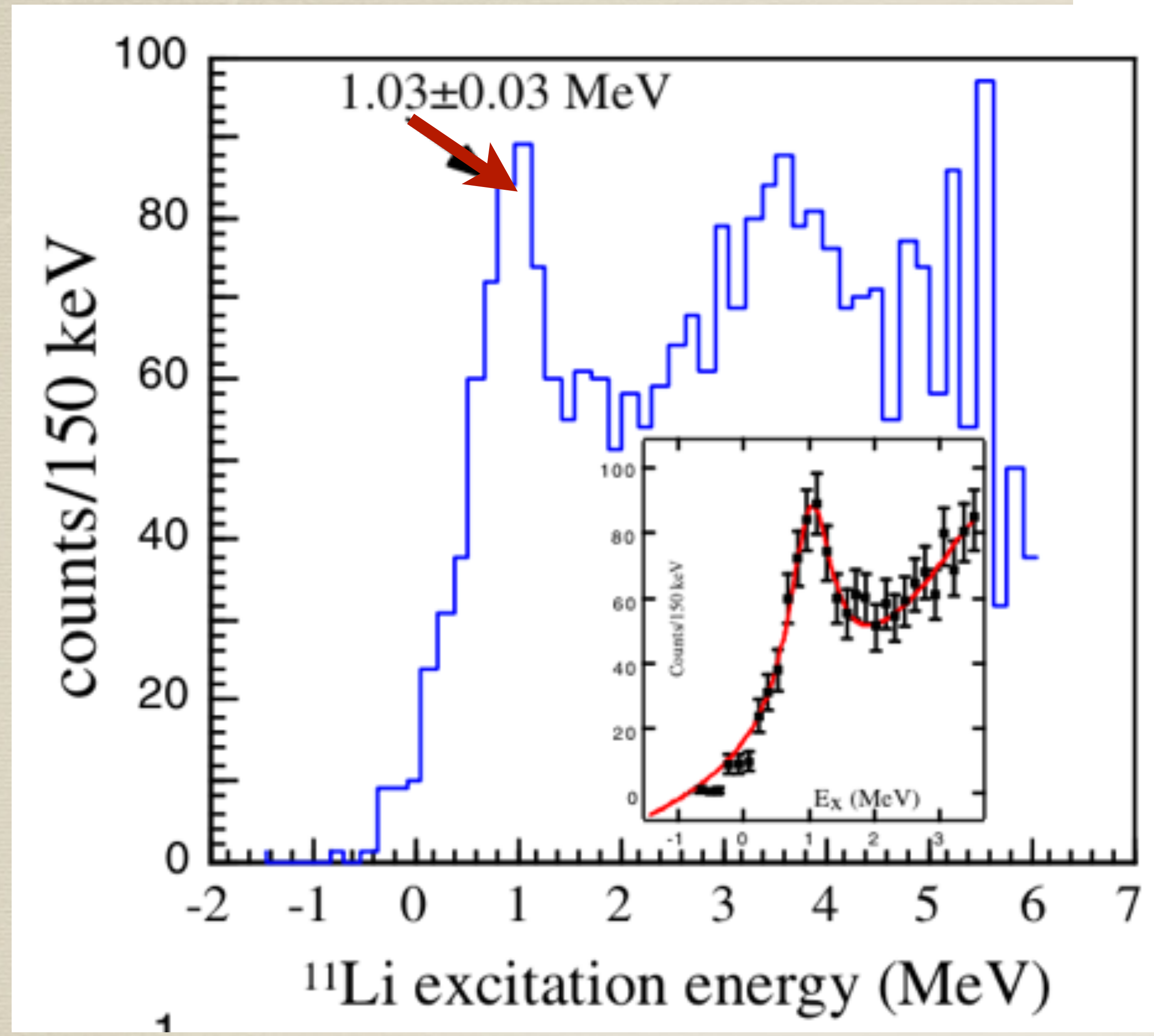
Non-resonant peak or Resonance ?

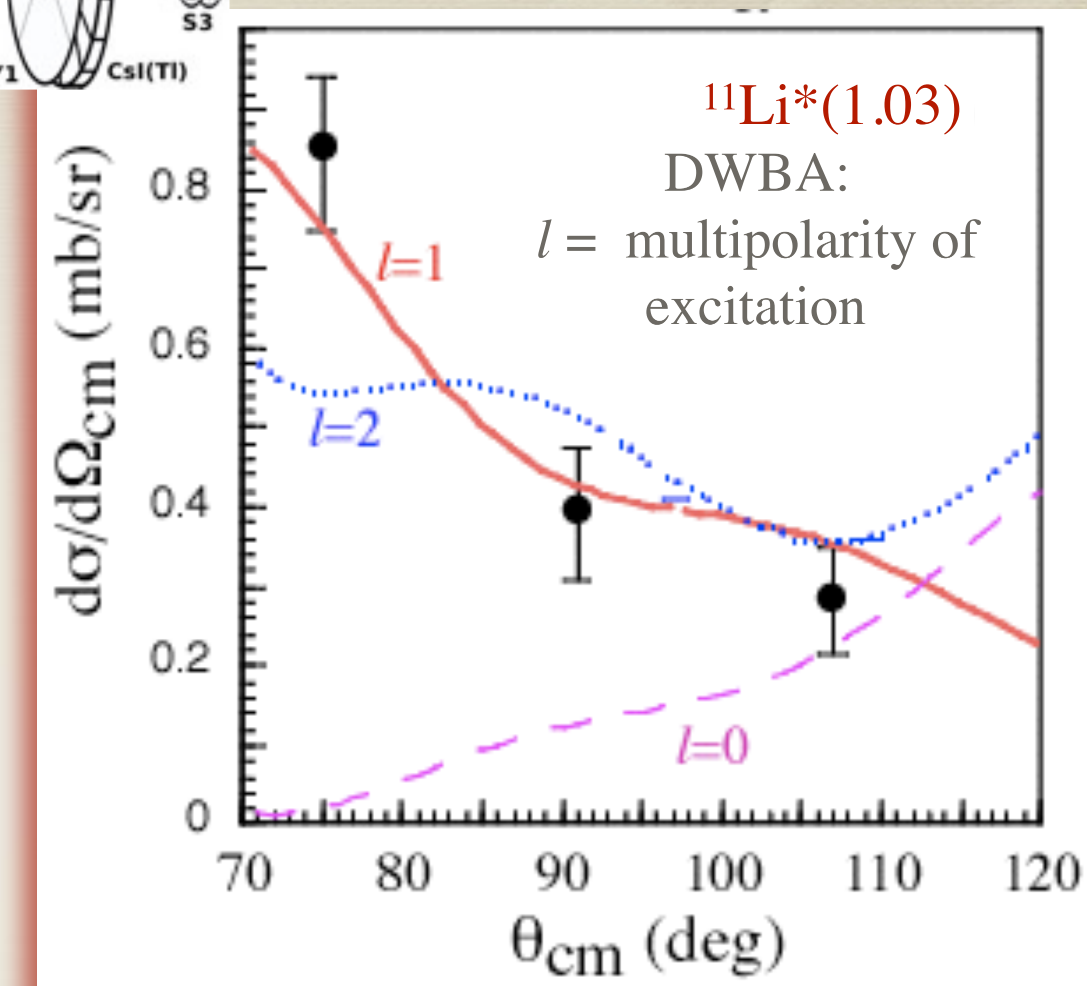
Dipole Resonance not known

^{11}Li(d,d') *first measurement* *E/A ~ 5 MeV*



d + ^{9}Li





Dipole Excitation

$$V_L(R) = -\frac{\delta_L}{\sqrt{4\pi}}\frac{dU(R)}{dR}$$

Resonance Peak @ ~ 1.03(03) MeV

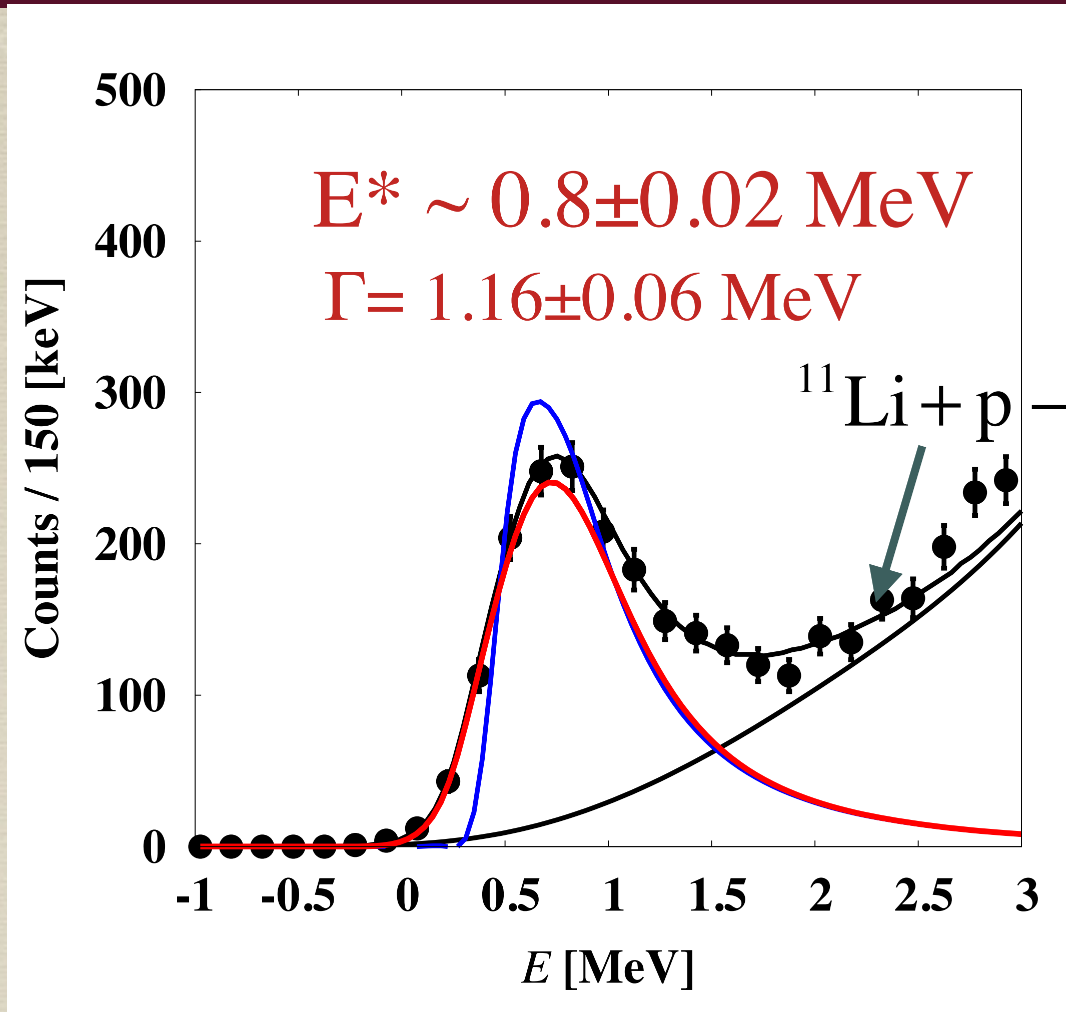
Γ = 0.51(11) MeV

R. Kanungo et al., Phys. Rev. Lett. 114 (2015) 192502

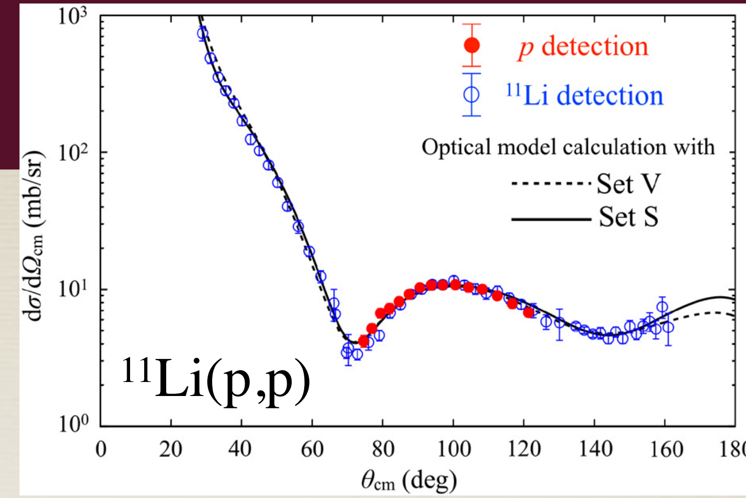
(d,d') ΔT = 0

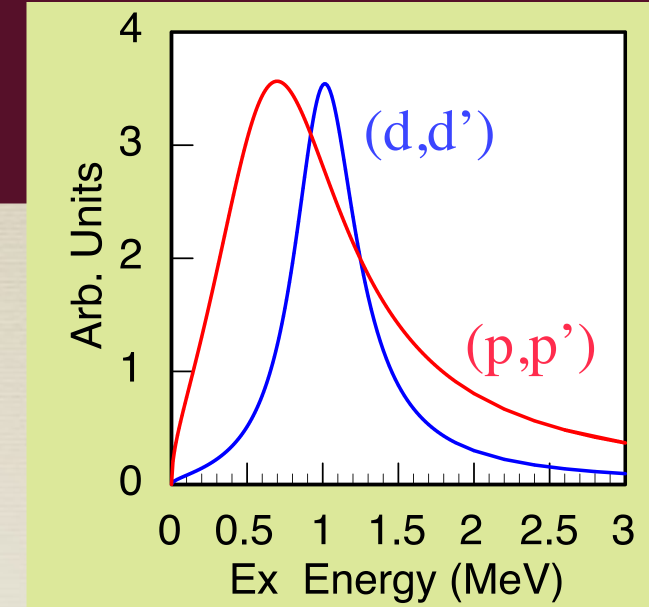
Isoscalar Soft Dipole Resonance Observed

^{11}Li(p,p') E/A = 6 MeV

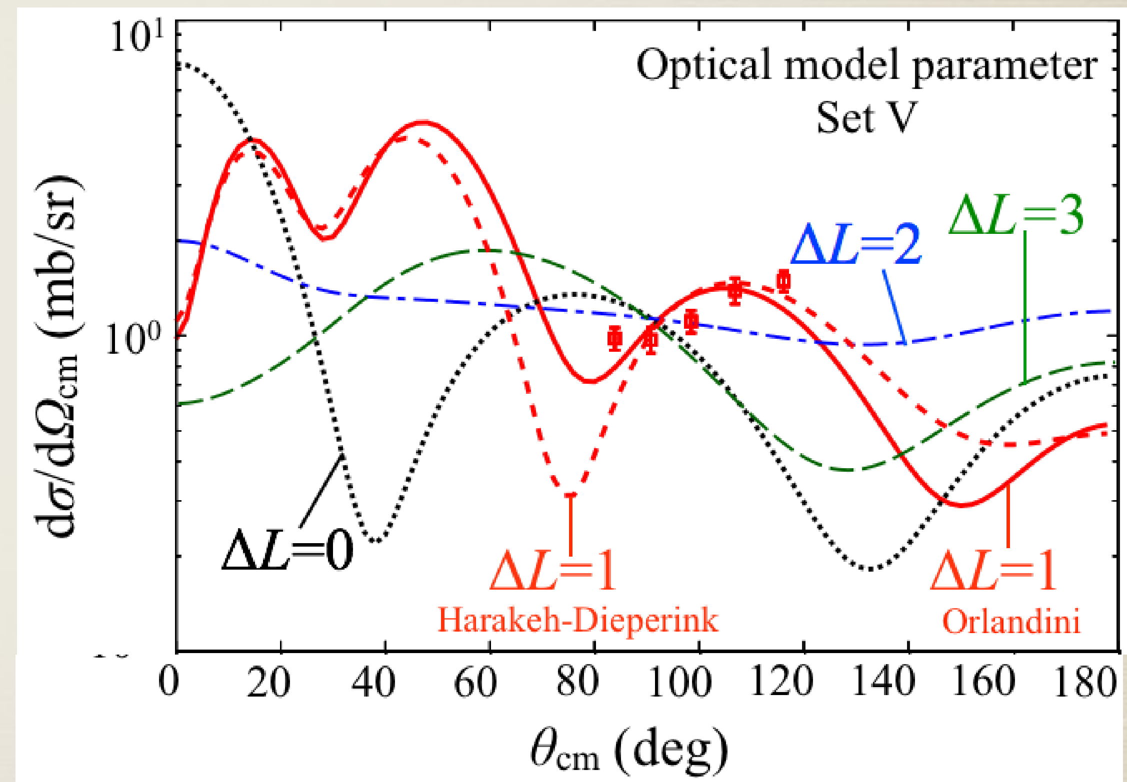


$$^{11}\mathrm{Li} + p \rightarrow {}^{9}\mathrm{Li} + n + n + p$$





J. Tanaka et al. Phys. Lett. B 774 (2017) 268

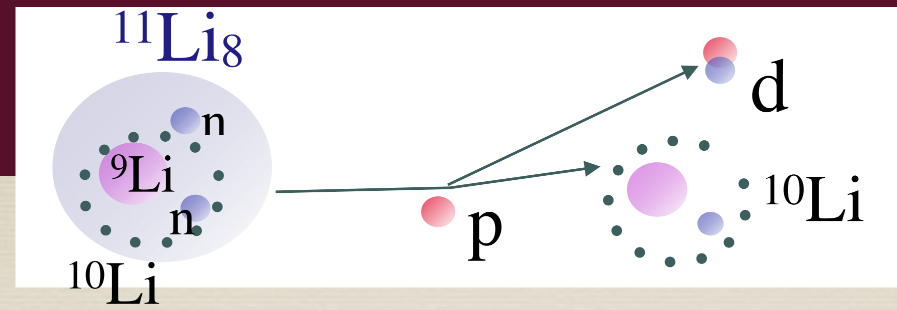


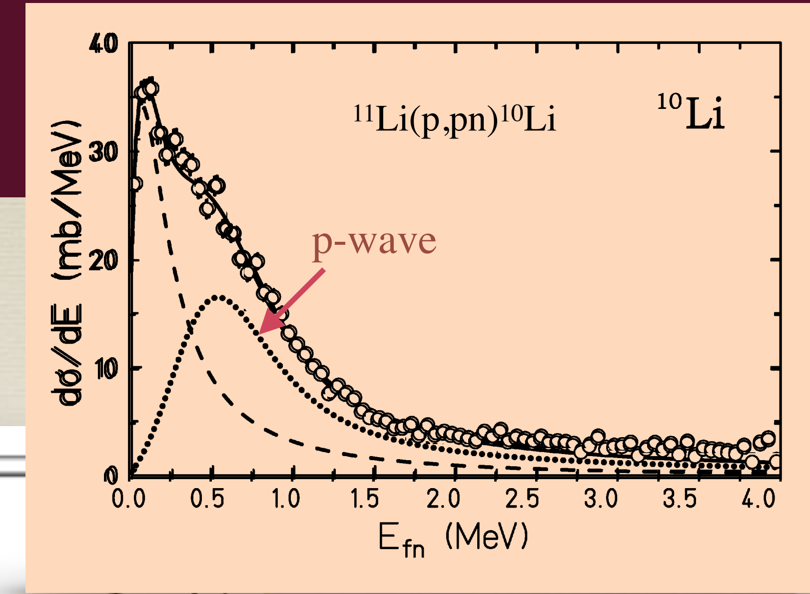
Large IS Diople Transition Strength : 1300 - 2600 e^2fm^6 (30-296 W.u.)

Agreement with halo model description of halo in ^{11}Li

2% - 21% IS - EWSR

^{11}Li(p,d)^{10}Li

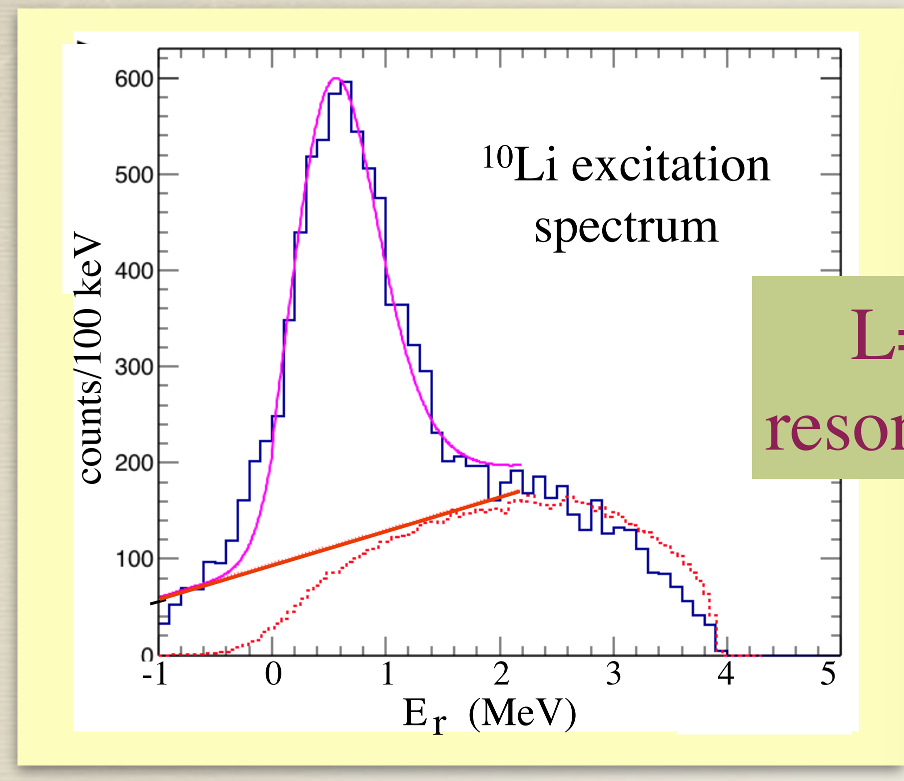




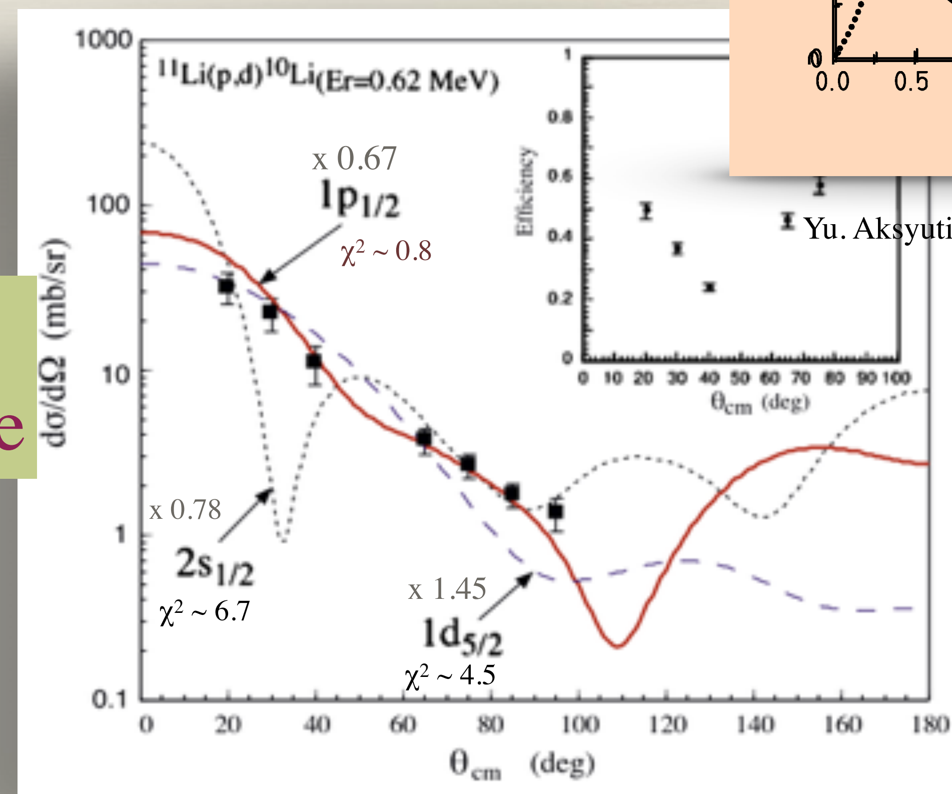
Yu. Aksyutina et al., Phys. Lett. B 666 (2008) 430.

$E_r = 0.62 \pm 0.04$ MeV

$\Gamma = 0.33 \pm 0.07$ MeV



L=1 resonance



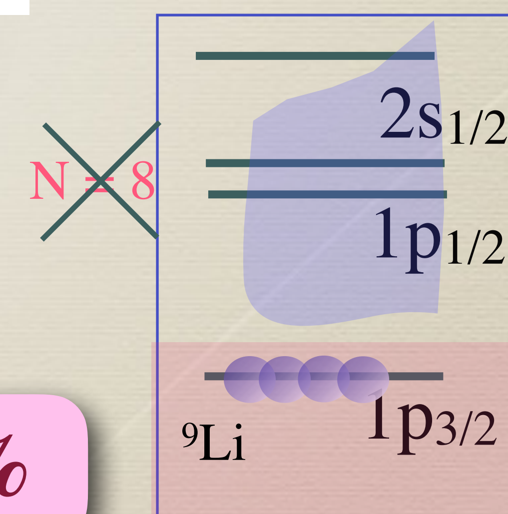
Full p-wave strength in observed peak

$$(d\sigma/d\Omega)_{ex} = S \times (d\sigma/d\Omega)_{DWBA}$$

$$S(p_{1/2})^2 = 0.67 \pm 0.12$$

smaller than 100%, deviating from conventional shell picture

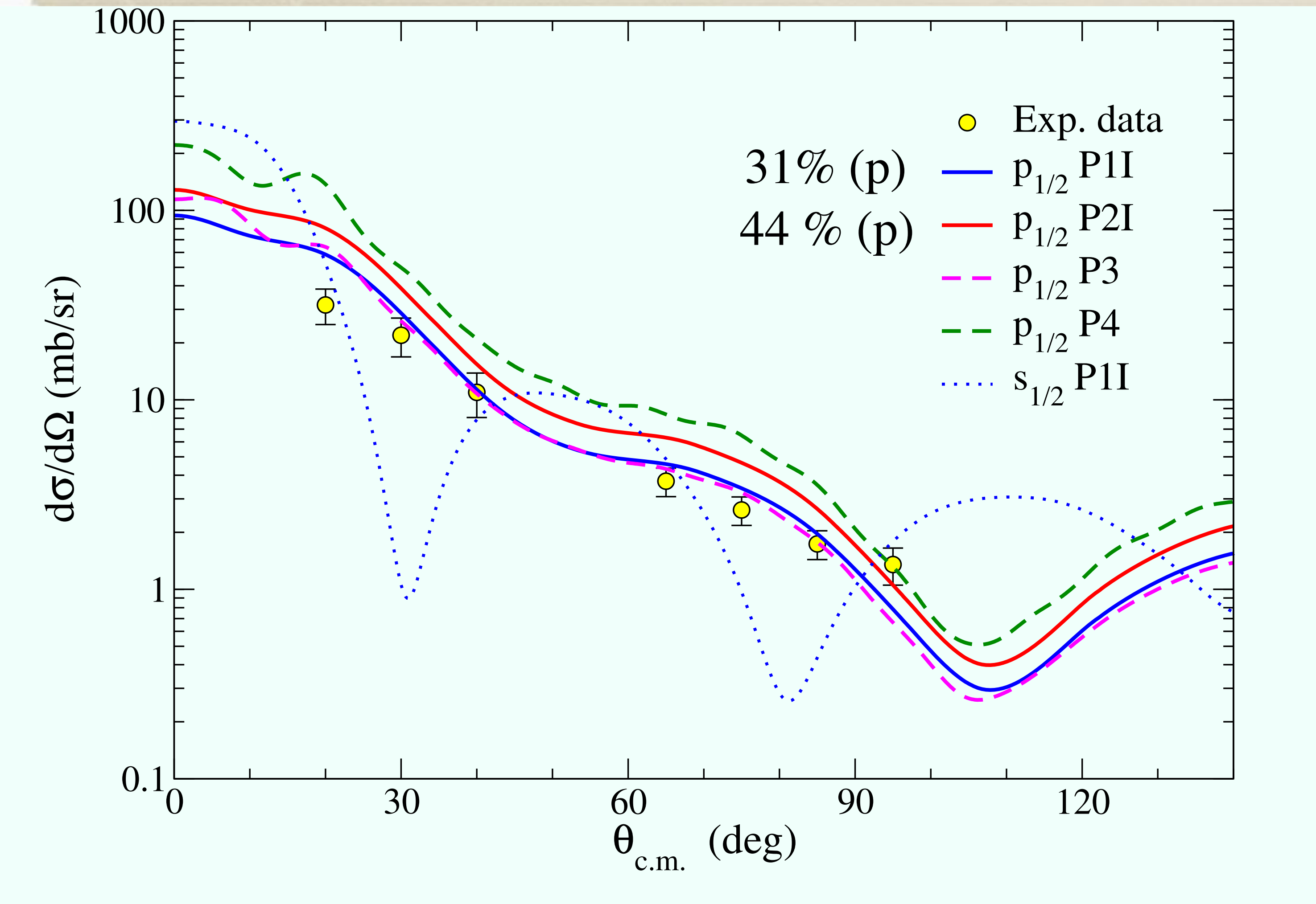
$(p_{1/2})$ % = 33(12) %



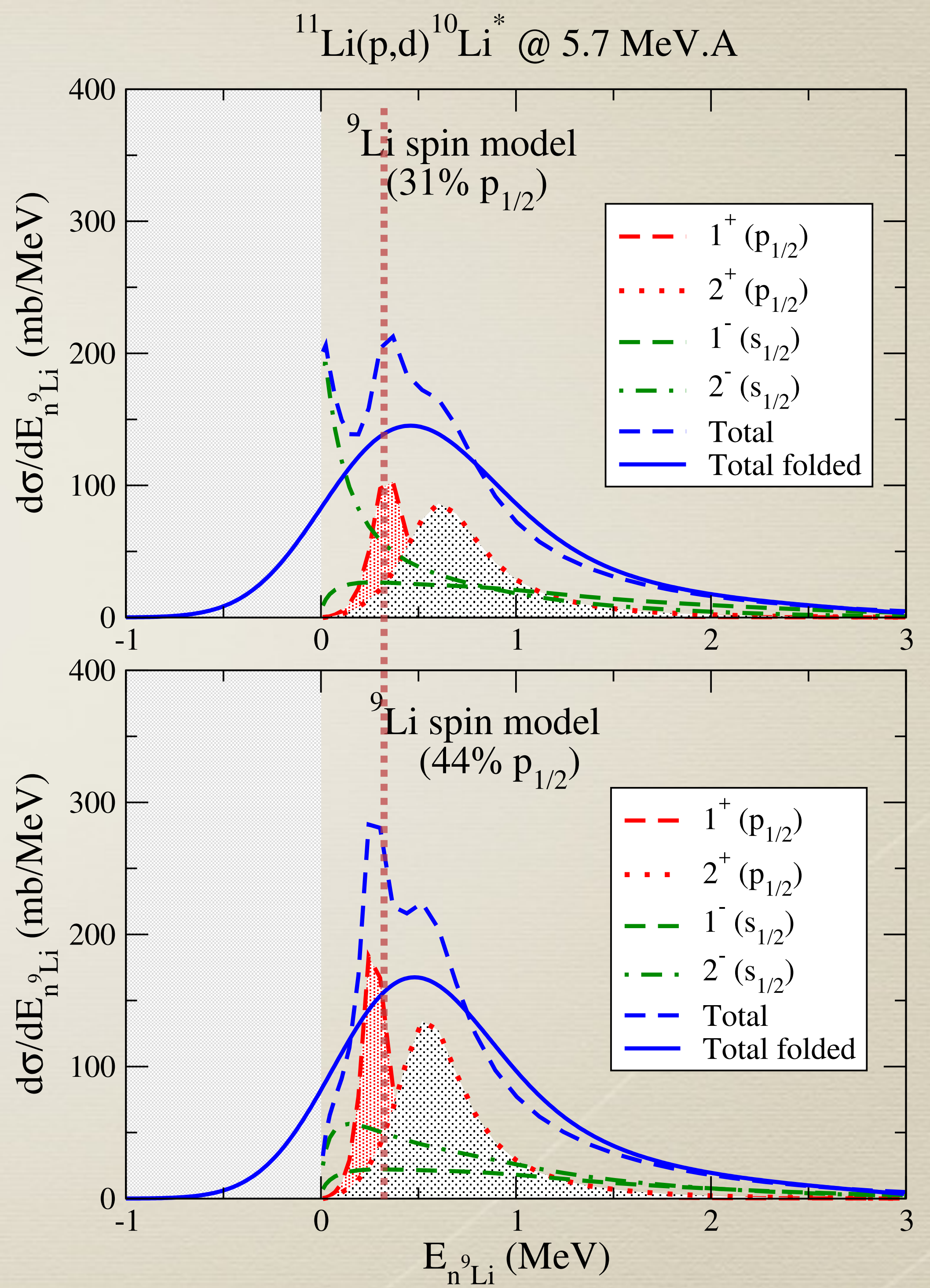
N = 8 shell gap broken

A. Sanetullaev et al., Phys. Lett. B 755 (2016) 481

$^{11}Li(p,d)^{10}Li$: in 3-body model

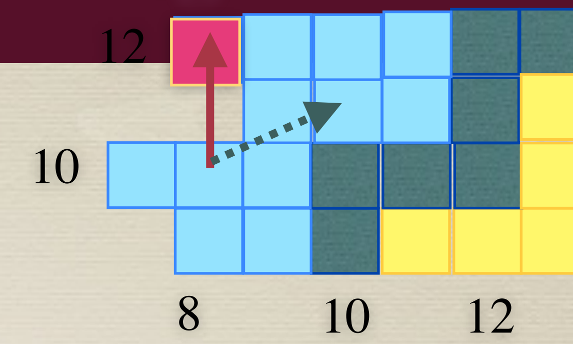


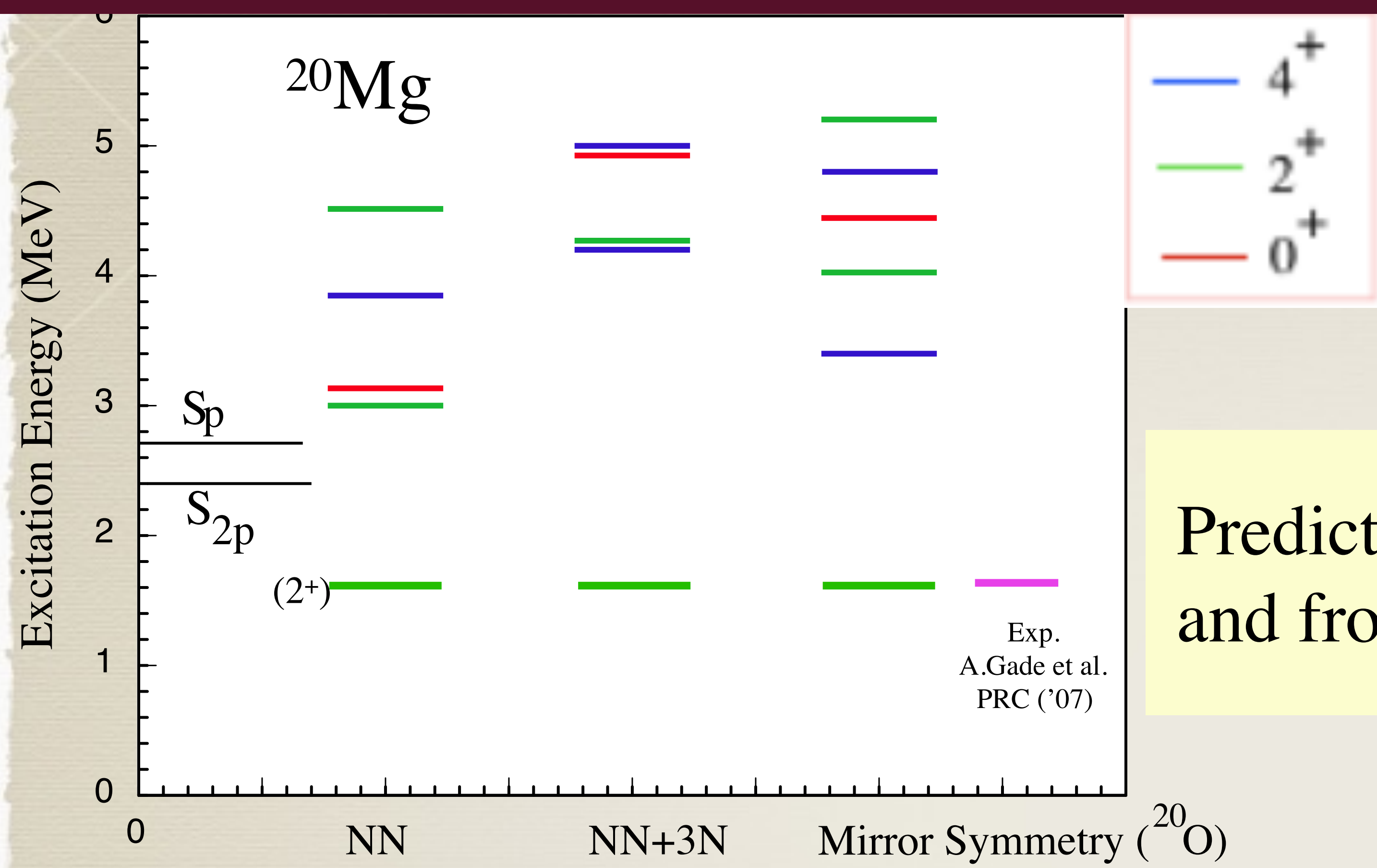
J.Casal, M. Gomez-Ramos, A.M.Moro PLB 767 (2017) 307



- 31% $p_{1/2}$ prediction consistent with $d\sigma/d\Omega$
- Both 1^+ and 2^+ resonances in (p,d) peak

^{20}Mg(d,d’) : Search for resonance in ^{20}Mg





MBPT
J.D. Holt et al.
PRL 110 ('13)022502

J. Gorres et al.
PRC 51 ('95)392

Predictions with chiral NN, NN+3N forces and from mirror symmetry differ widely

Mass Measurement (^{20}Mg) :

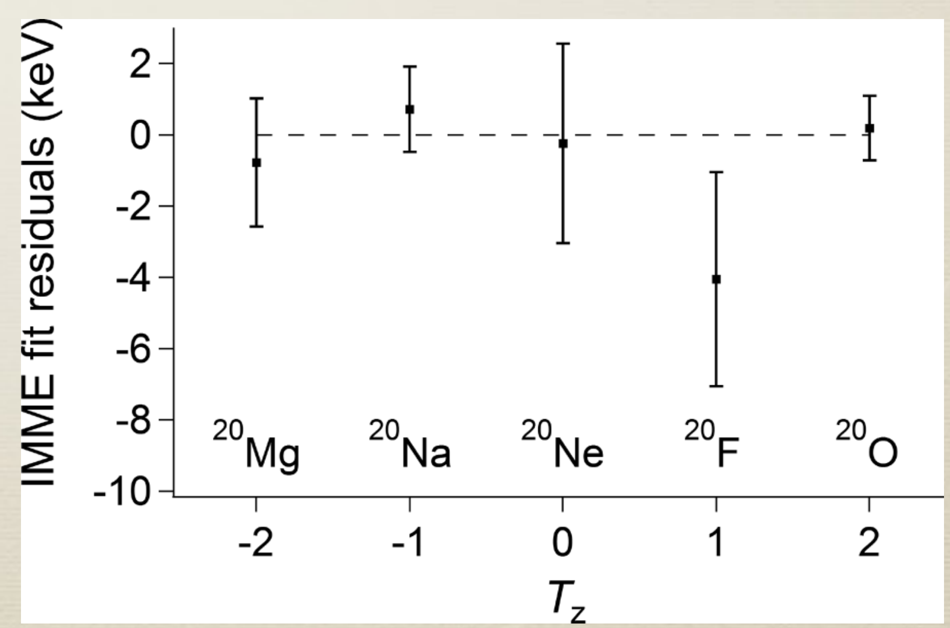
A=20 IMME breakdown

A.T. Gallant et al., PRL 113(’14) 082501

β^+ Measurement (^{20}Mg) :

A=20 IMME valid

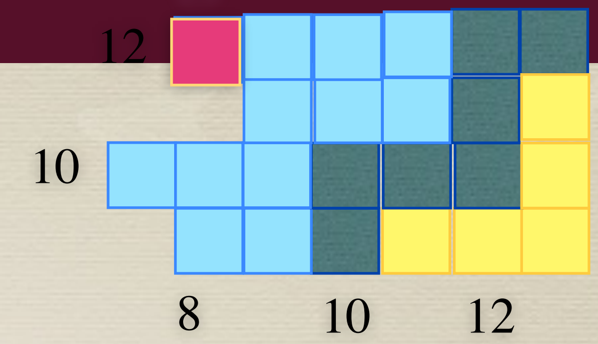
B.E. Glassman et al., PRC 92 (’15) 042501R



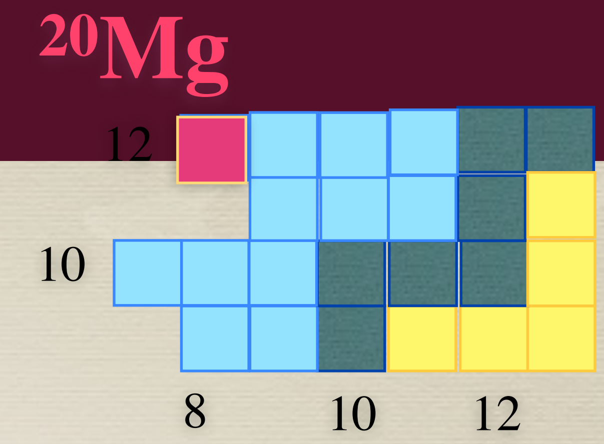
^{20}Mg(d,d') : Search for resonance in ^{20}Mg

^{20}Mg(d,d’) : Angular Distributions

^{20}Mg

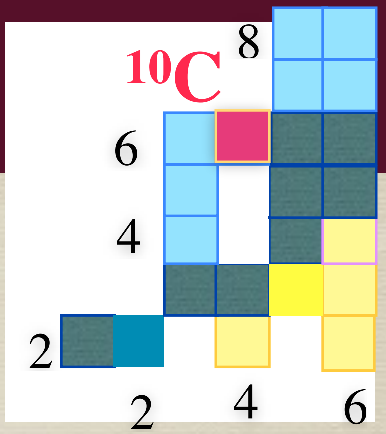


^{20}Mg(d,d') : Angular Distributions



Resonance in ^{20}Mg : Theories

^{10}C(p,p) : Constraining the nuclear force



Selected for a Viewpoint in *Physics*
PRL **118**, 262502 (2017) PHYSICAL REVIEW LETTERS week ending 30 JUNE 2017

Nuclear Force Imprints Revealed on the Elastic Scattering of Protons with ^{10}C

Inverse kinematics scattering at IRIS + *Ab initio* reaction theory

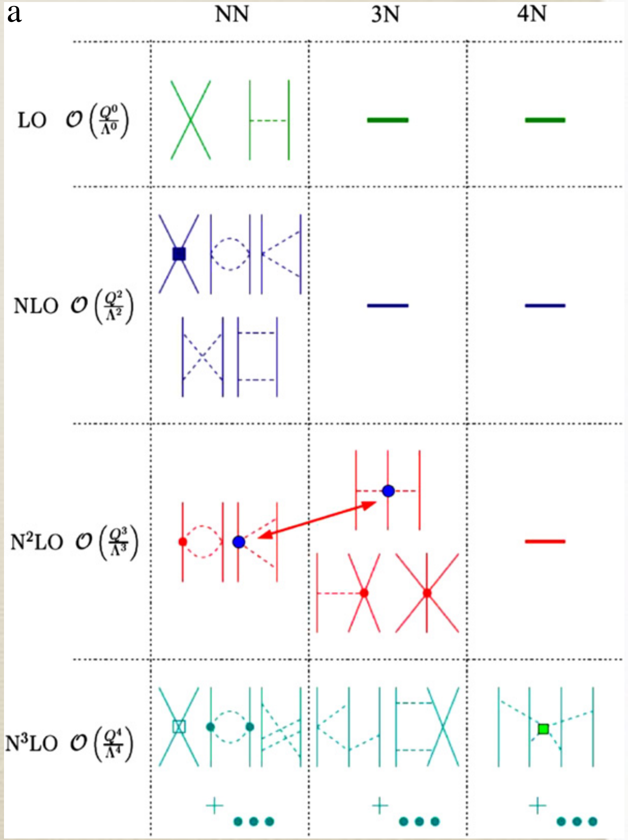
- No core-shell model with continuum (NCSMC) calculations

  ^{10}C : $0^+, 2_1^+, 2_2^+$ eigenstates

  ^{11}N : 6 -ve parity and 3 +ve parity NCSM eigenstates

$$\Psi^{(A)} = \sum_\lambda c_\lambda \left| {}^{(A)} \,{}^{11}\mathrm{N}, \lambda \right\rangle + \sum_\nu \int d\vec{r}\; \gamma_\nu(\vec{r})\; \hat{A}_\nu \left| \underset{(A-a)\;{}^{10}\mathrm{C}}{\bullet} \overset{\vec{r}}{\longrightarrow} \underset{(a)\;\mathrm{p}}{\bullet}, \nu \right\rangle$$

Q = pion mass
Λ = momentum cut off

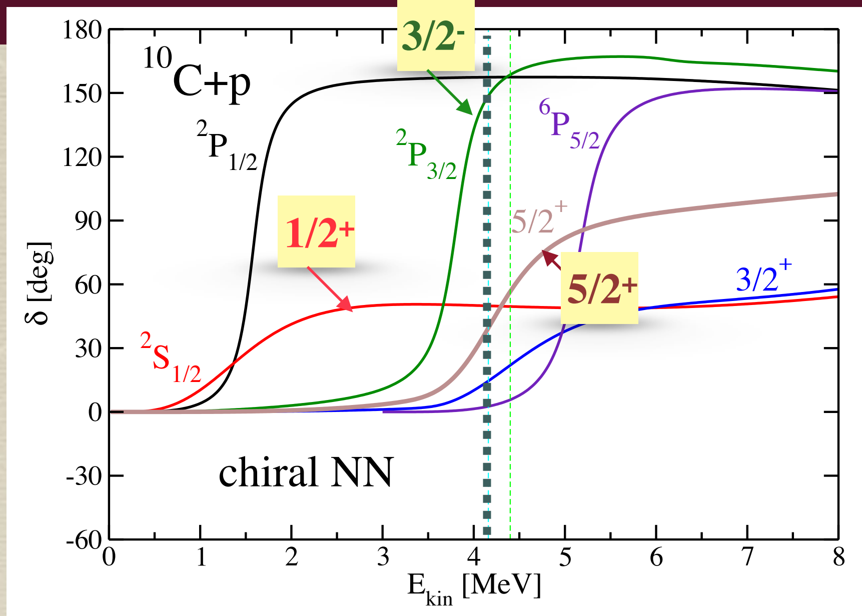


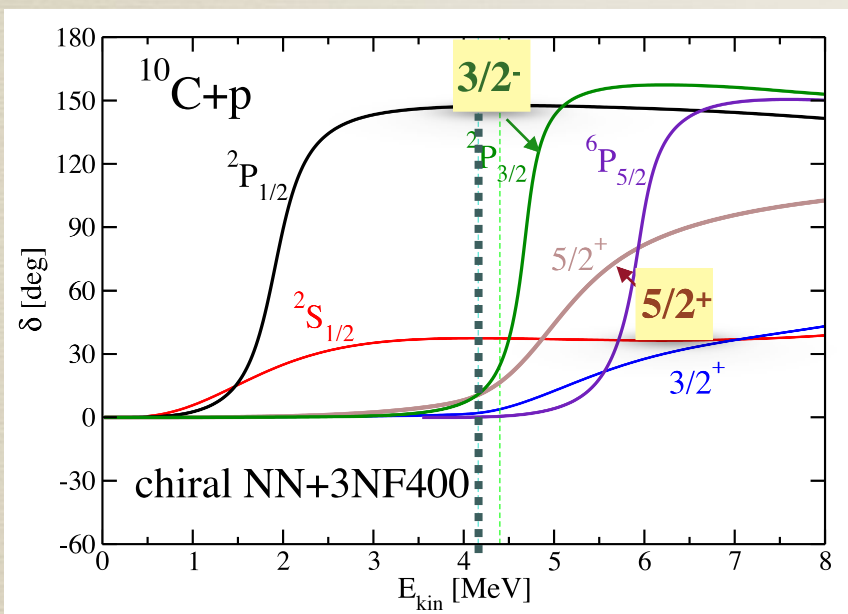
- Chiral EFT Forces : Expansion in (Q/Λ)

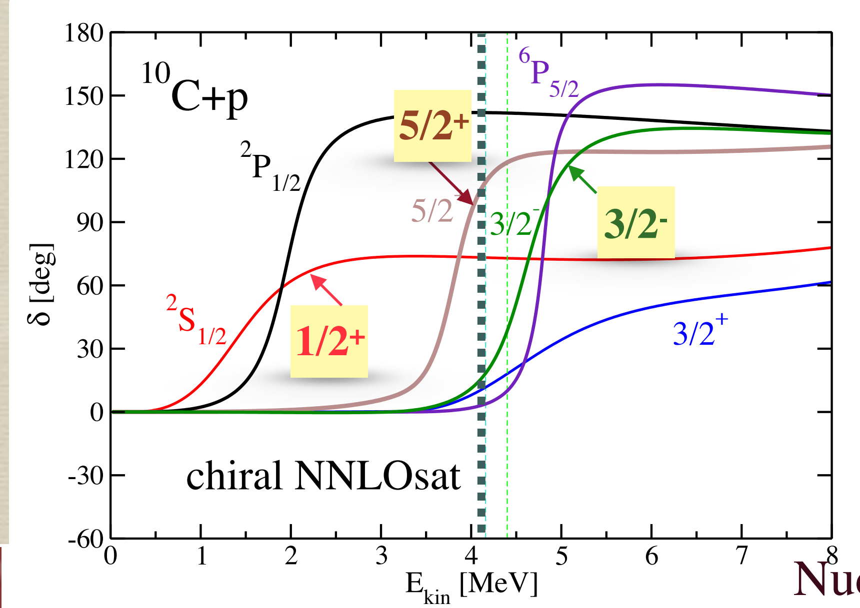
  - NN : N^{3}LO (500 MeV)
    Machleidt and Entem, PRC 2003
  - NN (N^{3}LO) +3NF (N^{2}LO); (400 MeV)
    Roth et al., PRL 2012.
  - NNLO$_{sat}$ (450 MeV)
    NN (N^{2}LO) +3NF (N^{2}LO)
    Simultaneous fit for NN phase shifts, B.E., radii
    Ekstrom et al., PRC 2015

A. Kumar, R.K., A. Calci, P. Navratil et al.

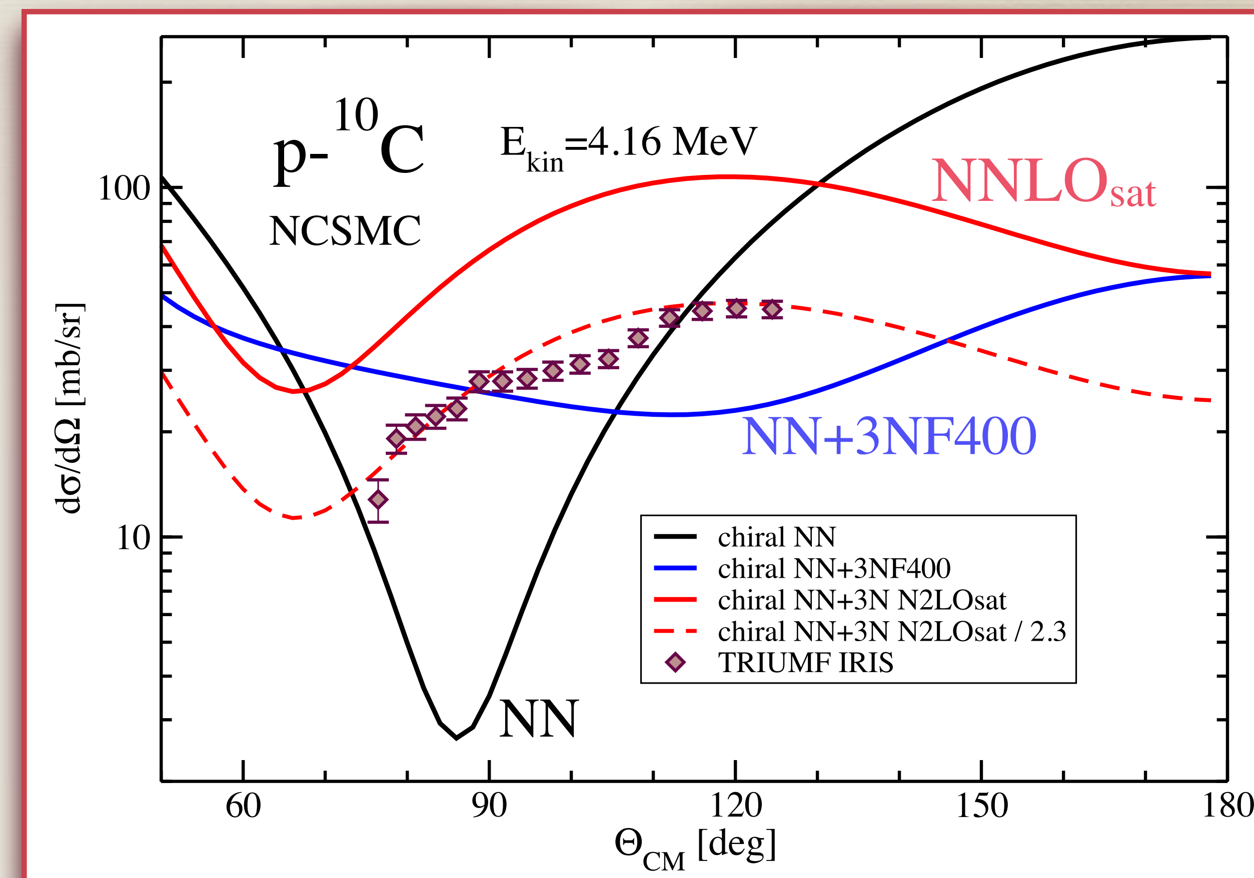
^{10}C(p,p) : Probing the nuclear force







$$\frac{d\sigma}{d\Omega} = \lambda\!\!\!{}^{-2} \sum_{l=0}^{\infty} \sum_{l'=|l-L|}^{l+L} (2l+1)(2l'+1)\left[\left(ll'00|ll'L0\right)\right]^2 \times \sin\delta_l \sin\delta_{l'} \cos(\delta_l - \delta_{l'}) P_L(\cos\theta)$$

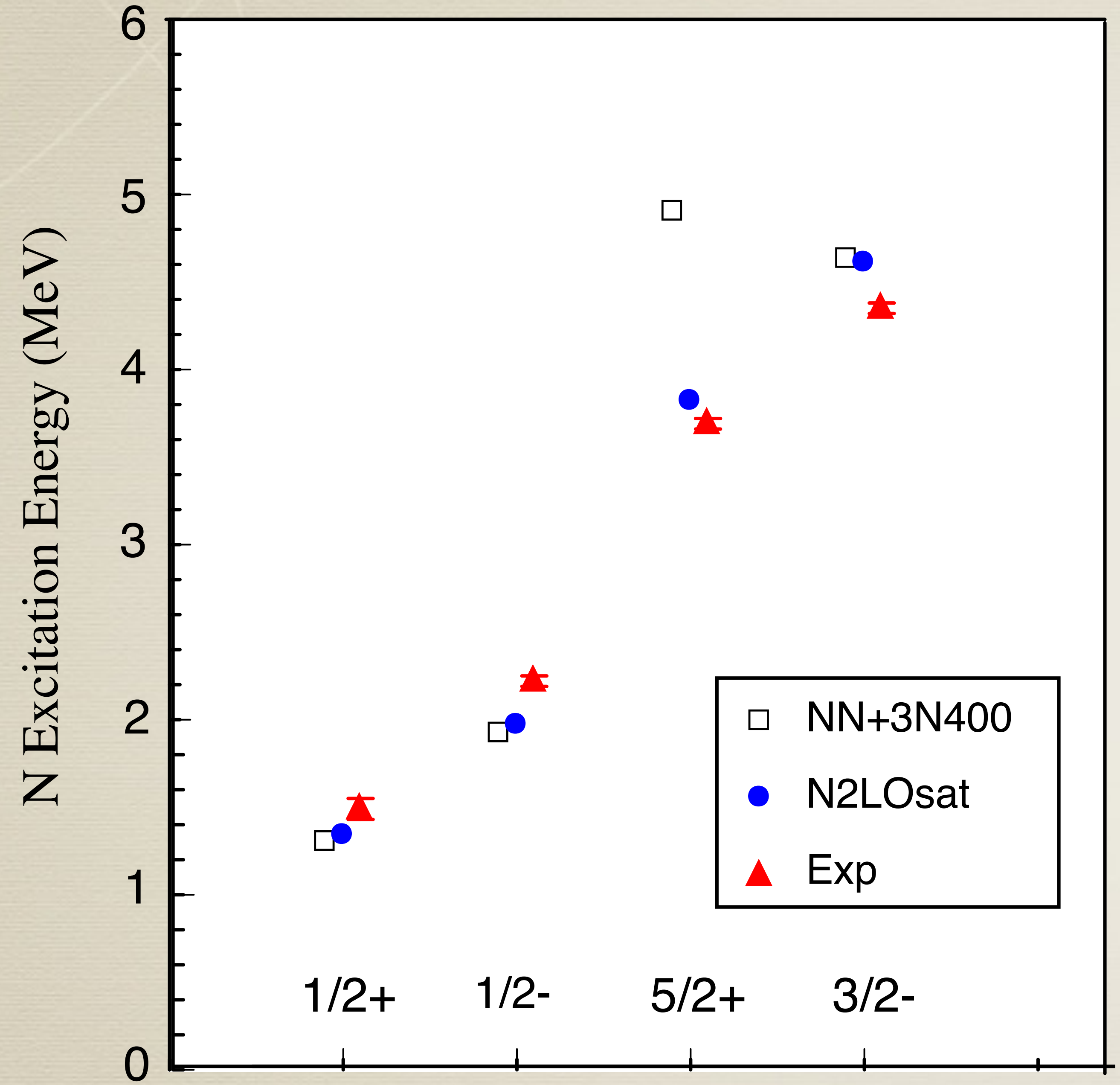


^{10}C(p,p) dσ/dΩ has strong sensitivity to the nuclear force.

NNLOsat force explains shape of dσ/dΩ *but fails in magnitude*.

NNLOsat is better out of the 3 choices but not complete

^{11}N Resonance energies



- 3N400, N^{2}LOsat give similar predictions for the 1/2$^+$, 1/2$^-$ & 3/2$^-$ resonances.

  less sensitivity to the different forces

- N^{2}LOsat in agreement with experiment would suggest this interaction is describes the nuclear force well.

  incomplete view of the forces

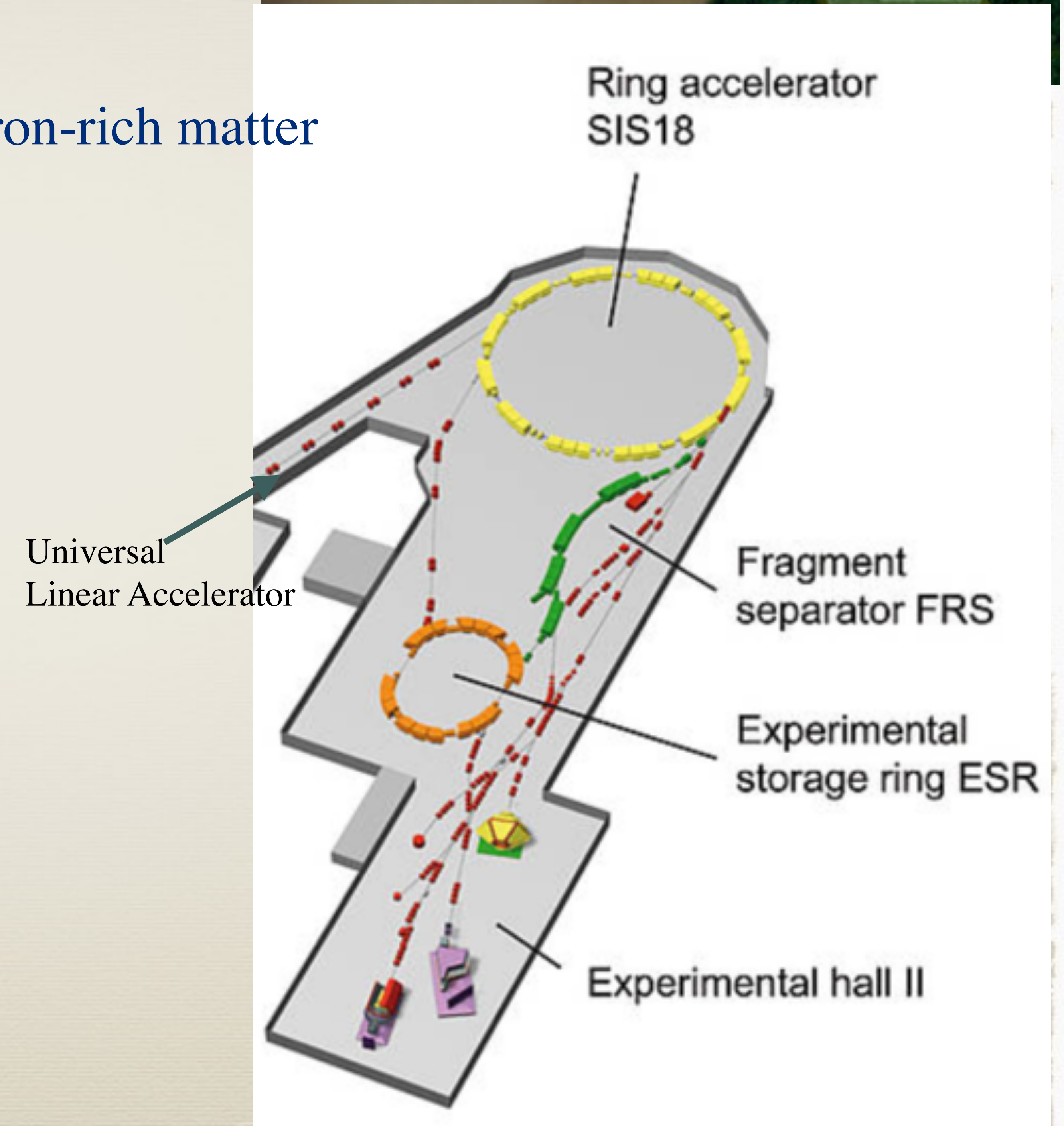
Reaction observable brings greater sensitivity for constraining the nuclear force

GSI, Germany

E/A~ 1 GeV

Matter (R_m) and Proton (R_p) Radii

- Discovering neutron skin and halo
- Defining the equation of state of neutron-rich matter
- Constrain the nuclear force
- Constrain nuclear structure models

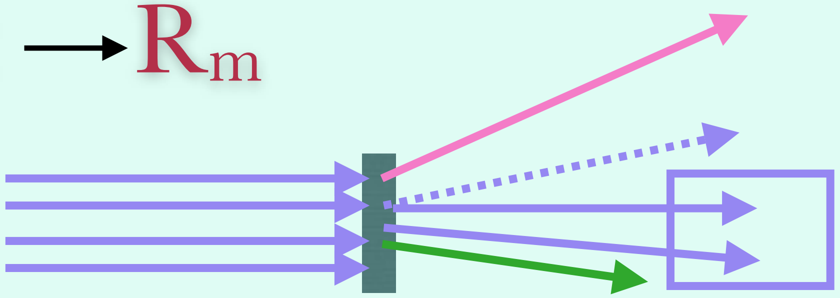


Nucleon Knockout Reactions : Momentum distribution

- Nuclear Orbitals and shell structure

Interaction Cross Section

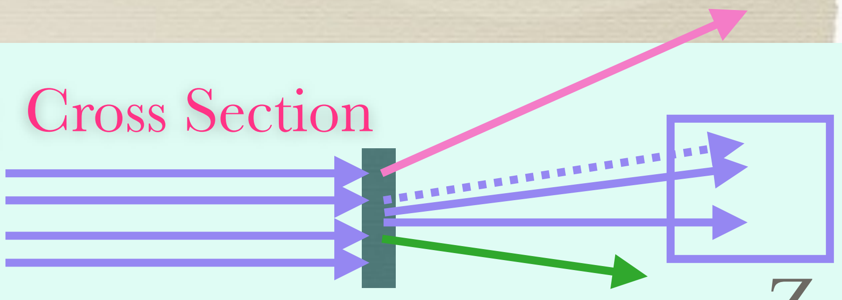
$\sigma_I \longrightarrow R_m$



$$N_{out} = N_{in} e^{-\sigma_I t}$$

Charge Changing Cross Section

$\sigma_{cc} \longrightarrow R_p$

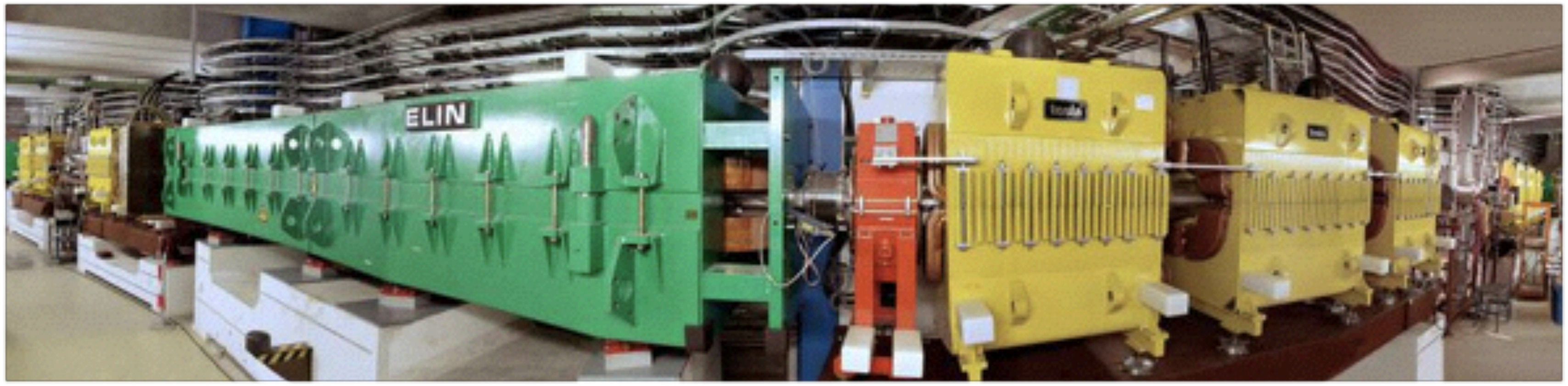


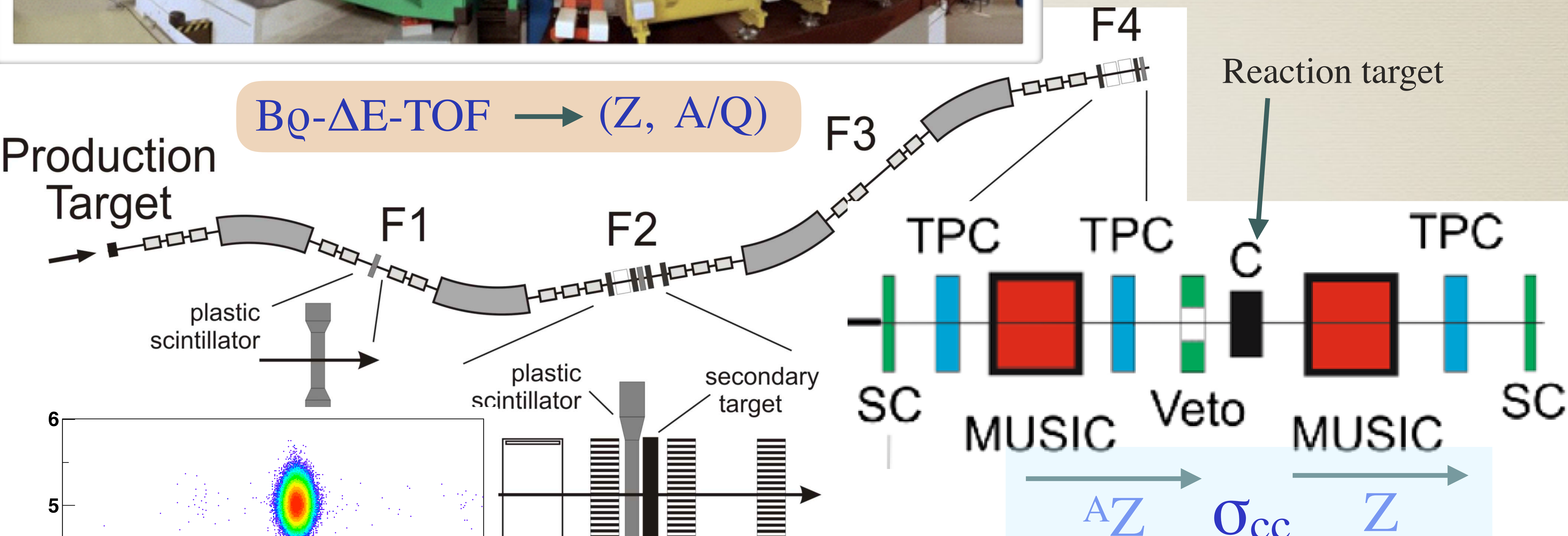
Sum of all interactions with the protons in a nucleus that changes the Z number.

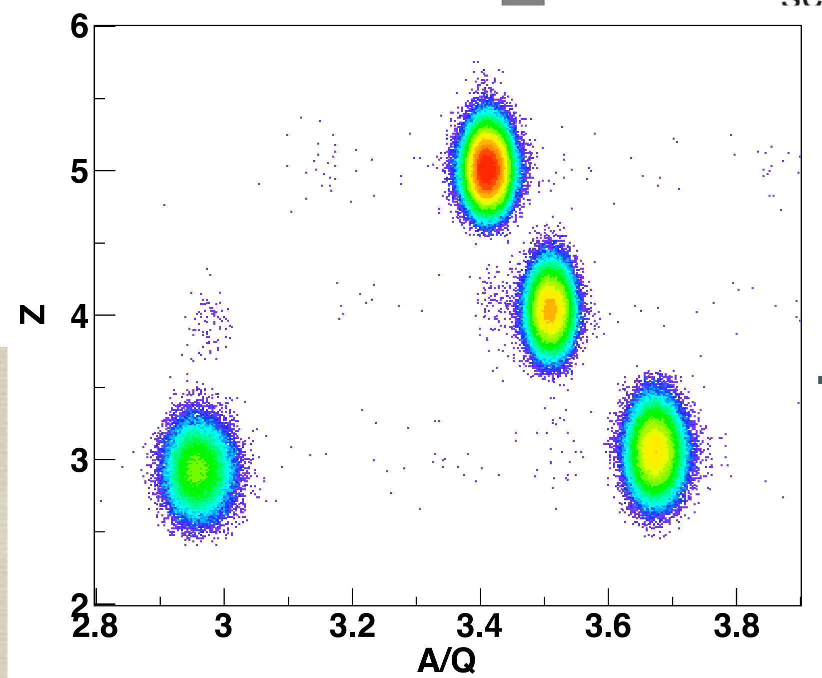
$$\sigma_{cc} = \frac{1}{t} \ln \left[\frac{\left(\frac{N_{sameZ}}{N_{in}} \right)_{Tout}}{\left(\frac{N_{sameZ}}{N_{in}} \right)_{Tin}} \right]$$

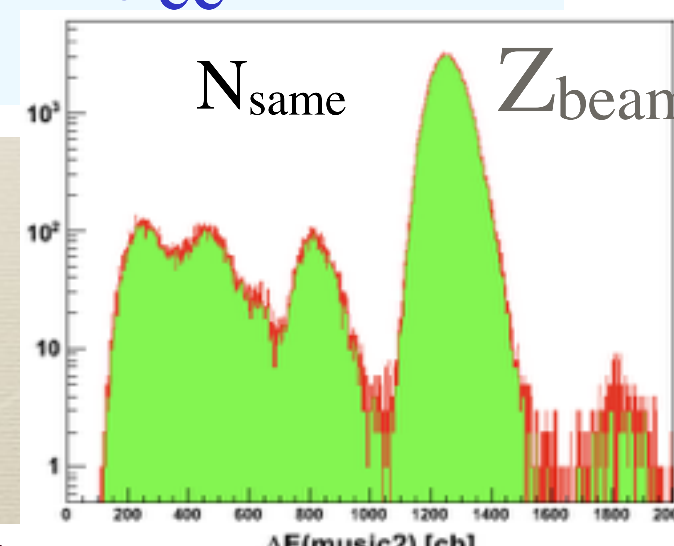
FRS @ GSI

E/A ~ 900A MeV









Glauber Model $\sigma \longrightarrow \mathbf{R}$

$$\sigma_{\mathrm{R}} = \int d\boldsymbol{b}(1 - |\mathrm{e}^{i\chi(\boldsymbol{b})}|^2)$$

$$\mathrm{e}^{i\chi(\boldsymbol{b})} = \langle \Psi_0 \Theta_0 | \prod_{i\in \mathrm{P}} \prod_{j \in \mathrm{T}} [1 - \Gamma_{NN}(\boldsymbol{s}_i - \boldsymbol{t}_j + \boldsymbol{b})] | \Psi_0 \Theta_0 \rangle$$

Optical Limit

$$\mathrm{e}^{i\chi_{\mathrm{OLA}}(\boldsymbol{b})} = \exp\left[- \iint d\boldsymbol{r} d\boldsymbol{r}' \rho_{\mathrm{P}}(\boldsymbol{r}) \rho_{\mathrm{T}}(\boldsymbol{r}') \Gamma_{NN}(\boldsymbol{s} - \boldsymbol{t} + \boldsymbol{b}) \right]$$

Projectile Density
$\rho_P = \rho_P^n + \rho_P^p$

Target Density
$\rho_T = \rho_T^n + \rho_T^p$

NTG

$$\begin{aligned}\mathrm{e}^{i\bar{\chi}(\boldsymbol{b})} = & \exp\bigg(- \frac{1}{2} \int d\boldsymbol{r} \rho_{\mathrm{P}}(\boldsymbol{r}) \\ & \times \left\{ 1 - \exp\left[- \int d\boldsymbol{r}' \rho_{\mathrm{T}}(\boldsymbol{r}') \Gamma_{NN}(\boldsymbol{s} - \boldsymbol{t} + \boldsymbol{b}) \right] \right\} \bigg) \\ & \times \exp\bigg(- \frac{1}{2} \int d\boldsymbol{r}' \rho_{\mathrm{T}}(\boldsymbol{r}') \\ & \times \left\{ 1 - \exp\left[- \int d\boldsymbol{r} \rho_{\mathrm{P}}(\boldsymbol{r}) \Gamma_{NN}(\boldsymbol{t} - \boldsymbol{s} + \boldsymbol{b}) \right] \right\} \bigg).\end{aligned}$$

W. Horiuchi et al., PRC 75, 044607 (2007)

Glauber Model

Profile Function parameters

$$\Gamma_{NN}(b) = \frac{1 - i\alpha}{4\pi\beta}\sigma_{NN}^{tot}\exp\left(-\frac{b^2}{2\beta}\right)$$

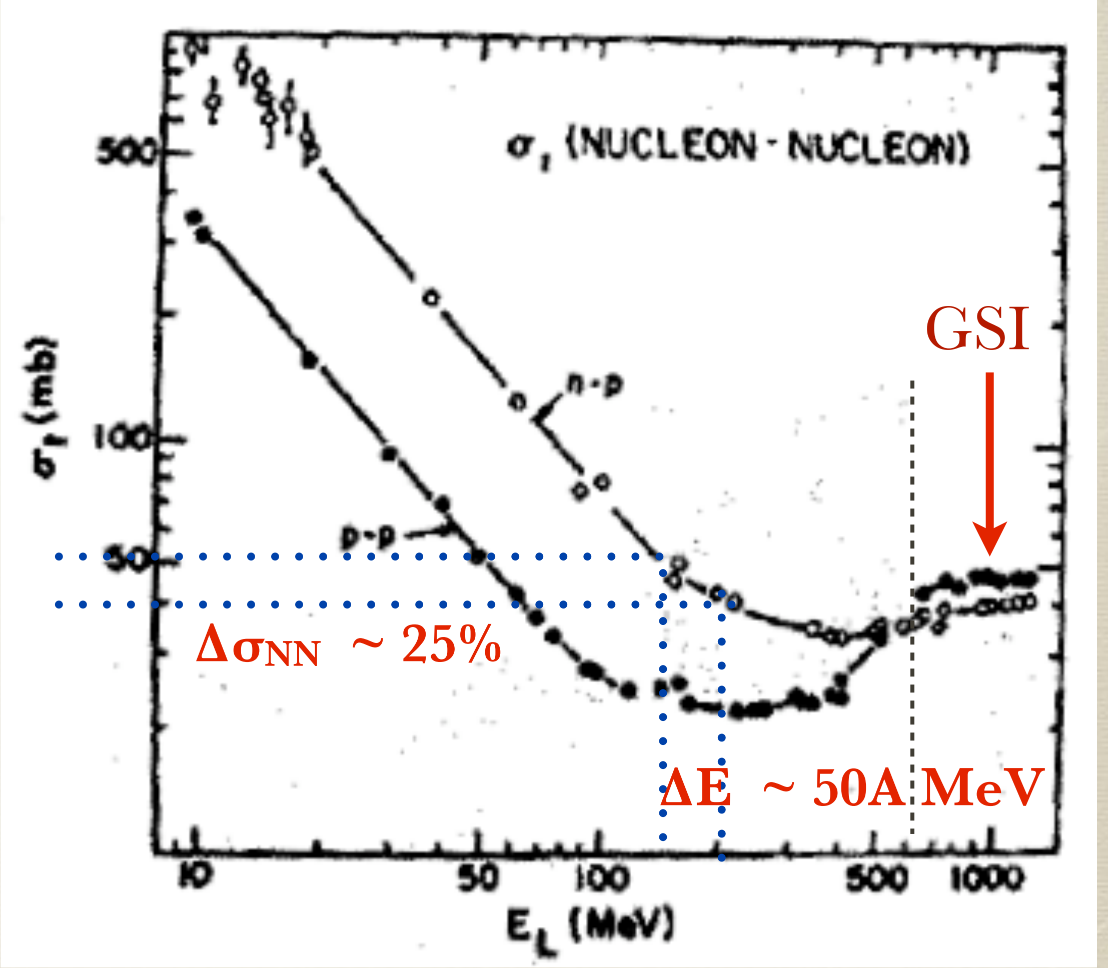
σ_{NN} = NN scattering cross section

α = ratio of Re/Im NN scattering amplitudes

β = slope parameter of NN elastic differential cross section

$$\sigma_{NN}^{el} = \frac{1+\alpha^2}{16\pi\beta}\left(\sigma_{NN}^{tot}\right)^2$$

E > 300 MeV



Uncertainties at lower energies

- Variation of σ_{NN} with energy causes uncertainty
- Effects of medium modification of σ_{NN}

Glauber Model validity

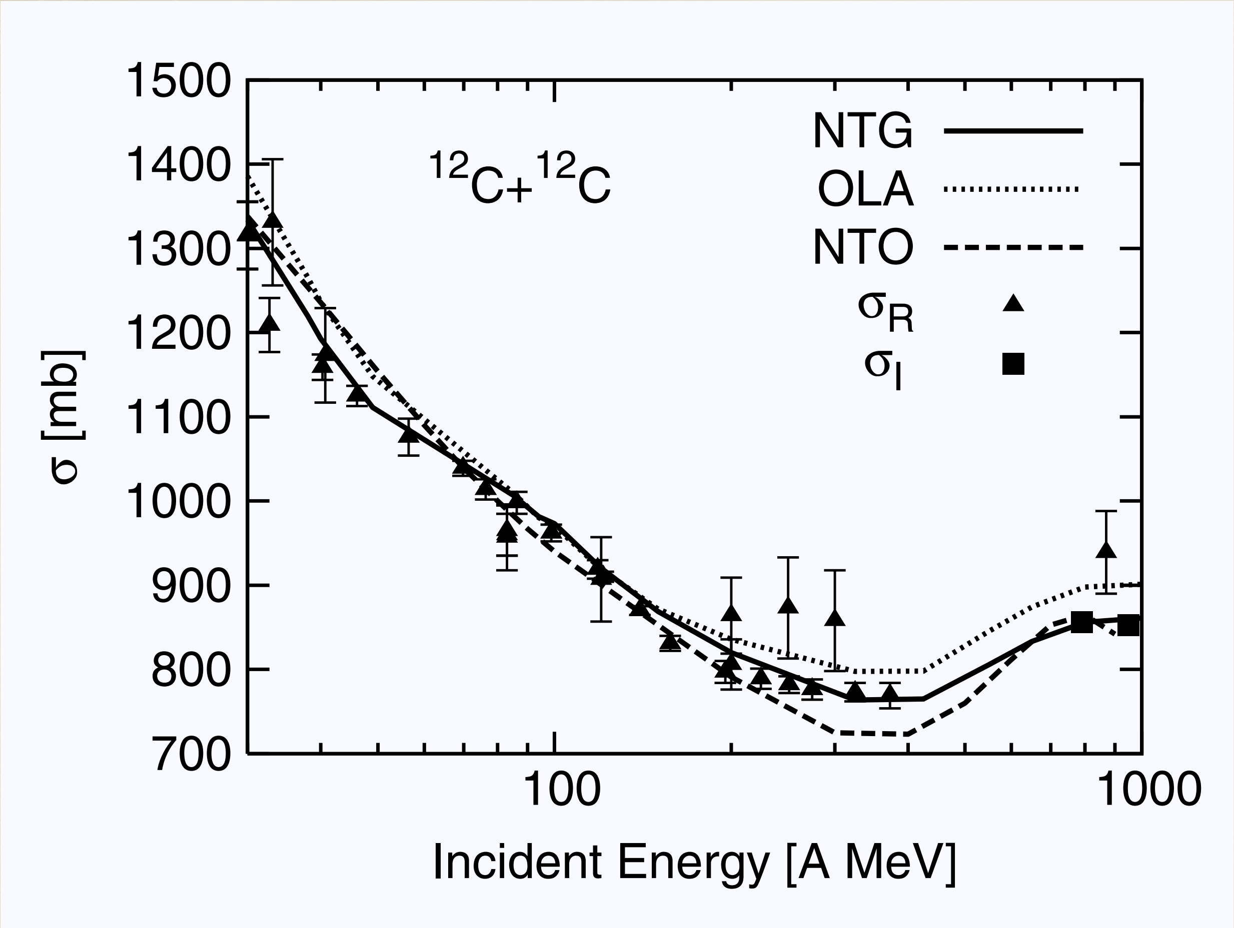
Finite Range calculations

Agreement of Rp from σ_{cc} and e^- scattering establishes the accurate determination of radii at ~ 900A MeV

Glauber Model : σ_R

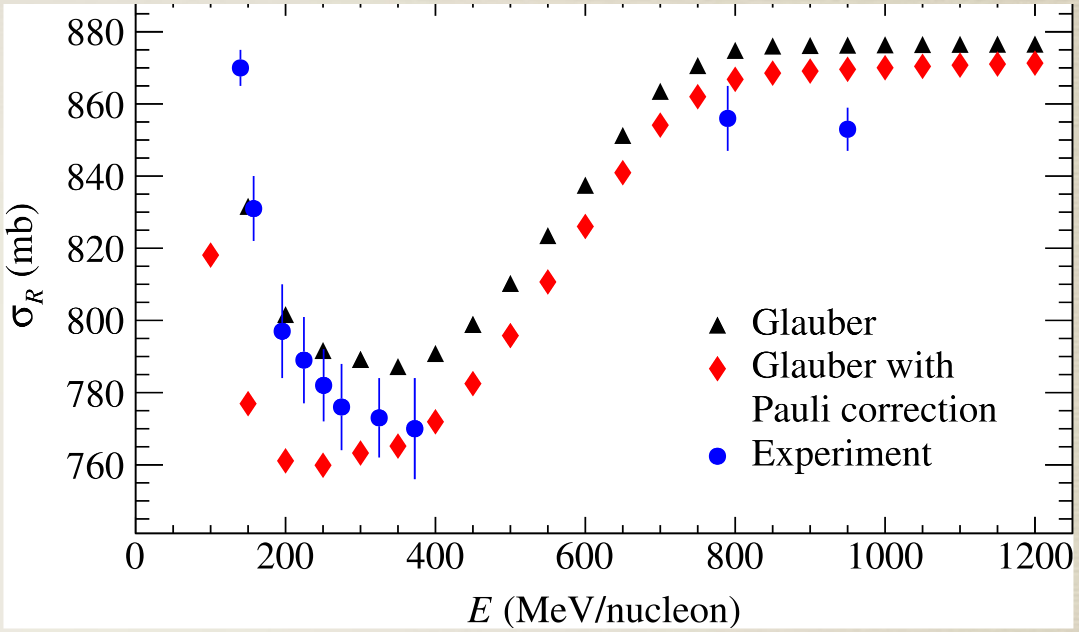
$^{12}C+^{12}C$

Finite Range



W. Horiuchi et al., PRC 75, 044607 (2007)

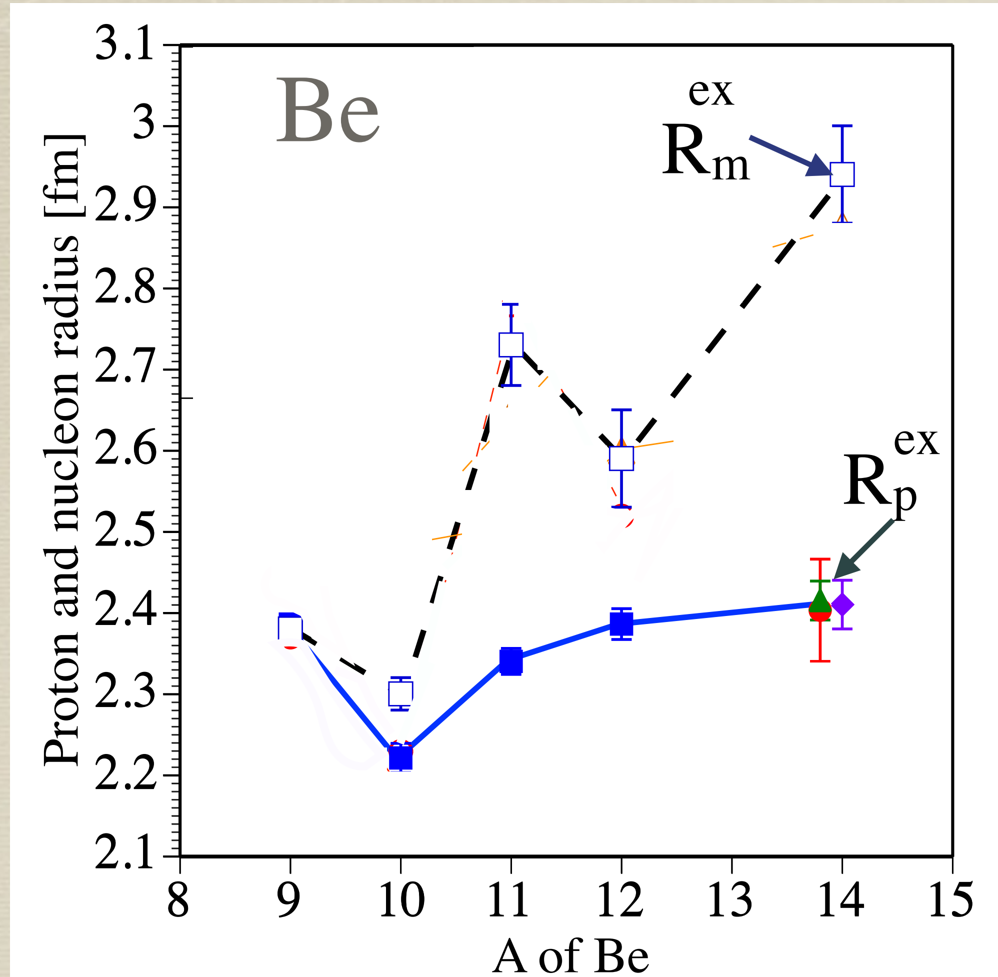
OLA : Zero Range



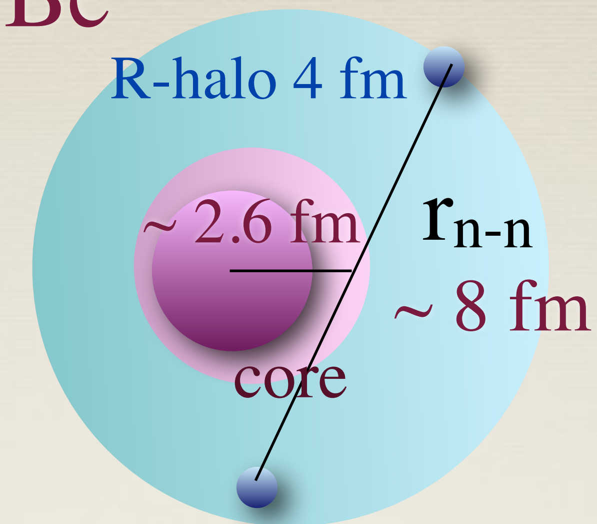
T. Aumann et al., PRL 119 , 262501 (2017)

NN scattering is not zero range

Two-neutron halo in Be and B



S. Terashima et al., PTEP Letter (2014) 101D02



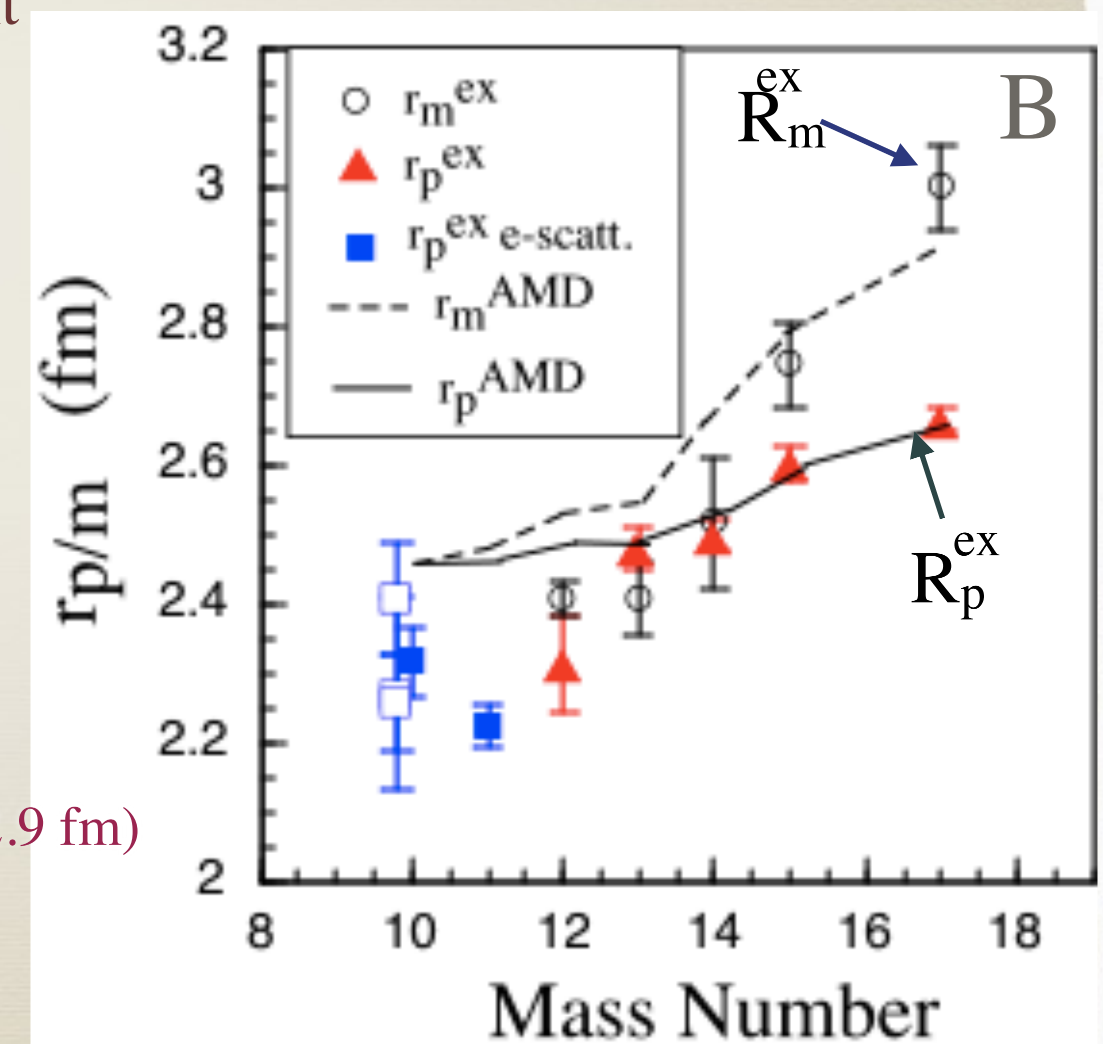
l=0, $2s_{1/2}$ dominant

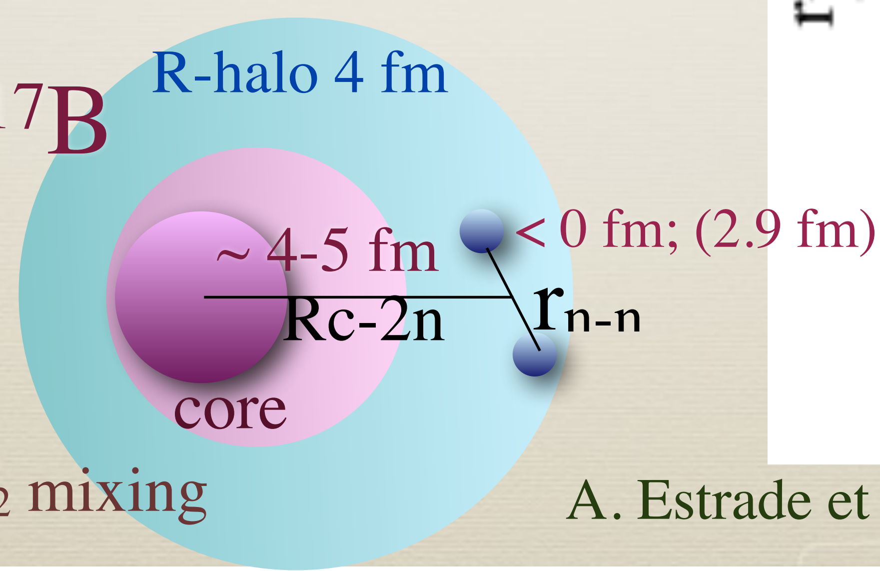
$$\langle r_p^2\rangle = \langle r_{pc}^2\rangle + \langle r_c^2\rangle$$

$$A_c^2\langle r_c^2\rangle = A_h^2\langle r_{2n}^2\rangle$$

$$A\langle r_m^2\rangle = A_c\left(\langle r_{mc}^2\rangle + \langle r_c^2\rangle\right) + A_h\langle r_h^2\rangle$$

$$\langle r_{n-n}^2\rangle = 4\left[\langle r_h^2\rangle - \langle r_{2n}^2\rangle\right]$$

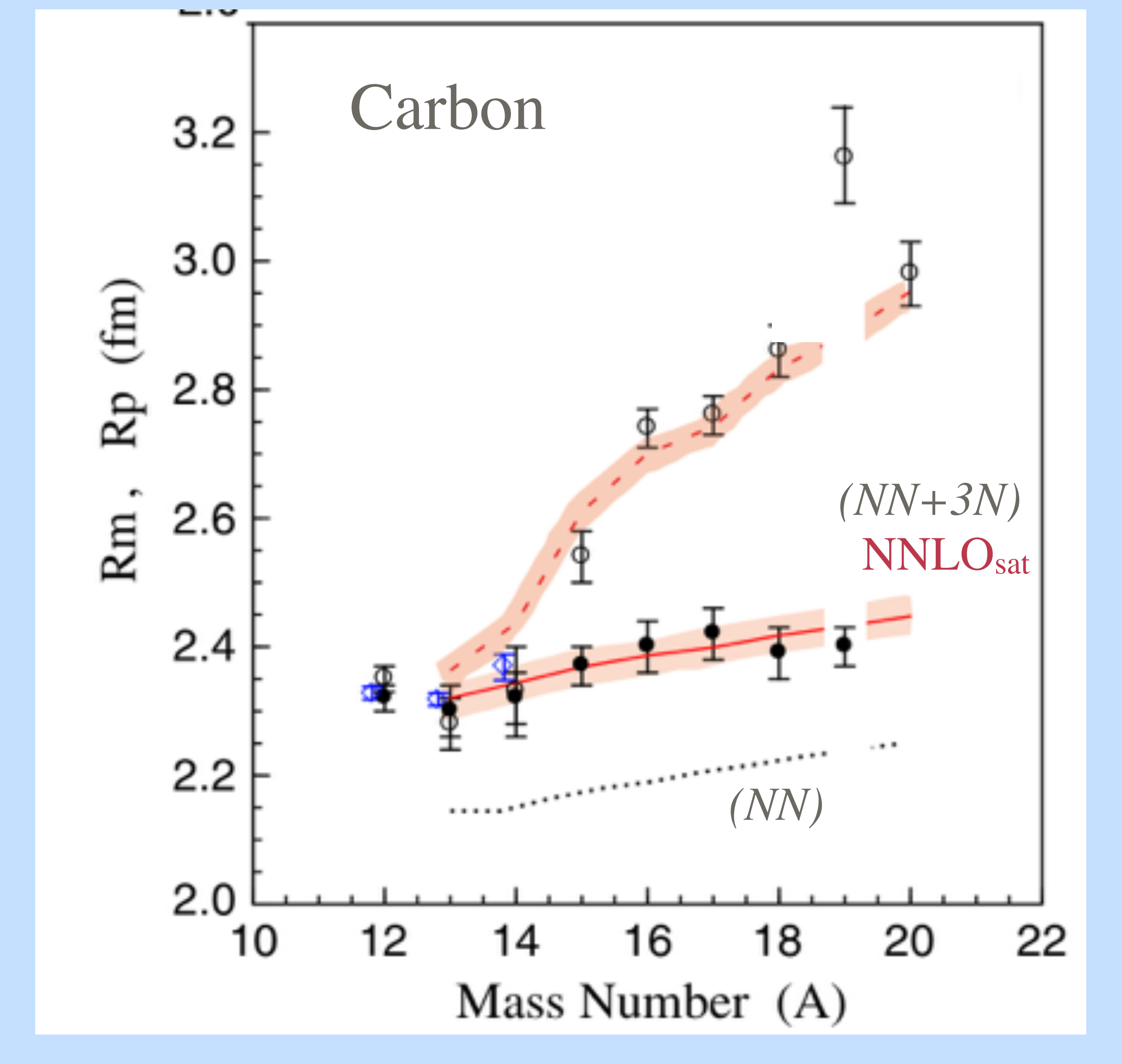




$2s_{1/2}$ - $1d_{5/2}$ mixing

A. Estrade et al., Phys. Rev. Lett. 113 (2014) 132501

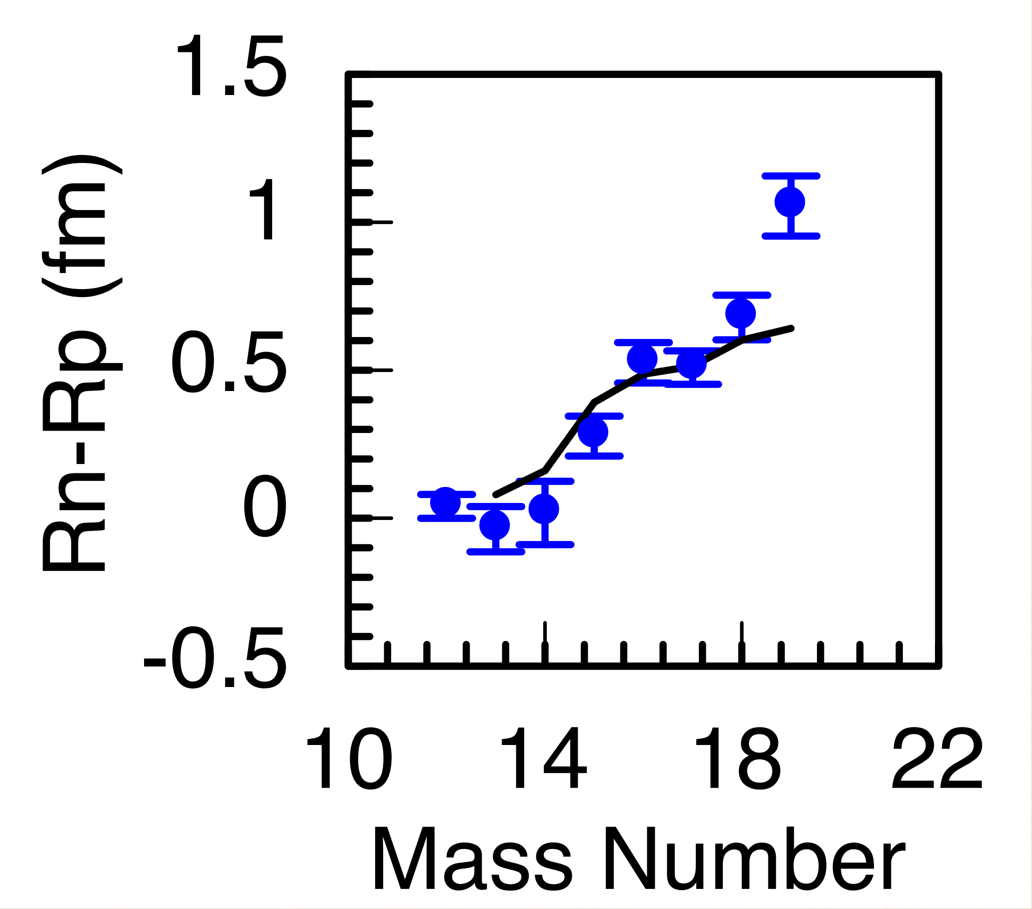
C radii



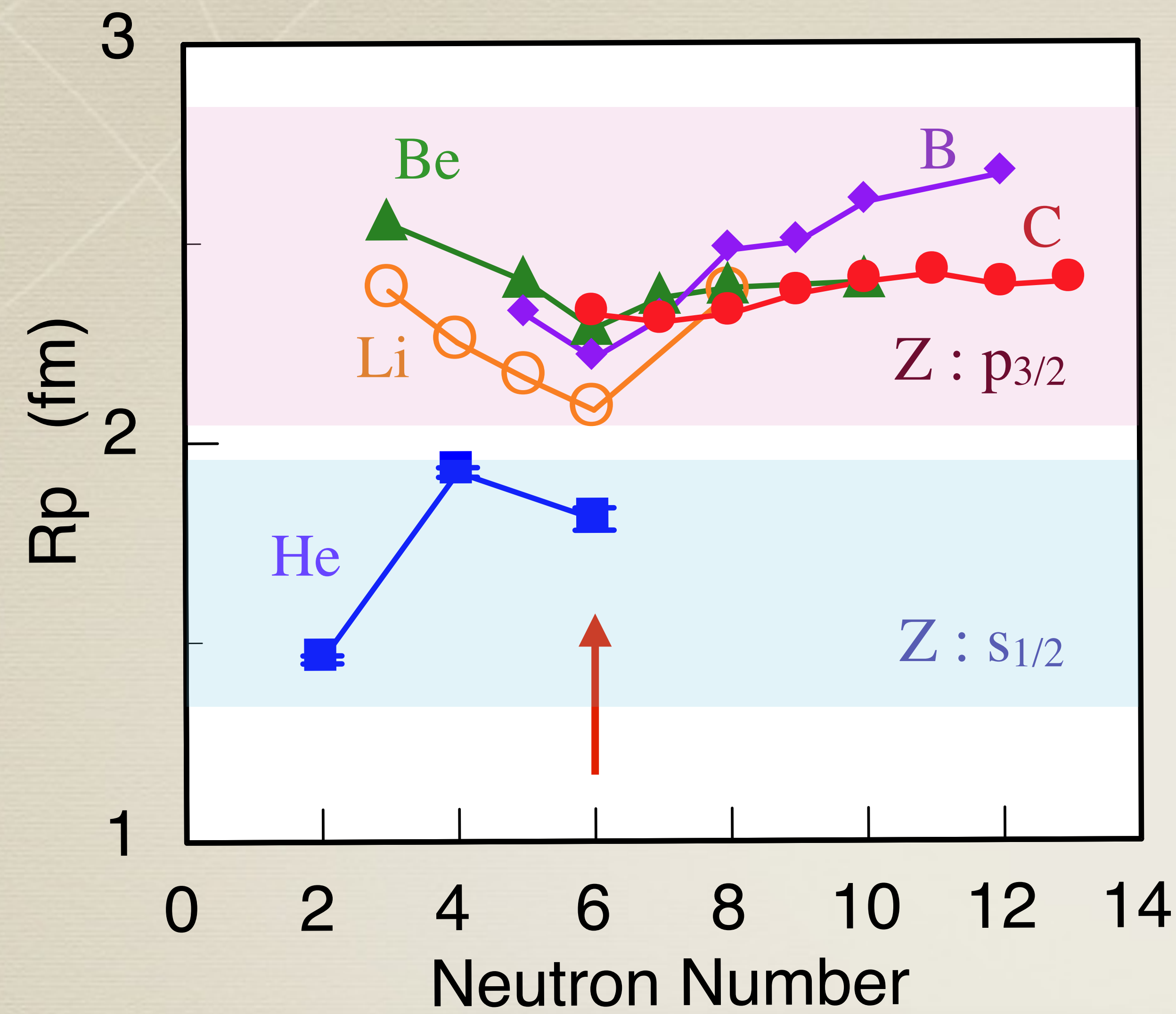
R.Kanungo et al, Phys. Rev. Lett. 117 (2016) 102501

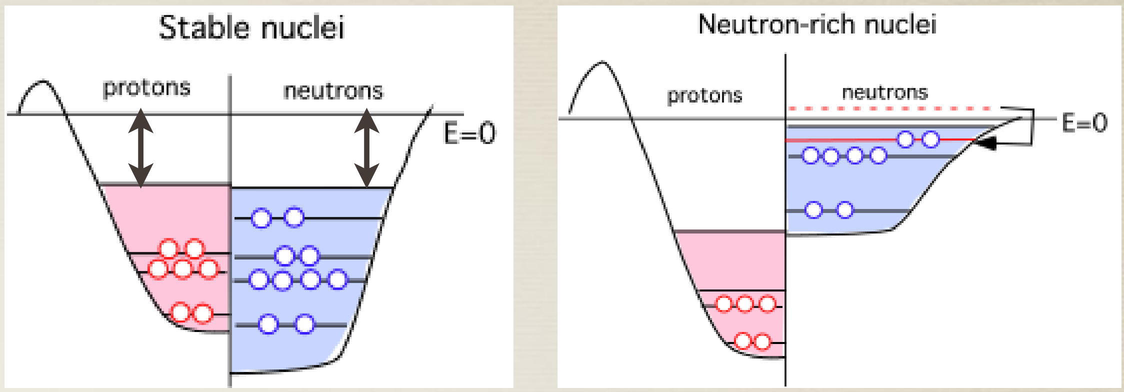
- Rp show only a small increase from ^{12}C to ^{19}C
- Excellent agreement with coupled cluster predictions using chiral NN+3N force ($NNLO_{sat}$).
- Predictions with NN force only ($NNLO_{opt}$) are lower than data.

$^{15-19}C$ rapid growth of thick neutron surface

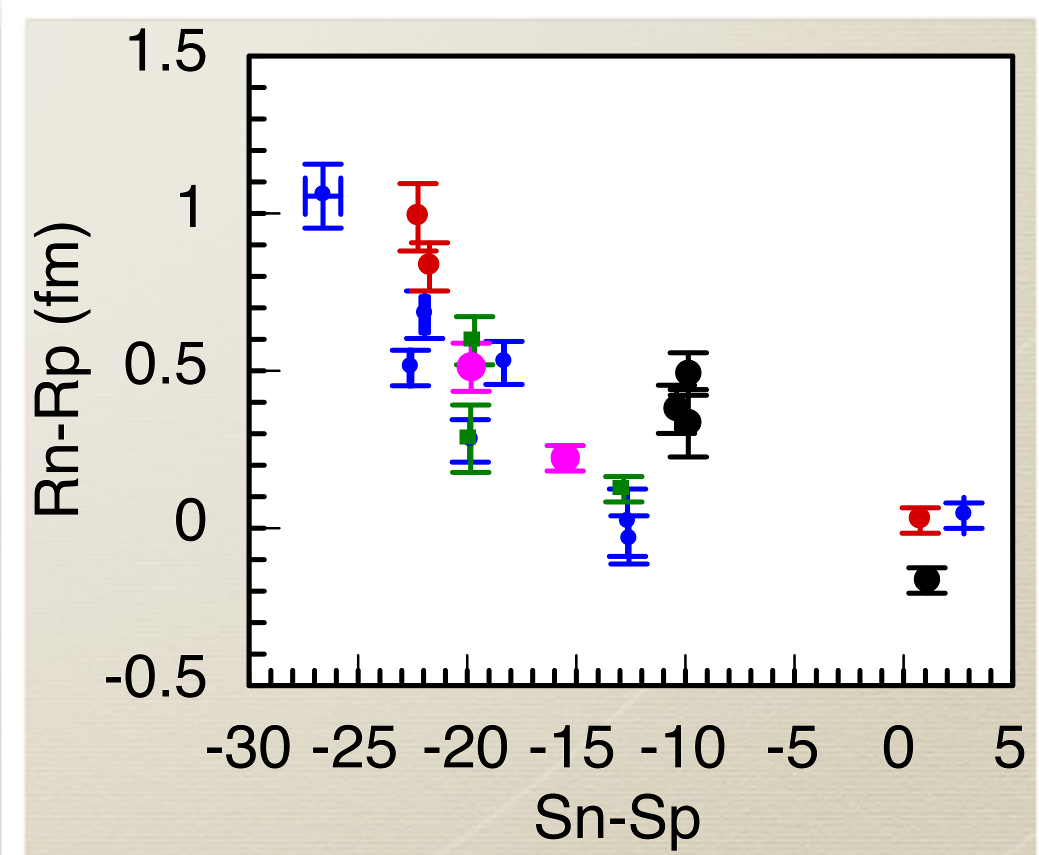


Proton Radii : Nuclear shell gap





Neutron skin thickness ∝ (Sn-Sp)



N=6 Sub-shell gap in Z ≤ 5

N radii

Summary

Direct reactions at low- and high- energies can reveal new features of exotic nuclei.

- Reactions discover and characterize nuclear halos and new shells — Transfer reactions, σ_I , σ_{cc}
- New Resonances are found through reaction spectroscopy — Inelastic Scattering
- Nuclear force finds new constraints through direct reactions — Elastic Scattering

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