Exploring Exotic Structures in Rare Isotopes with Relativistic Beams

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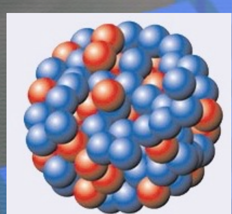
Proton Number

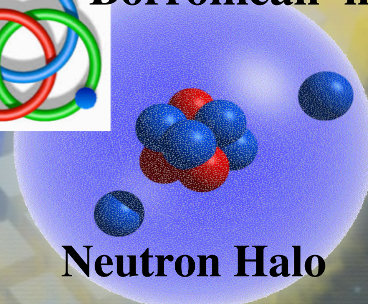
Rare Isotope

weak binding, N/Z>>1



Stable Nucleus

Borromean nucleus



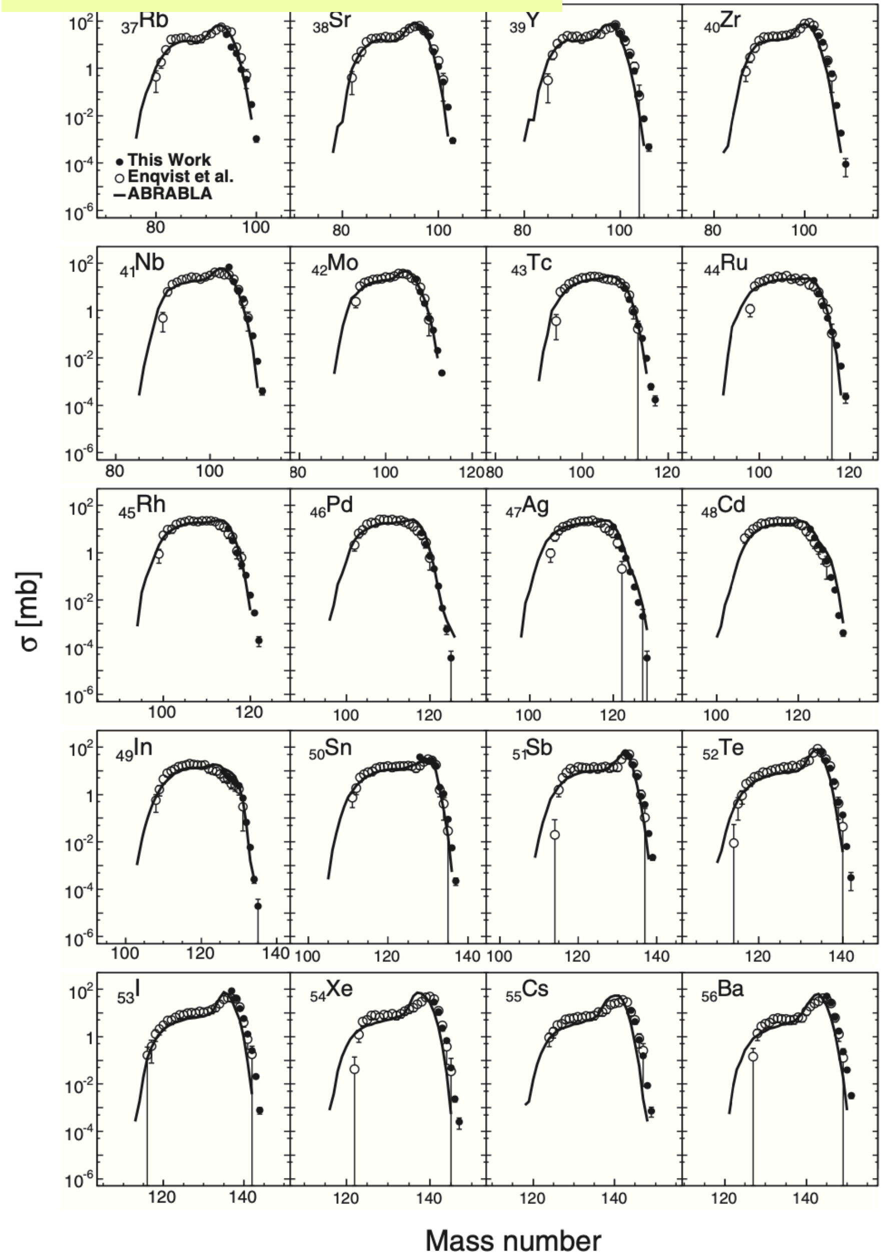
Neutron Halo

Neutron-rich matter

Neutron Number

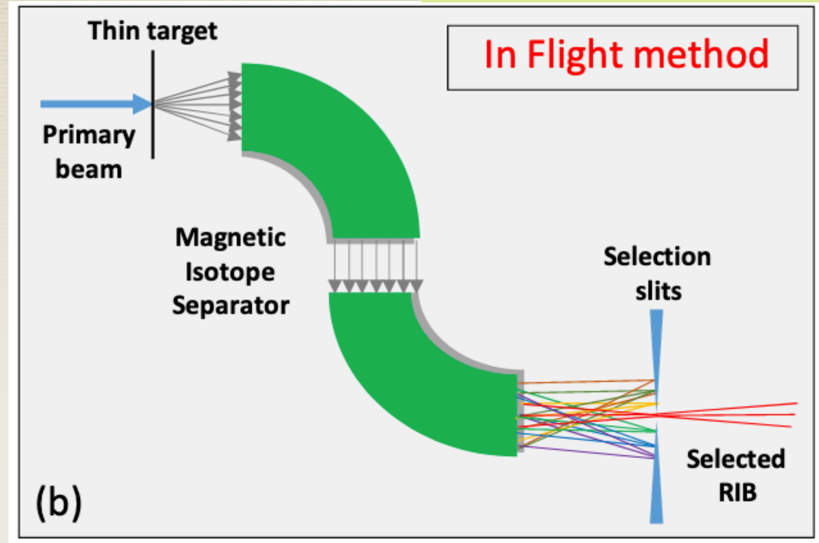
Rare isotopes in the laboratory

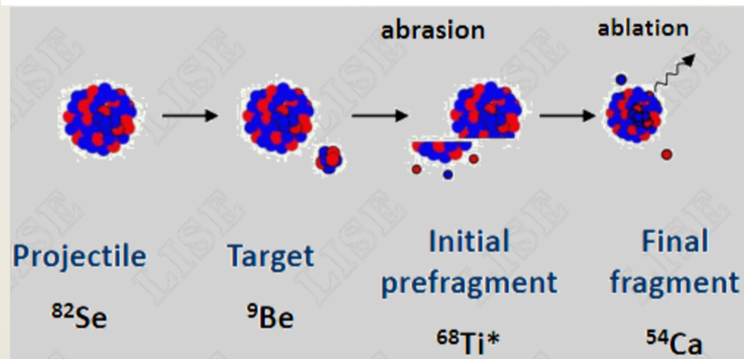
$^{238}U + ^{208}Pb \sim 1A$ GeV



D. Pérez-Loureiro PRC (2019)

High energy RI beam

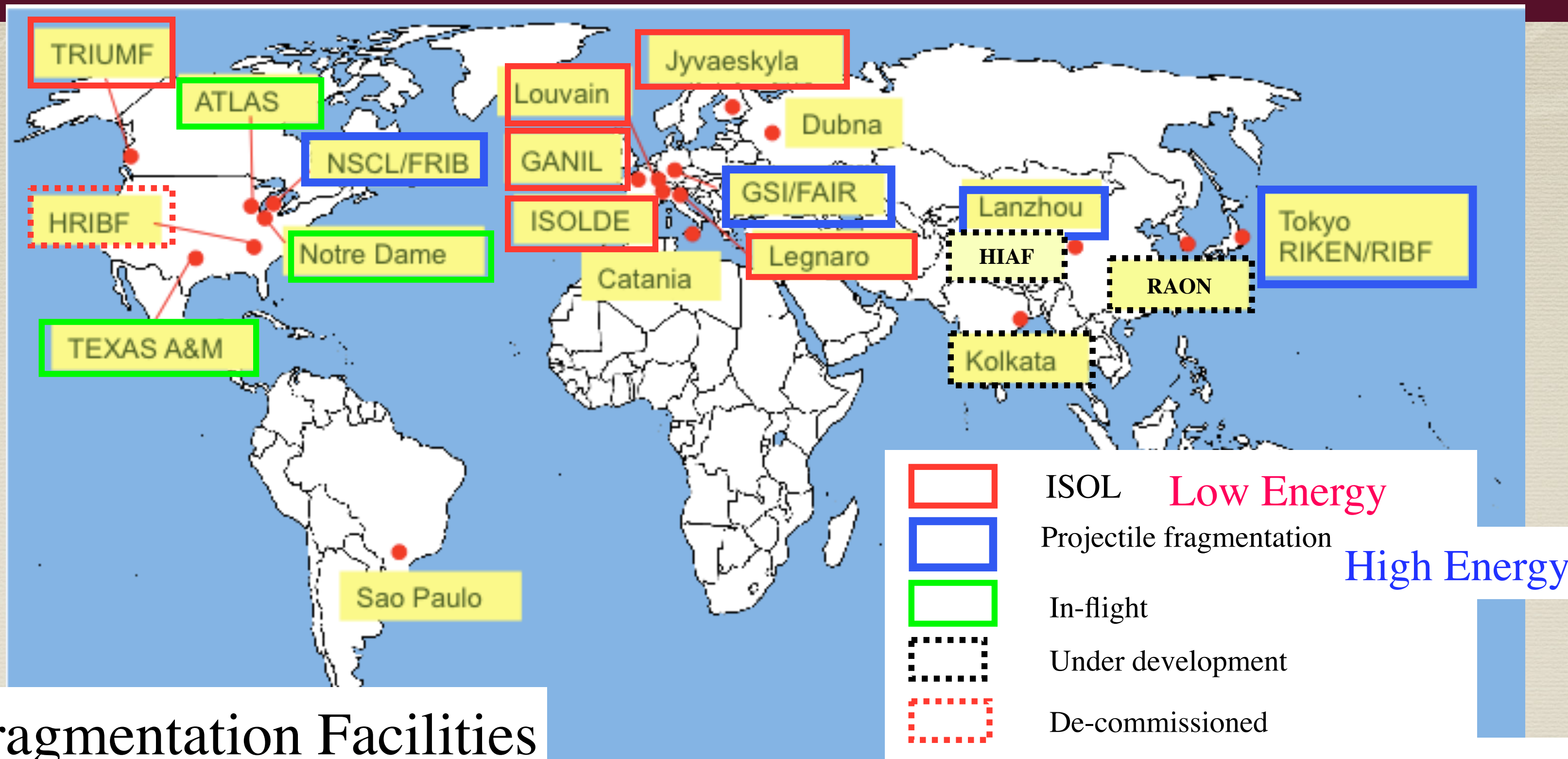




courtesy : LISE++

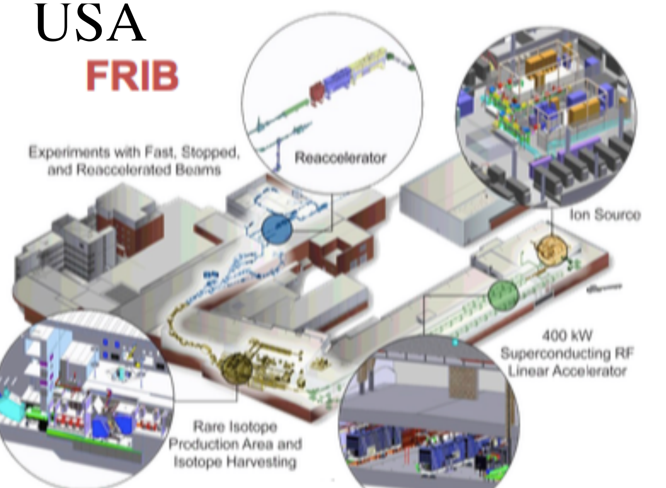
De-excitation channel	Collisions	Reaction
Abrasion – __Evaporation__ Abrasion – Ablation	peripheral	Projectile fragmentation
Abrasion – __Fission__	peripheral	In-flight fission ~~Projectile fission~~
Abrasion – __Breakup__	central	Multi-fragmentation

Rare Isotope Facilities

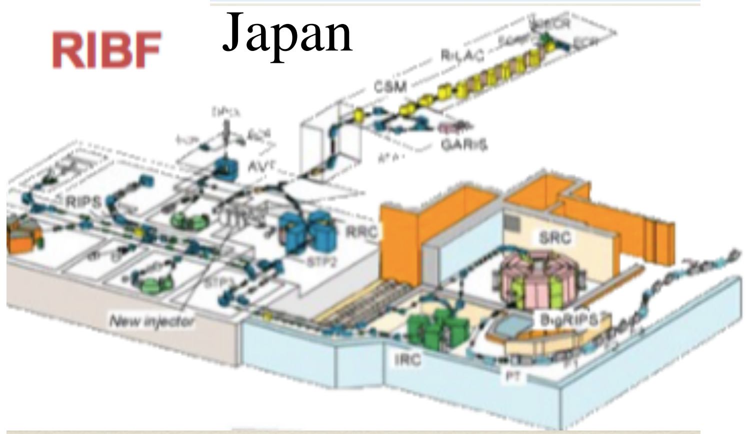


Projectile Fragmentation Facilities

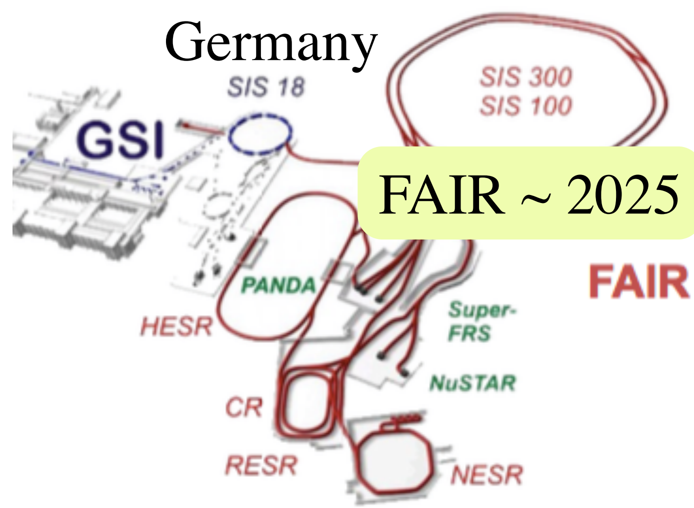
USA



Japan



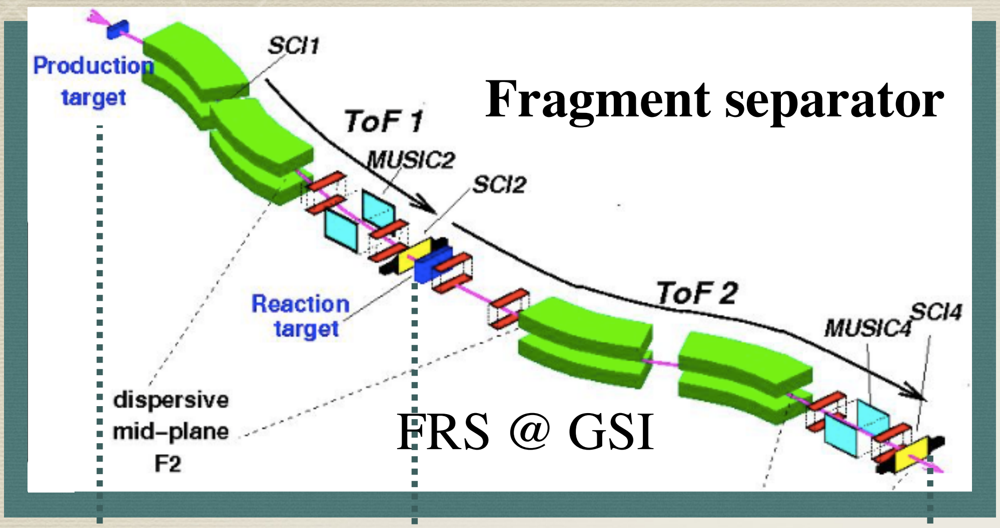
Germany



FAIR ~ 2025

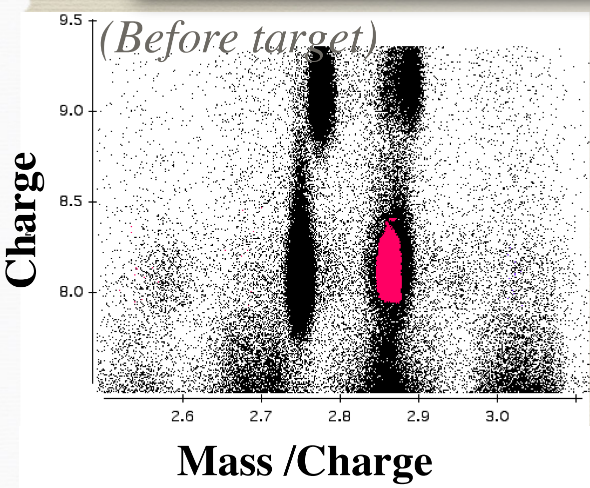
E/*A* ~ 70 - 300 MeV　　*E*/*A*~ 1 GeV

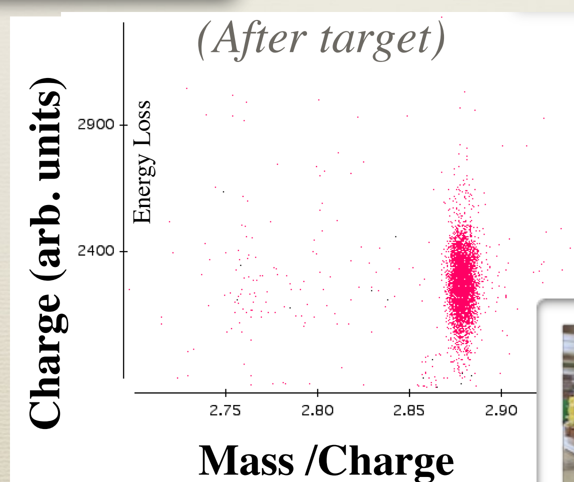
Point Matter (rms) Radii : Interaction Cross Section (σ_I)



$^{A}Z \longrightarrow {}^{A}Z$

Magnetic Rigidity (Bρ) -ΔE - TOF





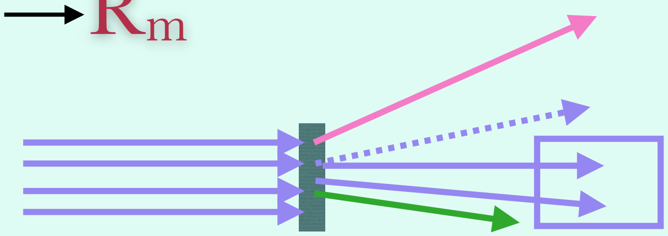
Reaction Cross Section (σ_R): Sum of all reactions *except elastic scattering*

$$\sigma_R = \sigma_I + \sigma_{inel} \text{ (bound states)}$$

Glauber calculation for R_m — Measure

Interaction Cross Section

$$\sigma_I \longrightarrow R_m$$



^{A}Z N_{in} — target — ^{A}Z N_{out}

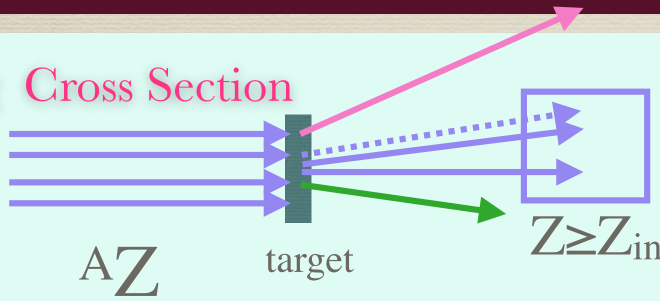
Transmission Technique

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

Point Proton (rms) Radii : Charge Changing Cross Section (σ_{cc})

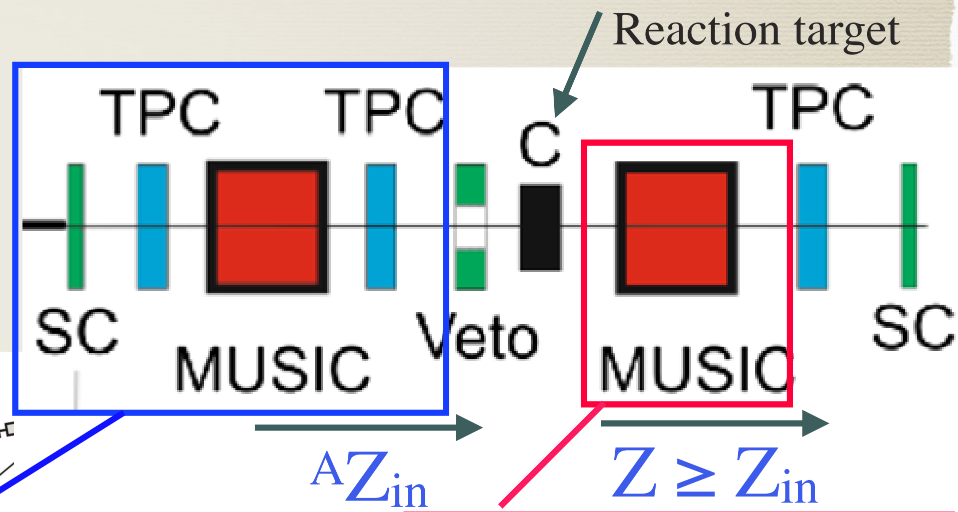
Charge Changing Cross Section

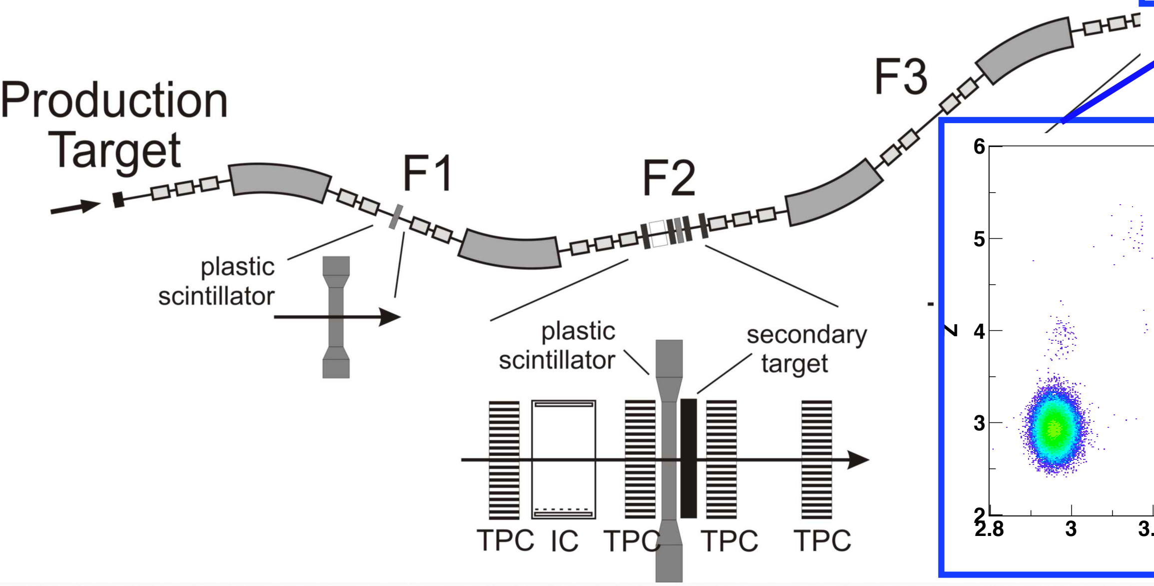
$\sigma_{cc} \longrightarrow R_p$

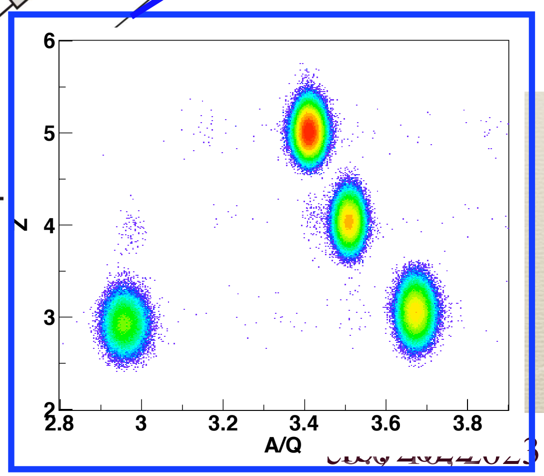


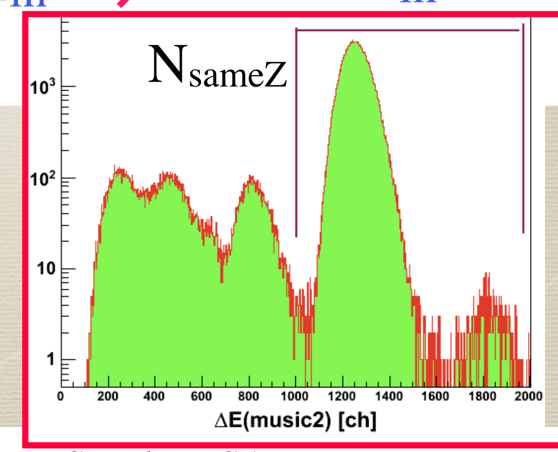
Sum of all interactions with the protons in a nucleus that **reduces the Z number.**

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









σ_R to R_m — Glauber Model

Measure

$$\sigma_R = \int\int d\vec{b}\left[1 - T\left(\vec{b}\right)\right] \qquad T(b) = \left|\exp\left(i\chi\left(\vec{b}\right)\right)\right|^2$$

T : Transmission Function

1 - elastic scattering

Does not require any reaction mechanism

$$i\chi\left(\vec{b}\right) = \int\int_P \int\int_T \sum_{ik}\left[\rho^z_{P_i}(s)\,\rho^z_{T_k}(t)\,\Gamma_{ik}\left(\vec{b}+\vec{s}-\vec{t}\right)\right]d\vec{s}\,d\vec{t}$$

Find ($\rho^z_{P_i}$) — *Known* ($\rho^z_{T_k}(t)\Gamma_{ik}(\vec{b}+\vec{s}-\vec{t})$)

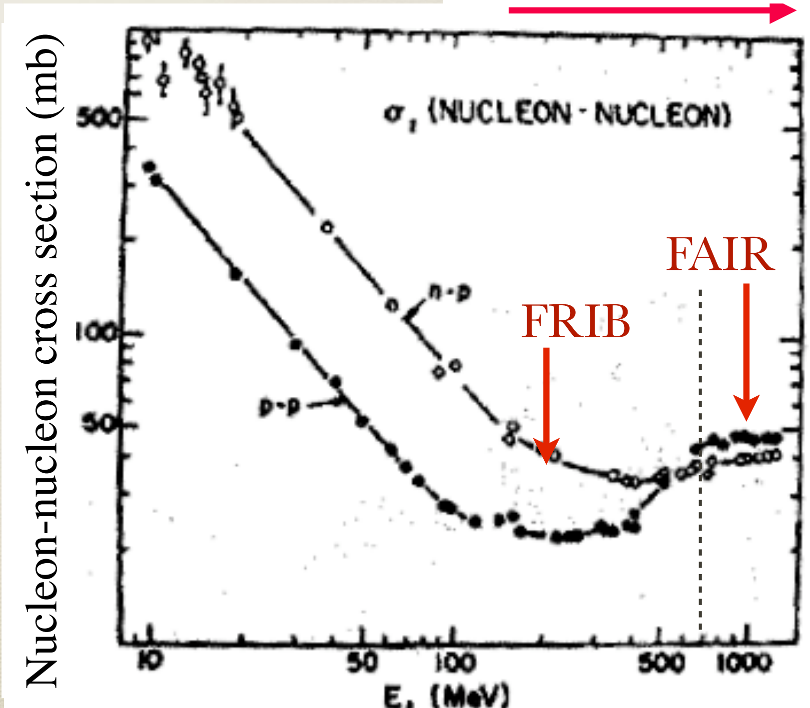
$$\Gamma_{ik}\left(\vec{b}\right) = \frac{1 - i\alpha_{ik}}{4\pi\beta^2_{ik}}\,\sigma_{ik}\exp\left(\frac{b^2}{2\beta^2{}_{ik}}\right)$$

nucleon-nucleon cross section (σ_{ik})

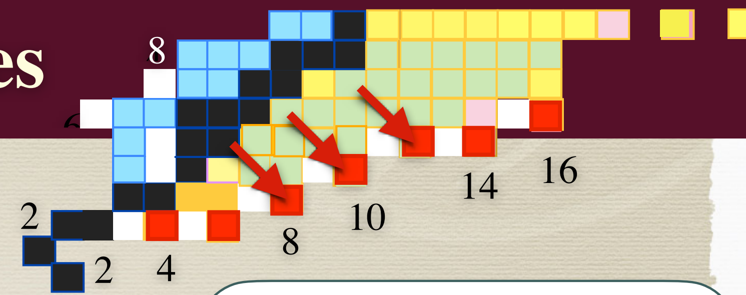
finite range parameter (β_{ik})
slope parameter of NN elastic differential cross section

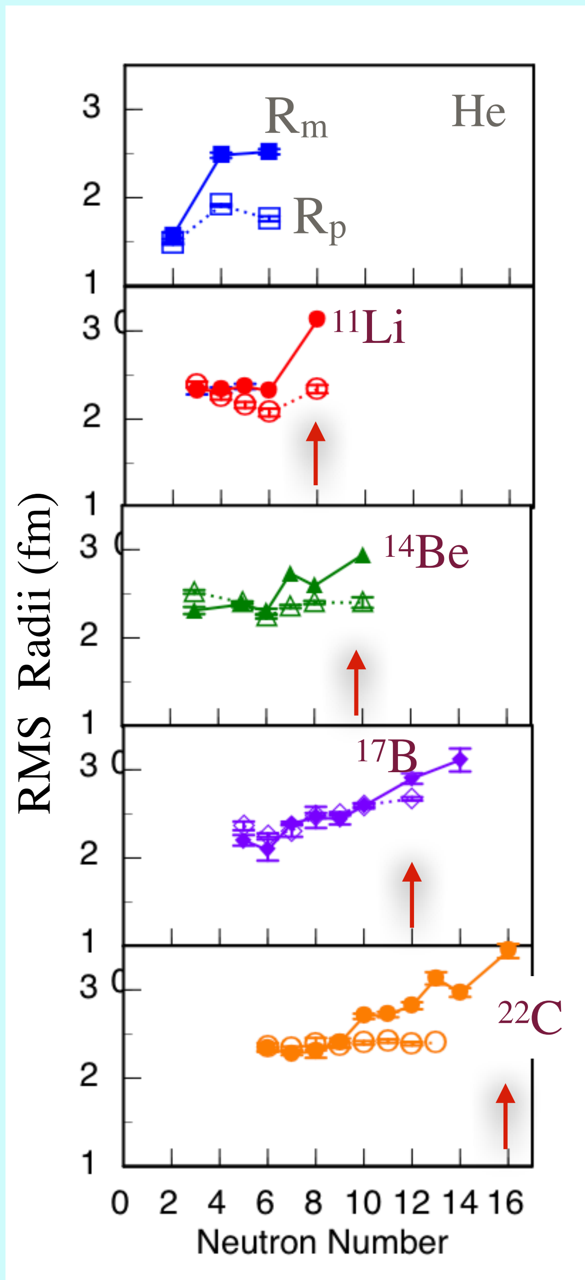
α = ratio of Re/Im NN scattering amplitudes

Suitable Energy for Glauber Model

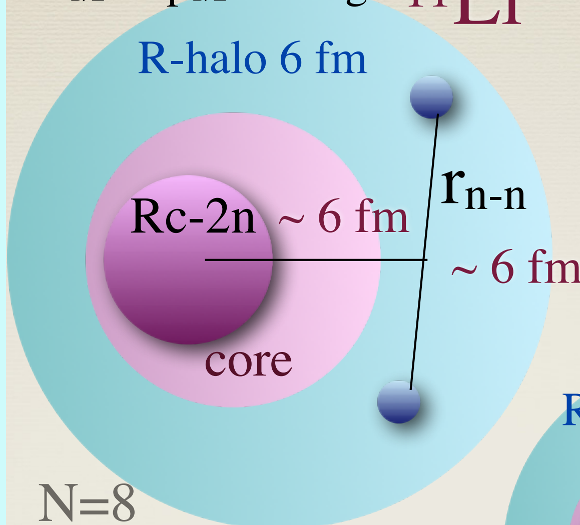


Radii and exotic neutron-rich structures





2s1/2 - 1p1/2 mixing ^{11}Li



N=8

■ Borromean nuclei
Core+n+n

Halo EFT

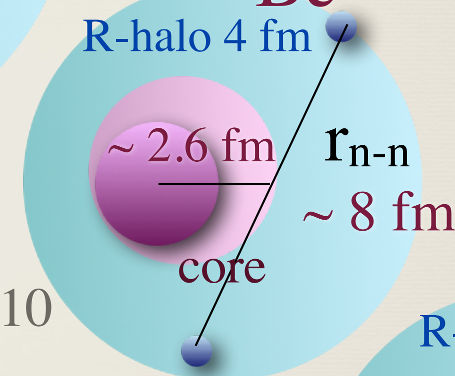
$$\delta\langle r_E^2\rangle := \langle r_E^2\rangle_{cnn} - \langle r_E^2\rangle_c.$$

$$\delta\left\langle r_E^2\right\rangle_{^{11}Li} = 1.68(62)\ fm^2$$

$$\delta\left\langle r_E^2\right\rangle_{^{14}Be} = 0.41(32)\ fm^2$$

P. Hagen, H.-W. Hammer, L. Platter, EPJA 49 (2013) 118

^{14}Be



N=10

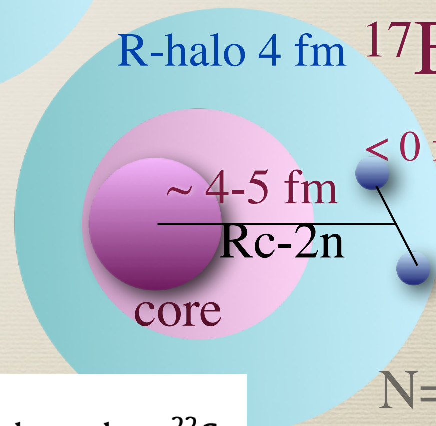
PTEP Prog. Theor. Exp. Phys. 2014, 101D02 (7 pages) DOI: 10.1093/ptep/ptu134

Letter

Proton radius of ^{14}Be from measurement of charge-changing cross sections

S. Terashima et al.,

R-halo 4 fm ^{17}B



PRL 113, 132501 (2014) PHYSICAL REVIEW LETTERS week ending 26 SEPTEMBER 2014

Proton Radii of $^{12-17}$B Define a Thick Neutron Surface in ^{17}B

A. Estrade et al.,

N=12

2s1/2 - 1d5/2 mixing

Physics Letters B Y. Togano et al.,

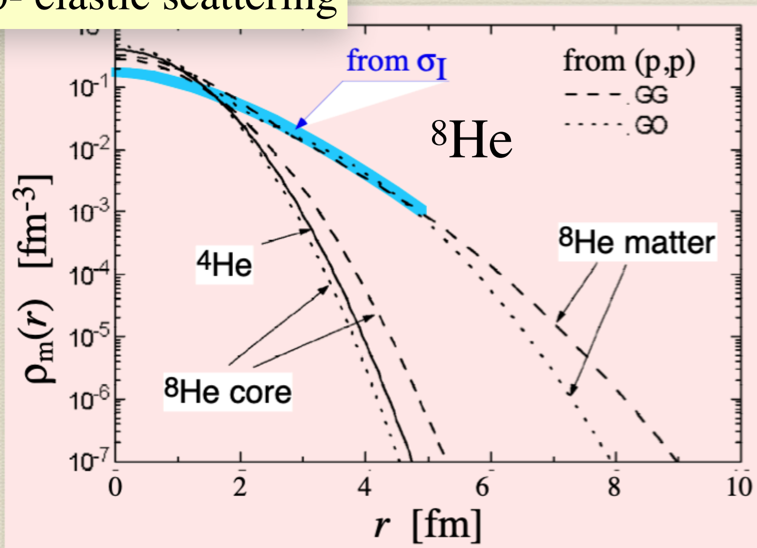
Interaction cross section study of the two-neutron halo nucleus ^{22}C

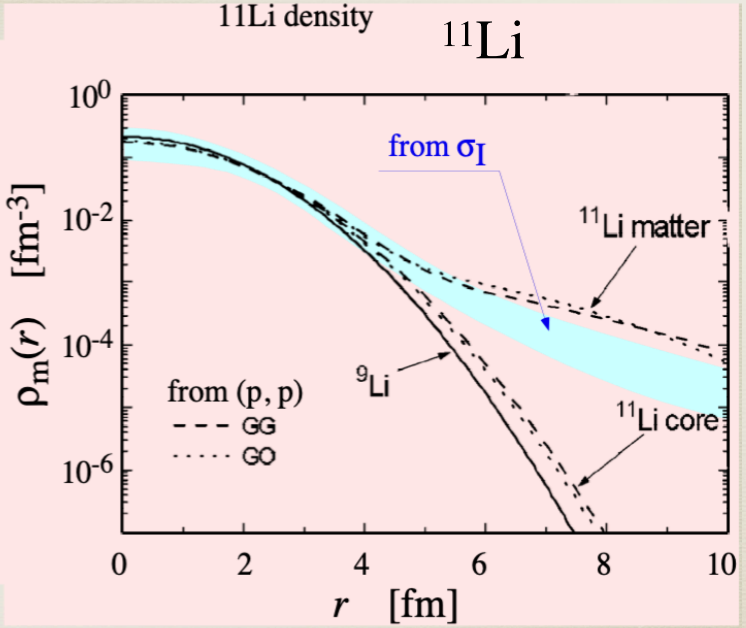
Observation of a Large Reaction Cross Section in the Drip-Line Nucleus ^{22}**C**

K. Tanaka *et al.* Phys. Rev. Lett. **104**, 062701

How well does transmission technique work?

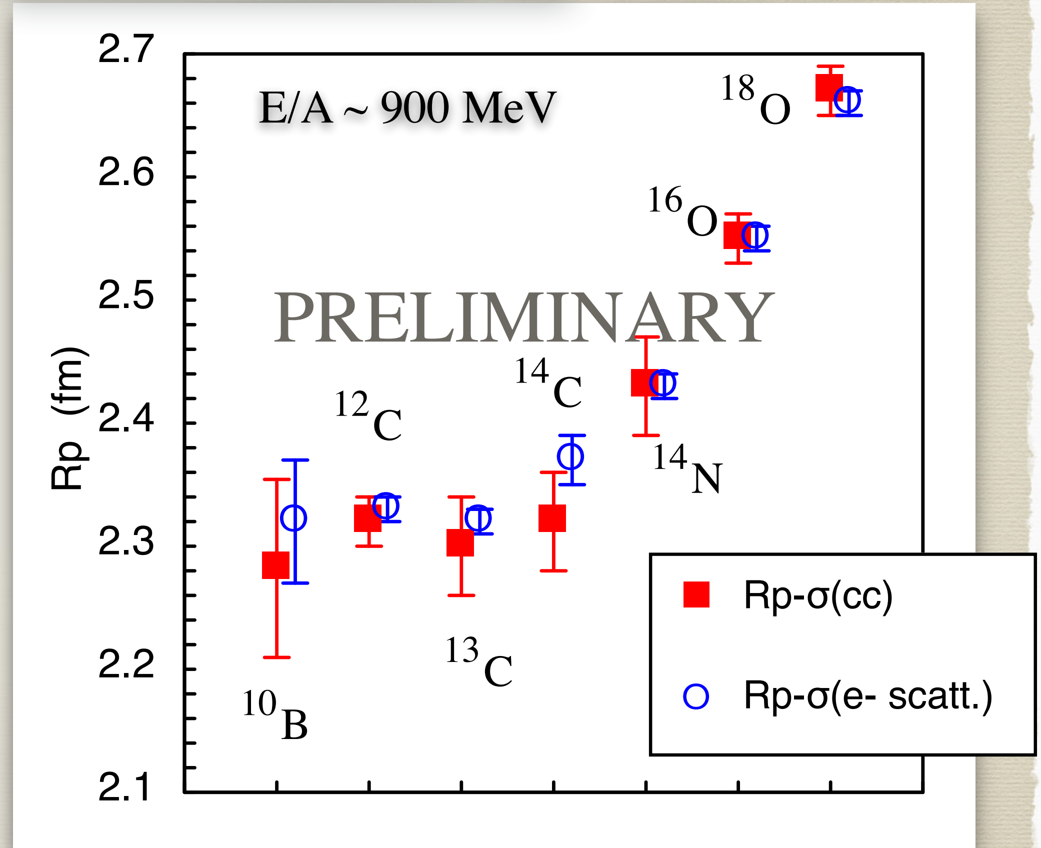
Rm : p- elastic scattering





Matter distribution from σ_I and (p,p) consistent

Rp : electron elastic scattering

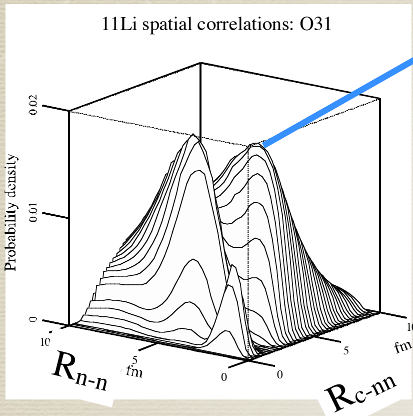


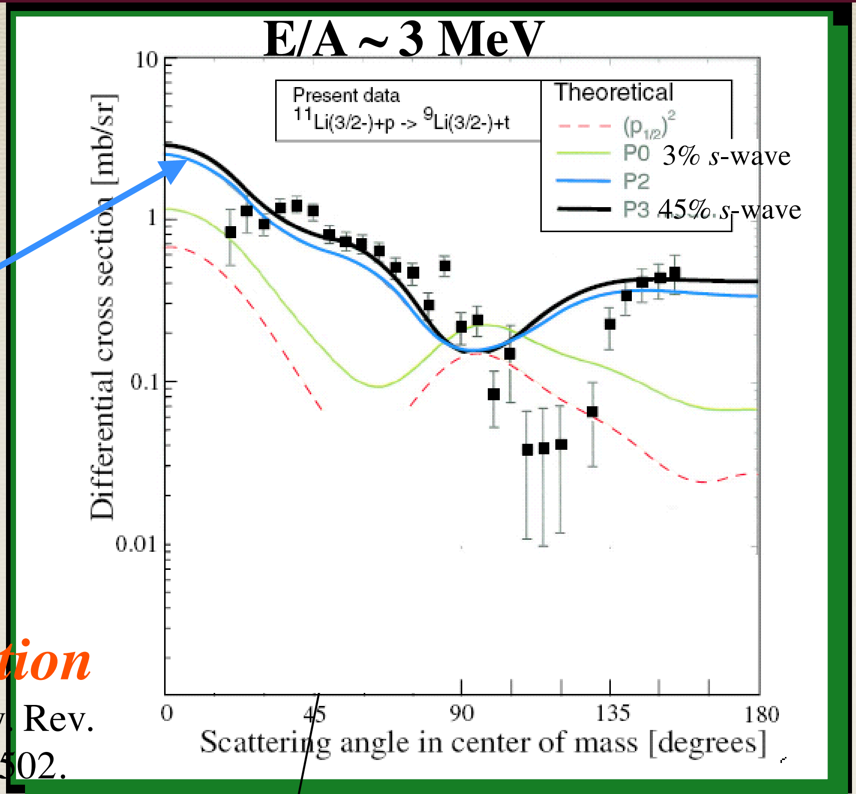
R_p of stable nuclei from σ_{cc} consistent with e^- scattering

^{11}Li Halo neutron correlation

Quantum entanglement

^{11}Li(p,t)^{9}Li @ TRIUMF

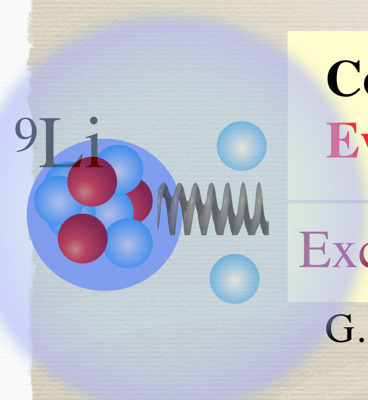




Strong *n-n* correlation

I. Tanihata et al., Phy. Rev. Lett. 100 (2008) 192502.

^{9}Li first excited state

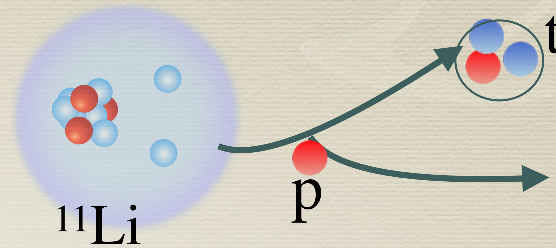


Core (^{9}Li) excited state : $J^{\pi}(n\text{-}n)=2^{+}, 1^{+}$

Evidence of phonon mediated pairing

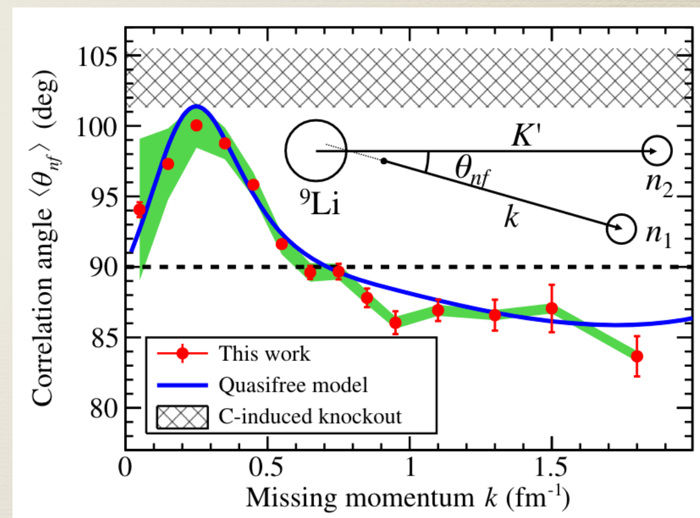
Exchange of *core-halo* vibration binds the halo

G. Potel et al., Phy. Rev. Lett. 105 (2010) 172502.



^{11}Li(p,pn)^{10}Li @ RIKEN

E/A = 246 MeV



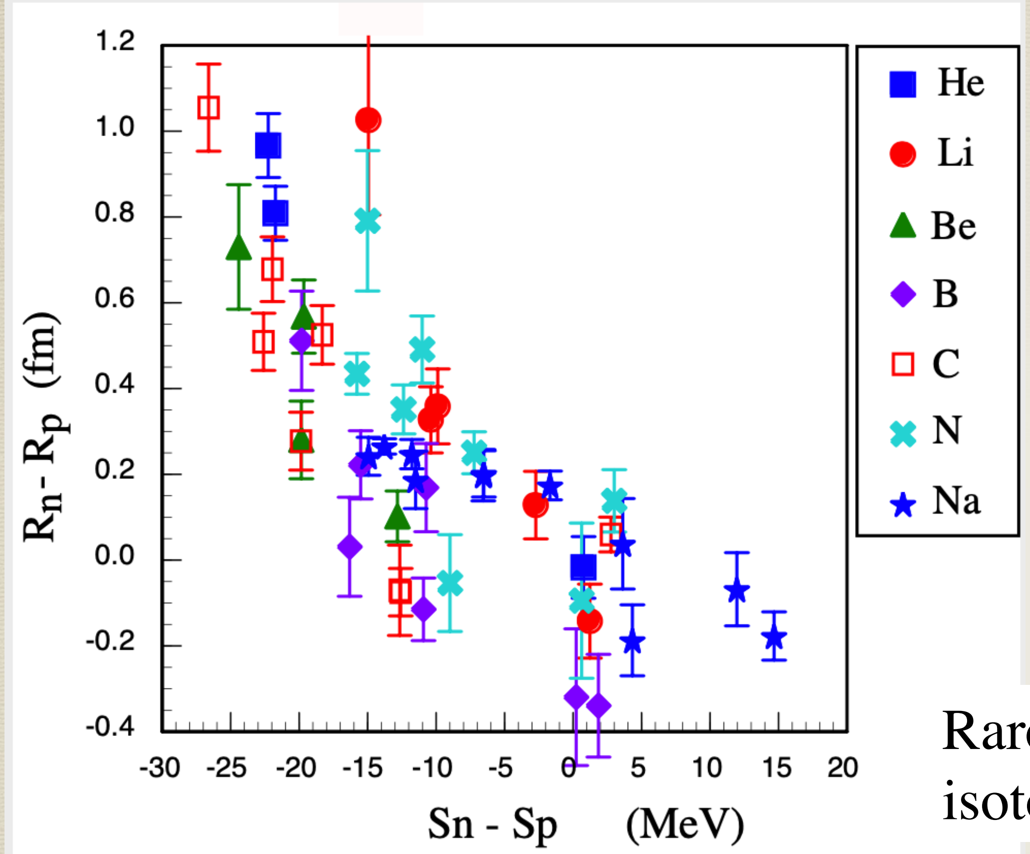
Y. Kubota et al., Phys. Rev. Lett. 125 (2020) 252501

Di-neutron correlation @ nuclear surface $r \sim 3.6$ fm

Neutron Surface

Neutron Skin : R_n - R_p

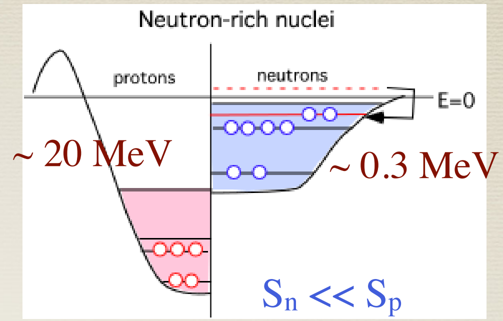
$$R_{skin} = \sqrt{\left(\frac{A}{N}\right)R_m^2 - \left(\frac{Z}{N}\right)R_p^2} - R_p$$



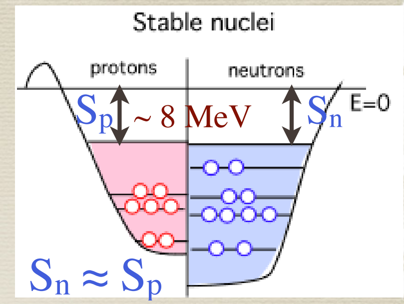
Neutron-rich nuclei

Stable nuclei

N/Z >> 1



N/Z ~ 1-1.5

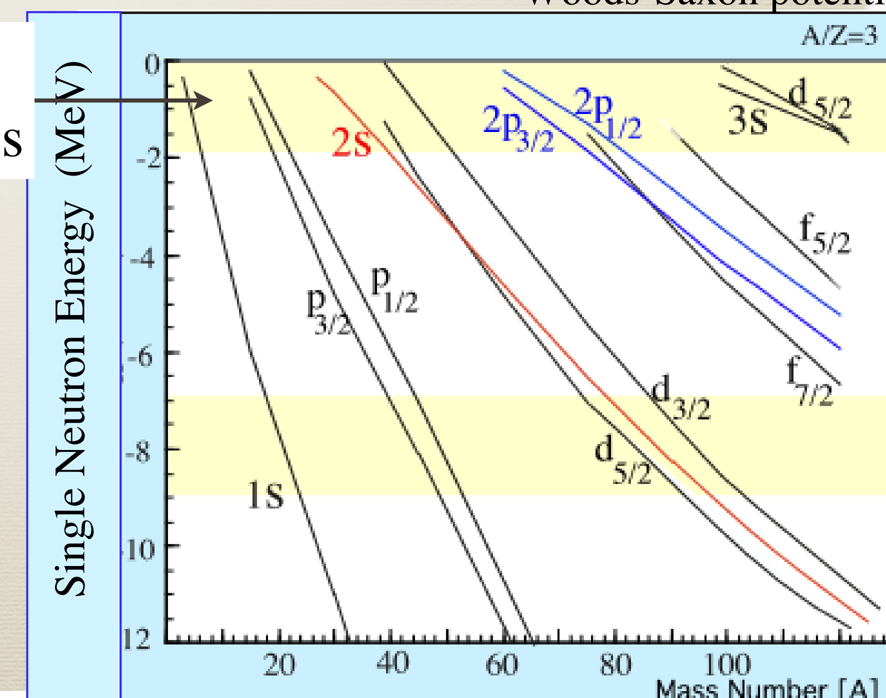


Fermi-levels of neutrons and protons are similar.

- Weak binding & *n-p* Fermi level difference

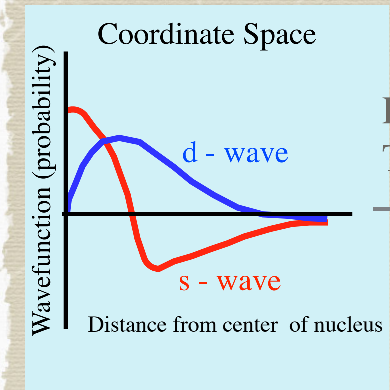
Rare isotopes

Woods-Saxon potentia

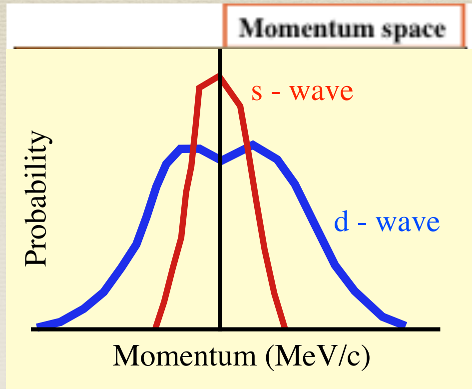


Low angular momentum orbitals are lowered in energy crossing over higher angular momentum orbitals

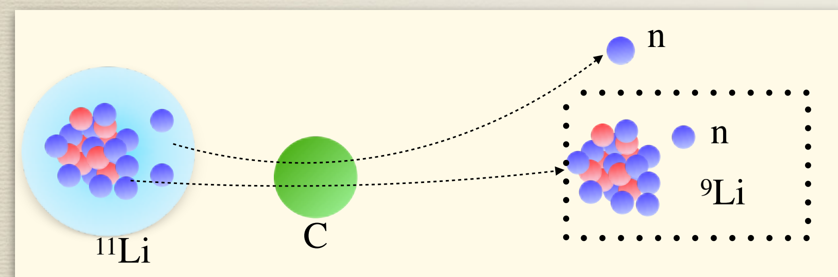
What lies behind the halo ? - a look at orbitals

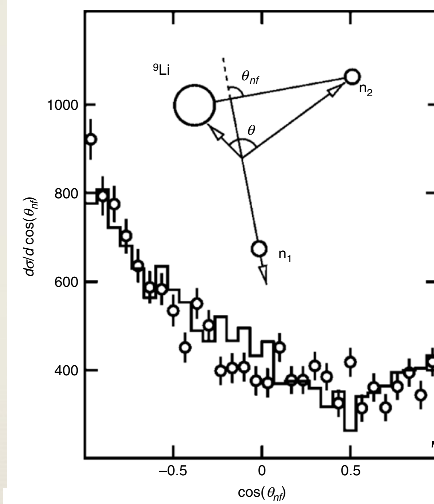


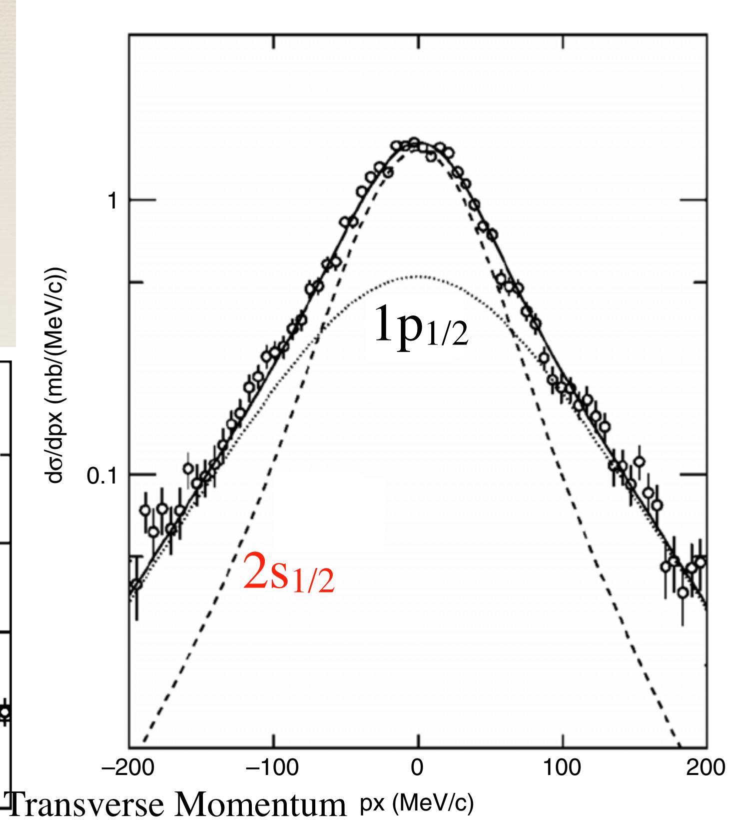
Fourier Transform



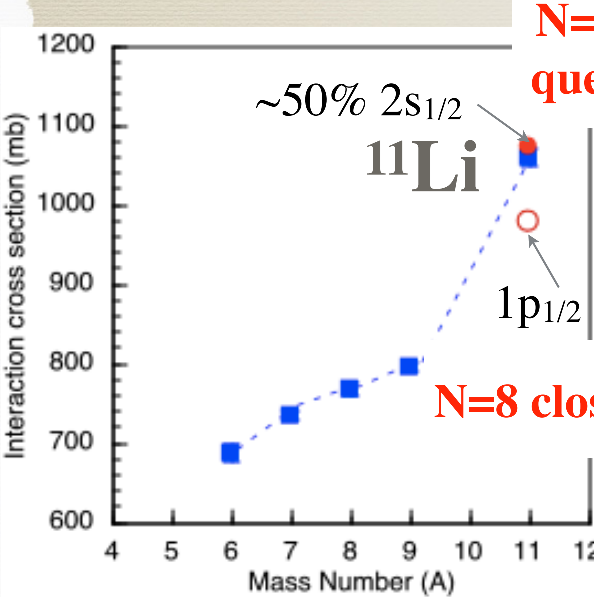
$^{11}Li + C \rightarrow {}^{10}Li$
Momentum distribution





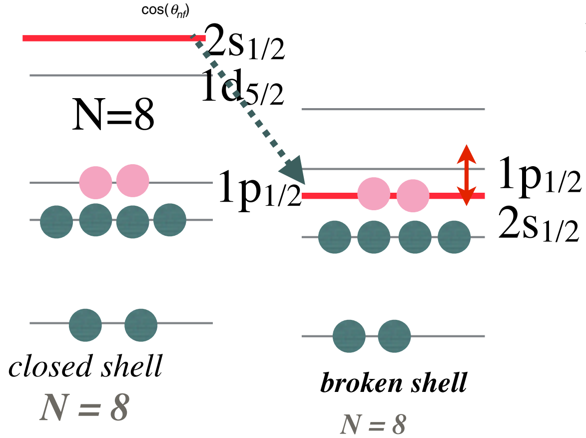


H. Simon et al., PRL (1999)



N=8 shell quenching

N=8 closed shell



What lies behind the halo ? - a look at orbitals

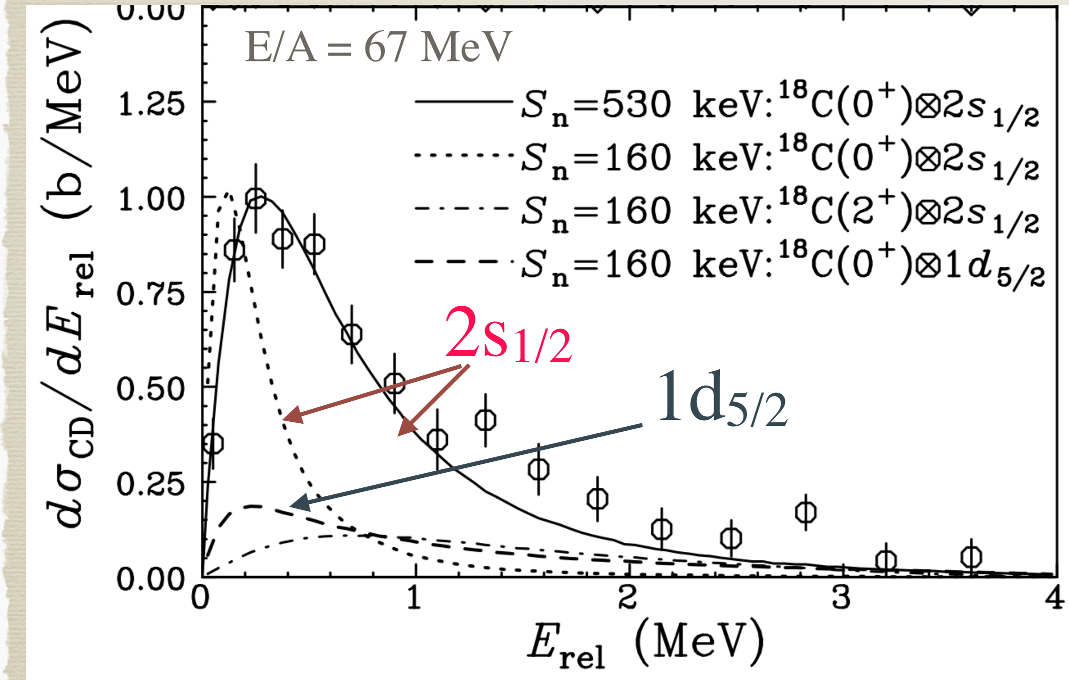
Coulomb dissociation

$^{19}C + {}^{208}Pb \rightarrow {}^{18}C + n$

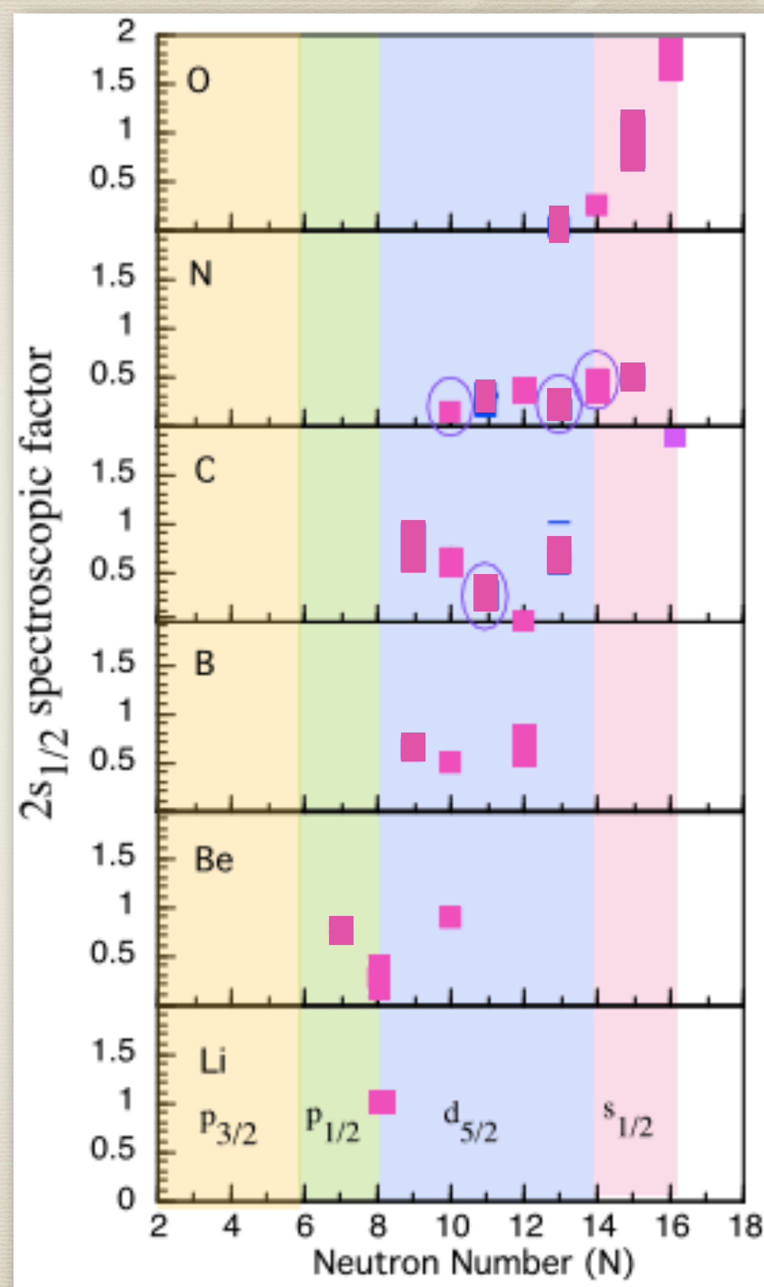
framework of direct breakup

$$\frac{d\sigma_{CD}}{dE_{rel}} = \frac{16\pi^3}{9\hbar c} N_{E1}(E_x) \frac{dB(E1)}{dE_{rel}}$$

$$\frac{dB(E1)}{dE_{rel}} = \left| \langle \mathbf{q} | \frac{Ze}{A} r Y^1_m | \Phi(\mathbf{r}) \rangle \right|^2$$

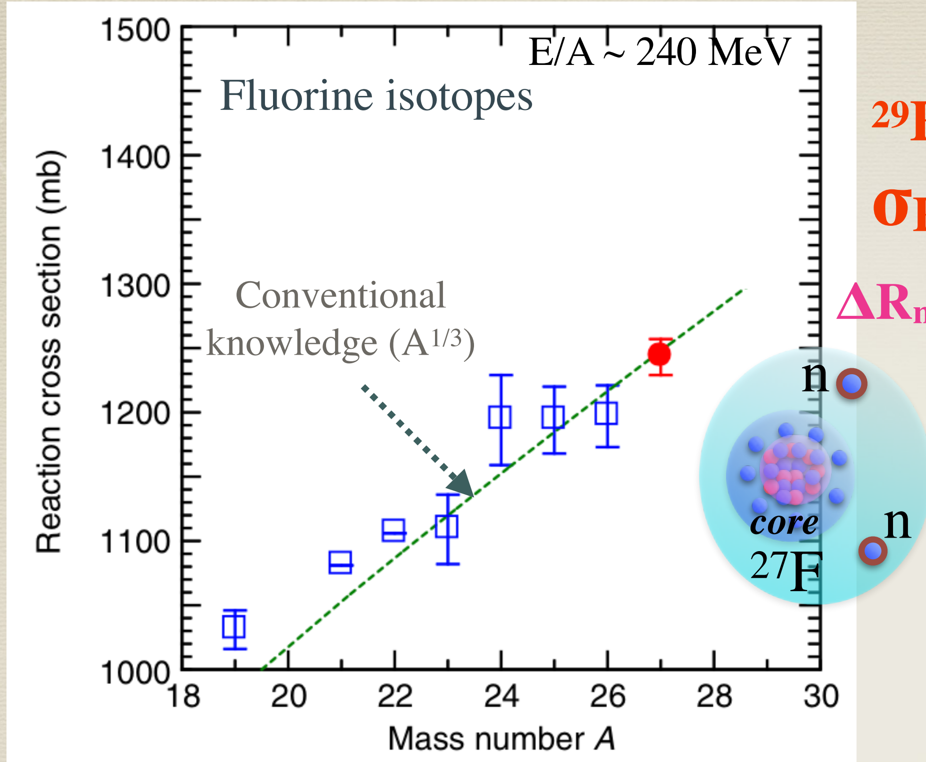


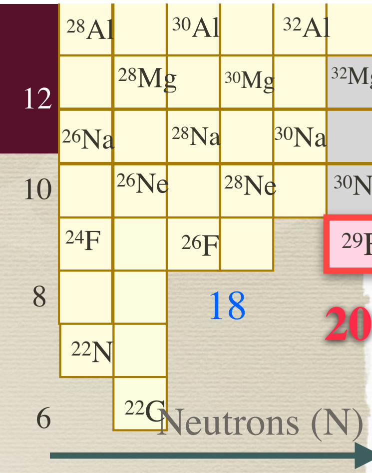
T. Nakamura et al., PRL 83 (1999) 1112



Do all shells dissolve into halos ?

^{29}F





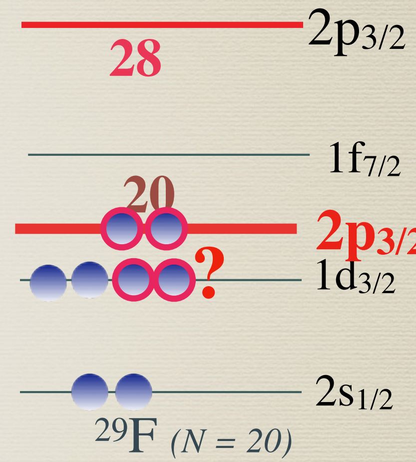
S_{2n} = 1.4(6) MeV

^{29}F Large increase in

σ_R —> matter radius

$\Delta R_m [^{29}F - ^{27}F] \sim 0.39(18)$ fm

Two-neutron halo



■ A. Honma et al., JPS Proc. 14 (2017) 021010

● PHYSICAL REVIEW LETTERS **124** 222504 (2020)

S. Bagchi et al. **Two-Neutron Halo is Unveiled in ^{29}**

N = 20, 28 shells vanish in a Borromean halo

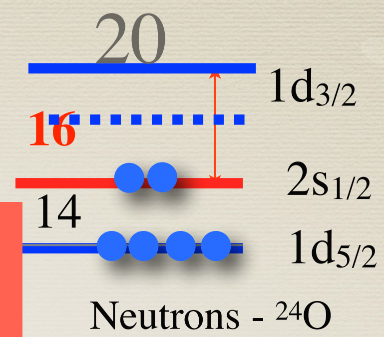
New shell seen at the neutron drip-line

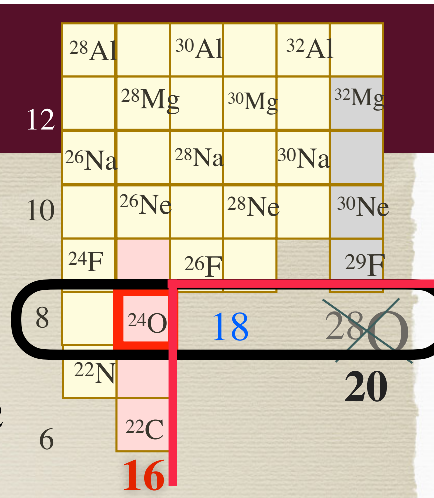
^{24}O new doubly magic nucleus

PRL 102, 152501 (2009) PHYSICAL REVIEW LETTERS week ending 17 APRIL 2009

One-Neutron Removal Measurement Reveals ^{24}O as a New Doubly Magic Nucleus

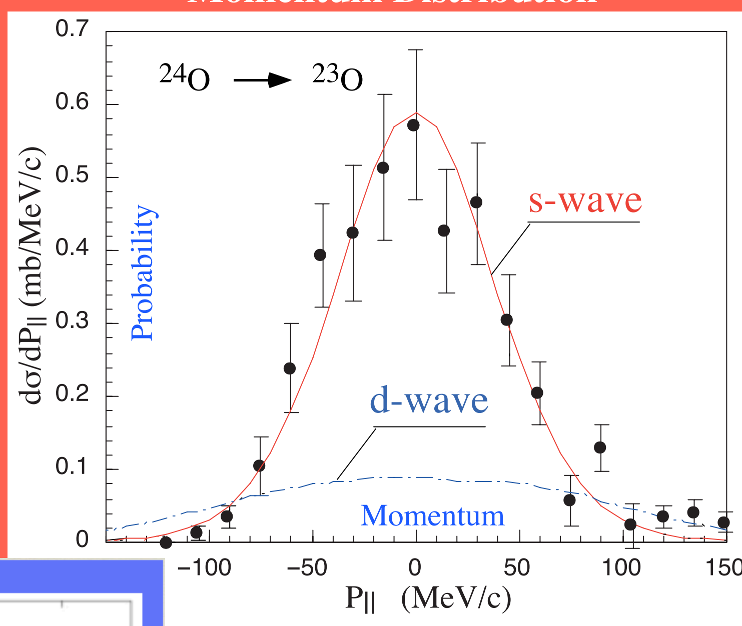
R. Kanungo et al.

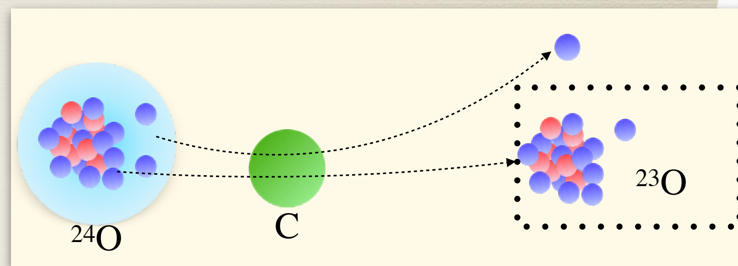




$^{24}O+C \rightarrow {}^{23}O$

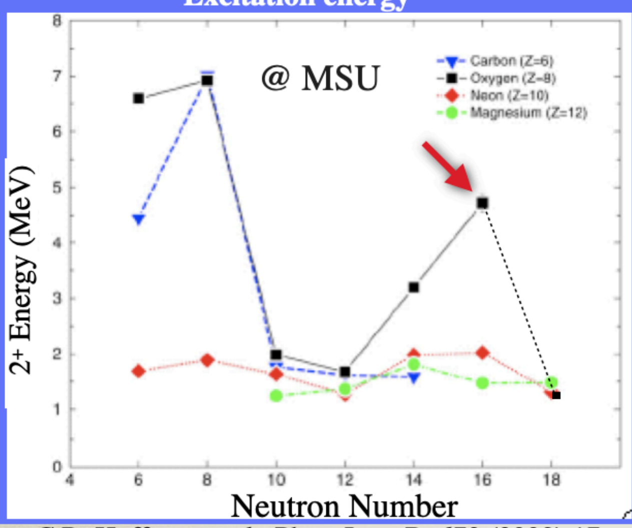
Momentum Distribution





$^{26}F+Be \rightarrow {}^{23}O + n$

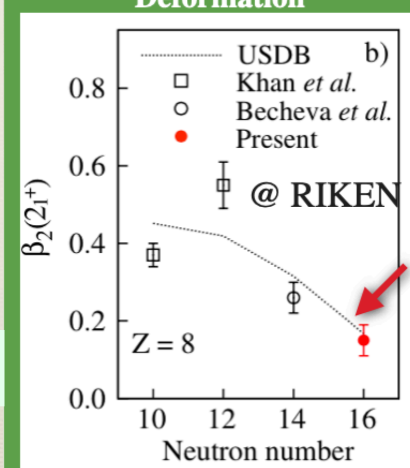
Excitation energy



C.R. Hoffman et al., Phys. Lett. B 672 (2009) 17

$^{24}O(p,p')^{23}O+n$

Deformation



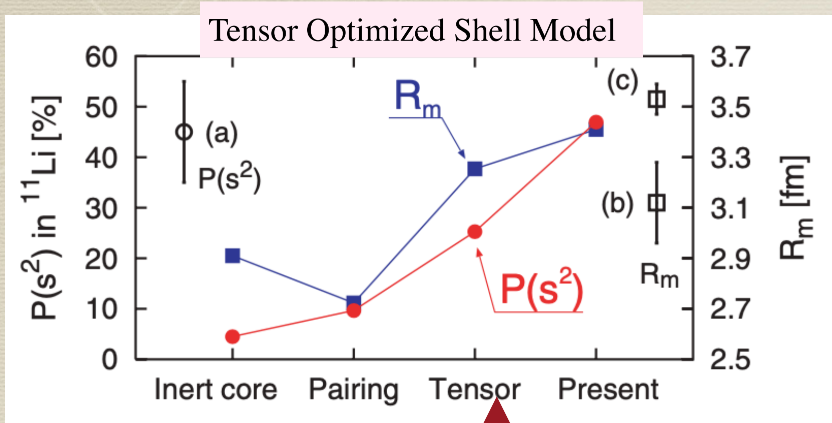
K. Tshoo et al., Phys. Rev. Lett. 109 (2012) 022501

NUCLEAR PHYSICS New & Views :Nature 459 (2009) 1069

Unexpected doubly magic nucleus

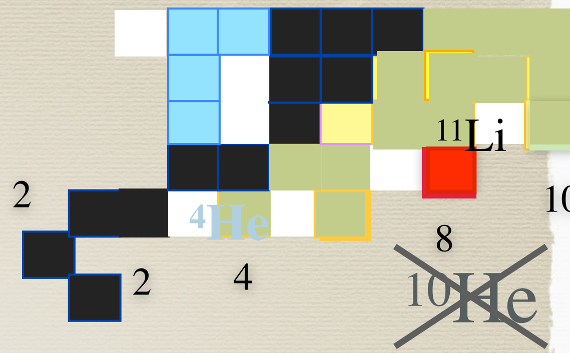
Evolution of orbitals : Tensor Force

❖ Tensor Force in High Momentum

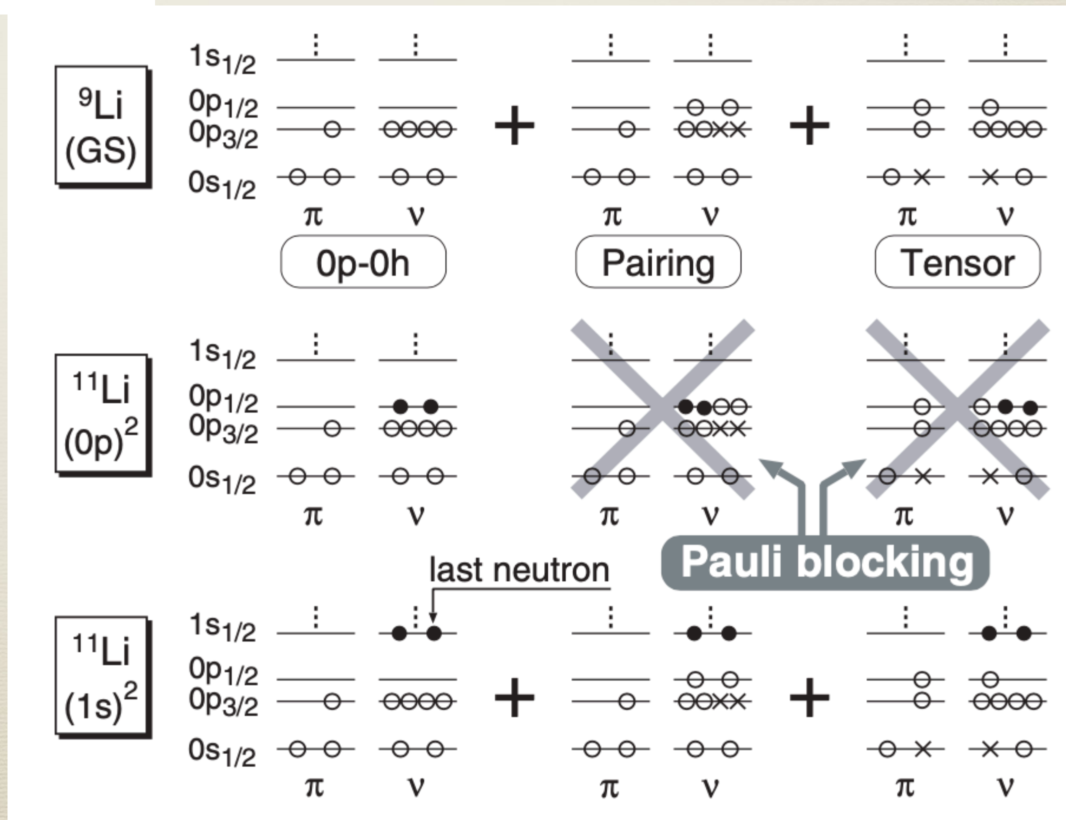


T. Myo *et al*., PRC (2007)

2s$_{1/2}$ lowering : predicted due to Tensor force - 2π exchange



^{11}Li$_8$



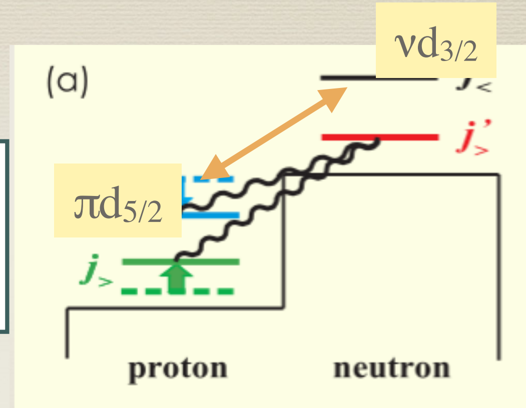
N = 8 shell vanishes

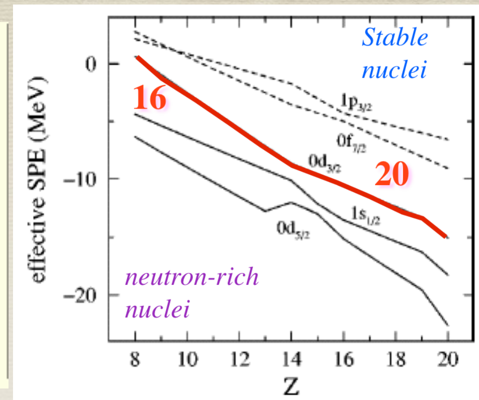
Evolution of orbitals : Tensor Force

❖ Monopole Tensor Interaction

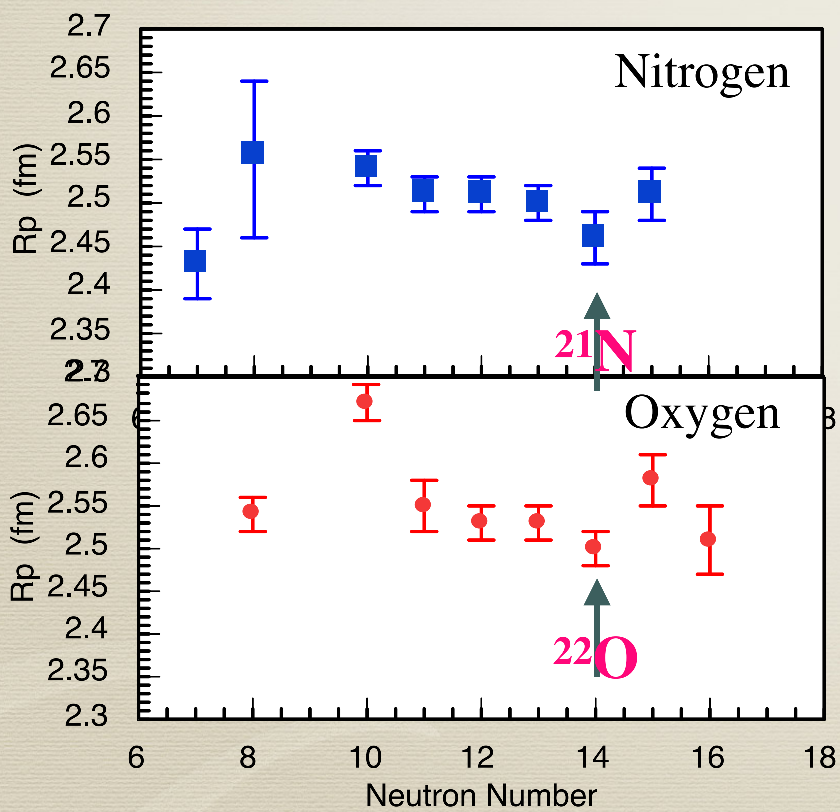
p($j_< = l$-1/2) - n($j_>$=l+1/2) attractive
p($j_>$ =l+1/2) - n($j_>$ =l+1/2) repulsive

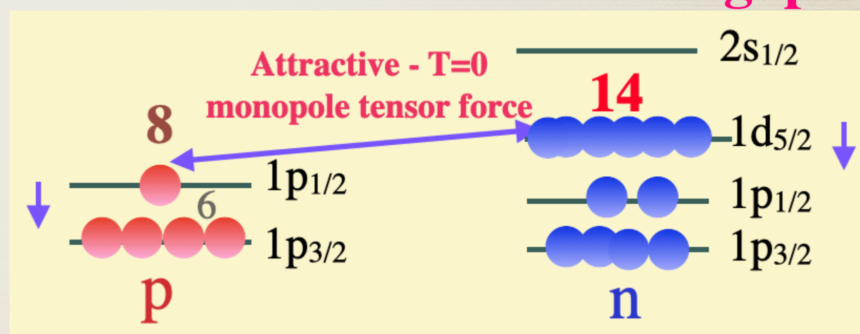
T. Otsuka *et al*., Phys. Rev. Lett. 2005





^{21}N, ^{22}O : Dip in R_p directly shows effect of tensor force for N = 14 new shell gap





Proton $p_{1/2}$ more strongly bound -> Smaller R_p. &
***Z* = 6 gap reduced**

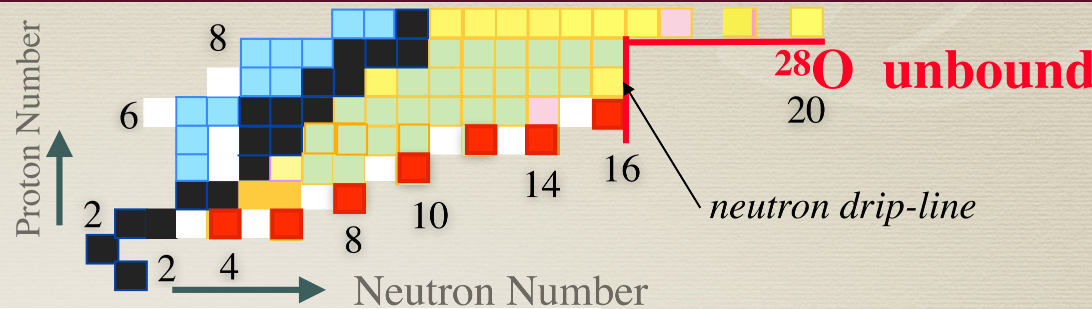
Neutron $d_{5/2}$ more strongly bound -> Smaller R_m. & ***N* = 14 gap**

■ S. Bagchi, R.K., W. Horiuchi *et al*. Phys. Lett. B (2019)

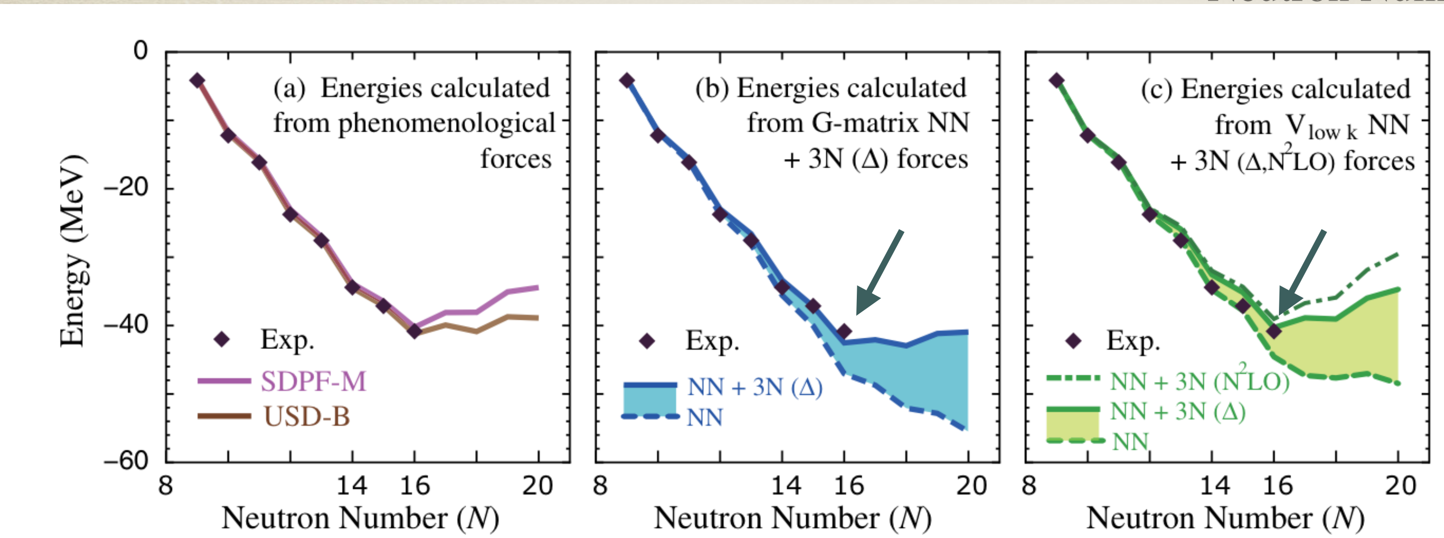
● S. Kaur, R.K., W. Horiuchi *et al*. Phys. Rev. Lett. (2022)

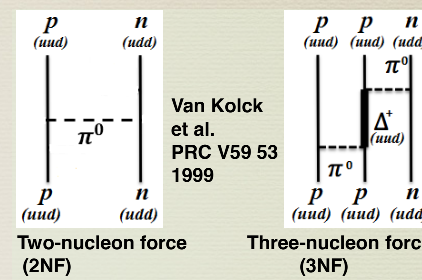
Evolution of orbitals : Three Nucleon Force

❖ Three-nucleon force



Drip-line at $N = 16$ in O isotopes



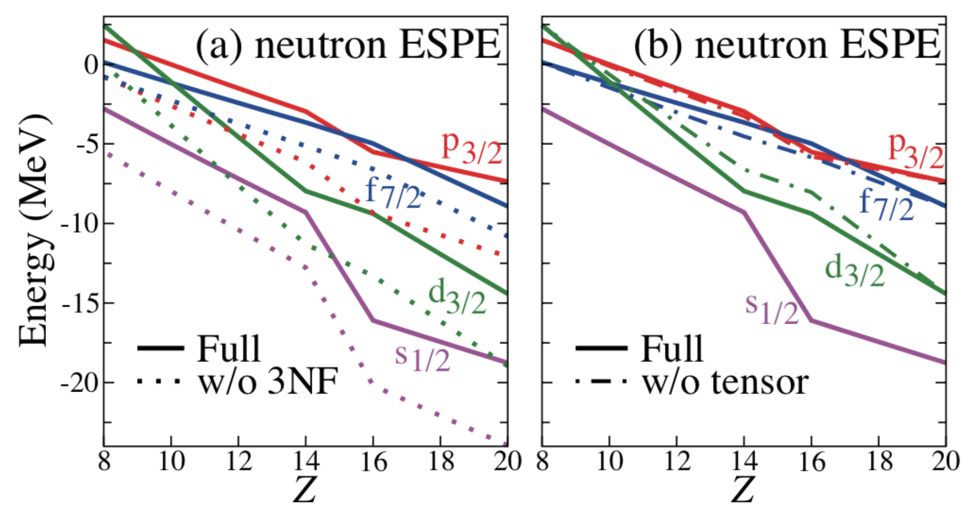


N = 20

T. Otsuka et al., 2010

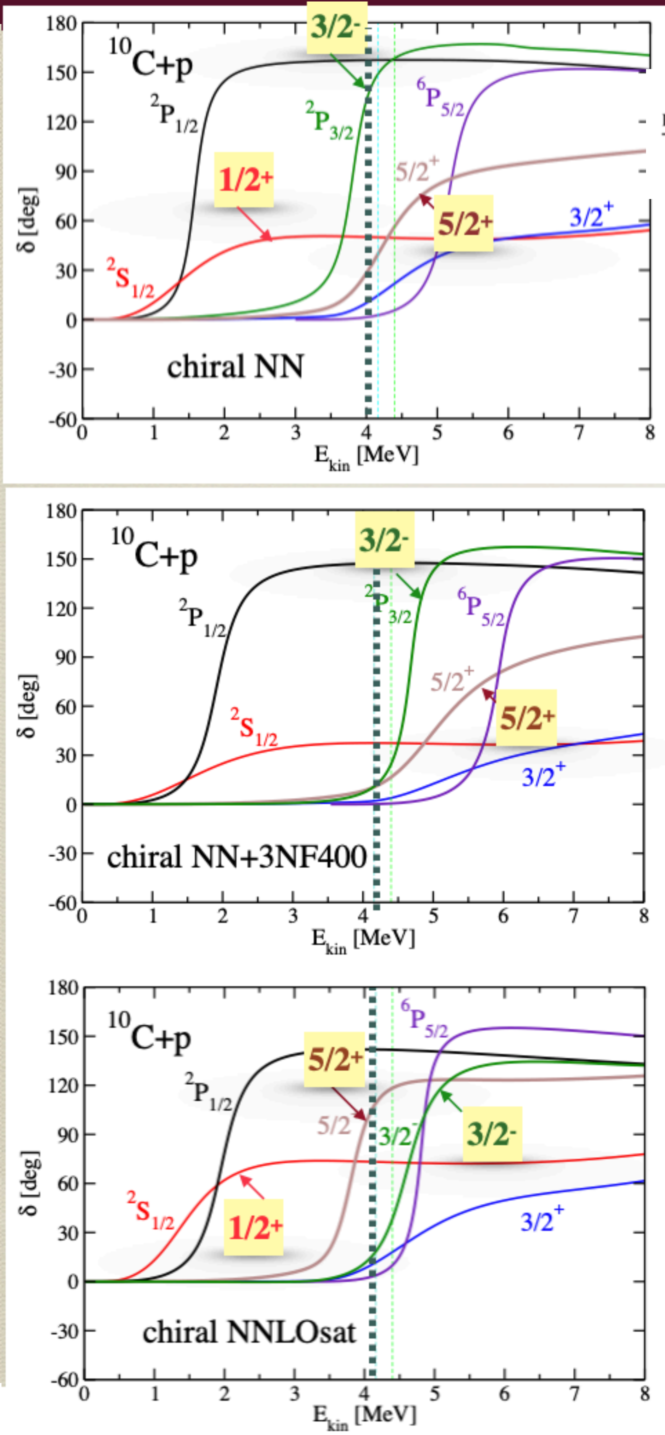
Three-nucleon force essential for binding

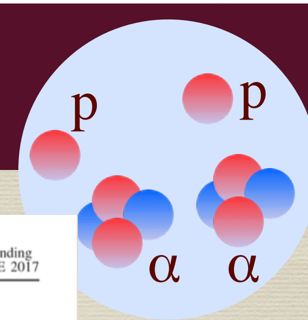
repulsive effect

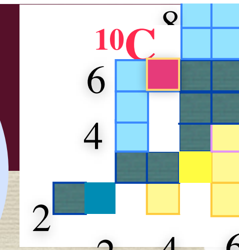


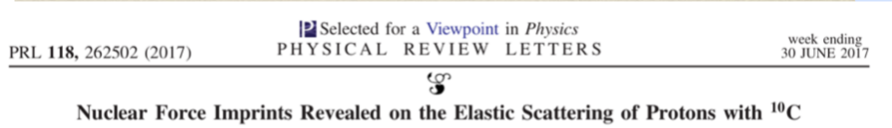
T. Tsunoda et al., 2017

^{10}C+p scattering : probing the nuclear force







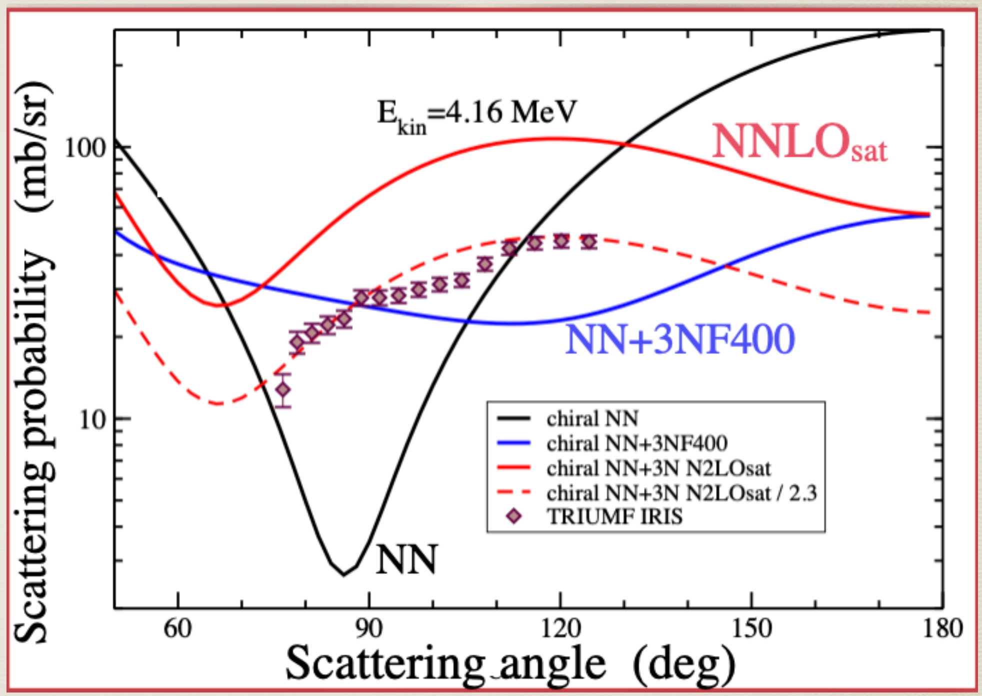

Selected for a Viewpoint in Physics

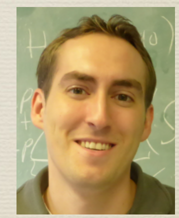
PRL 118, 262502 (2017) PHYSICAL REVIEW LETTERS week ending 30 JUNE 2017

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

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

$E_{cm} = 4.16$ MeV @ TRIUMF

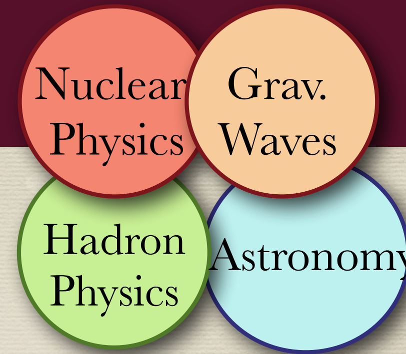




^{10}C(p,p) dσ/dΩ has strong sensitivity to the nuclear force.

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

Equation of state of asymmetric nuclear matter



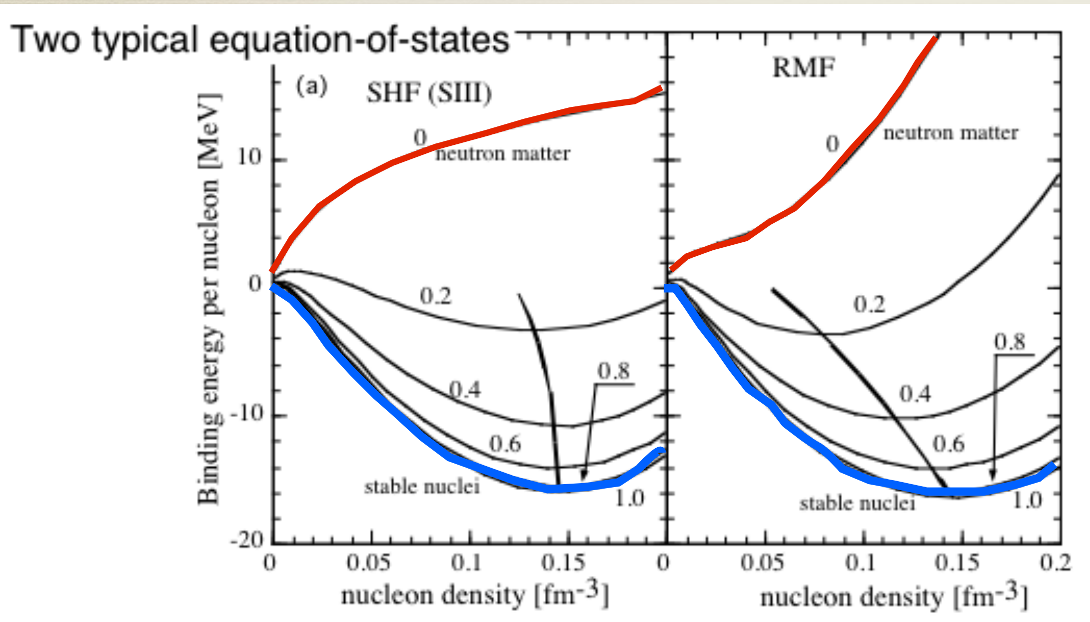
$$e(\rho,\delta) = e(\rho,0) + c_{\text{sym}}(\rho)\delta^2 + \mathcal{O}(\delta^4)$$

$$\delta = \frac{\rho_n - \rho_p}{\rho}$$

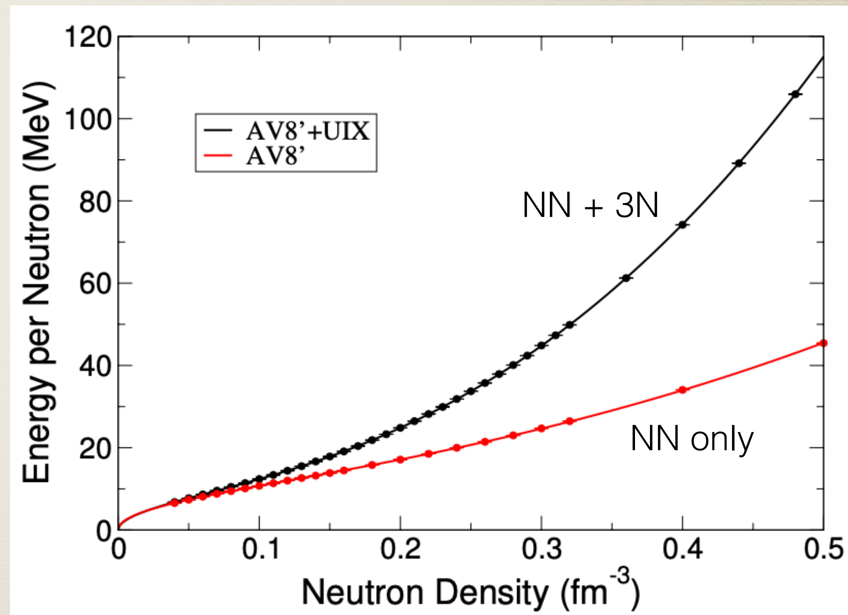
e = energy per particle

Symmetry Energy is poorly constrained

$$c_{\text{sym}}(\rho) = J - L\epsilon + \tfrac{1}{2}K_{\text{sym}}\epsilon^2 + \mathcal{O}(\epsilon^3) \qquad \epsilon = (\rho_0 - \rho)/(3\rho_0)$$



K.Iida and K. Oyamatsu, Prog. Theor. Phys. 109(2003)631



Gandolfi et al. (2013)

Models for EOS differ widely for asymmetric nuclear matter

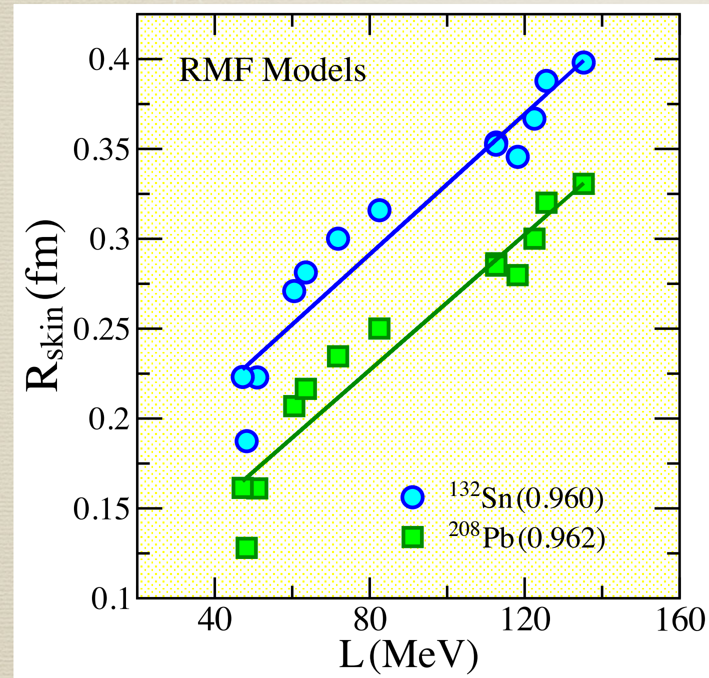
EOS predictions vary for nuclear force prescriptions

Neutron Skin : EOS - Symmetry energy

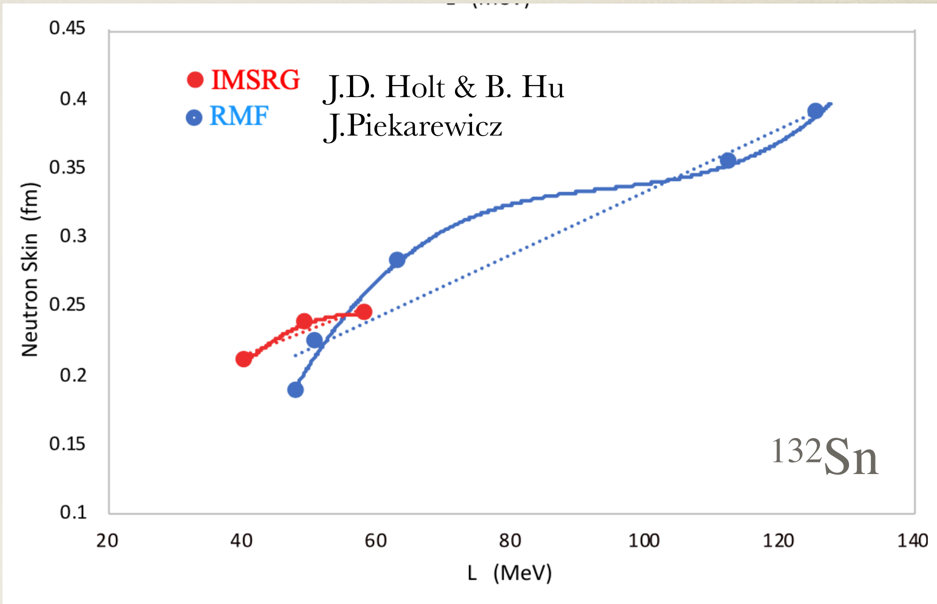
$$L = 3\rho\partial c_{sym}(\rho)/\partial\rho|_{\rho_0}$$

Neutron skin is strongly correlated with L

Correlation differs for RMF and *ab initio* frameworks



J. Piekarewicz



Ab initio **calculations have now reached predictions of R_{skin} for ^{208}Pb**

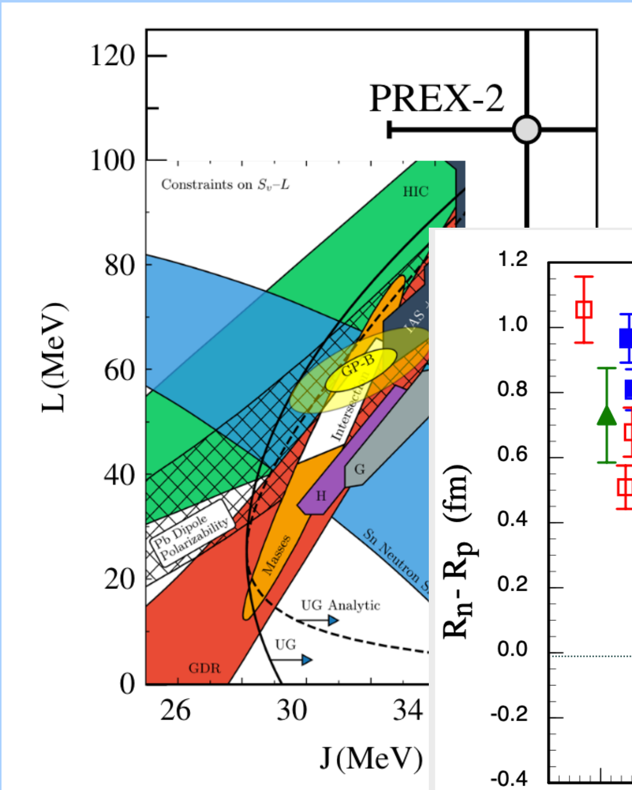
B. Hu et al.

Determine R_{skin} of rare isotopes

$$R_{skin} = R_n - R_p = \sqrt{\left(\frac{A}{N}\right)R_m^2 - \left(\frac{Z}{N}\right)R_p^2} - R_p$$

Neutron skin (PREX & CREX @ JLab) : Symmetry energy

Parity violating electron scattering

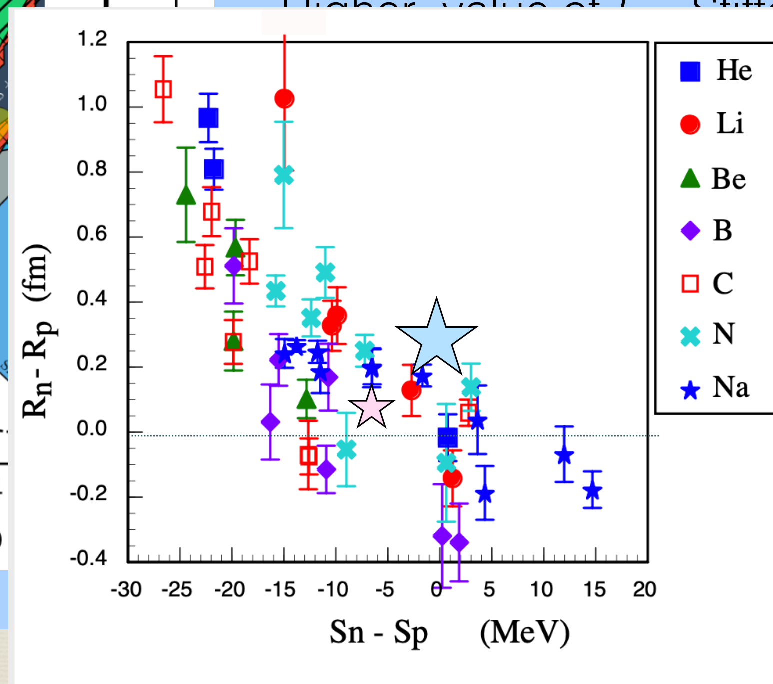


Reed et al., PRL (2021)

PREX value of neutron skin of 208Pb is higher than other measurements

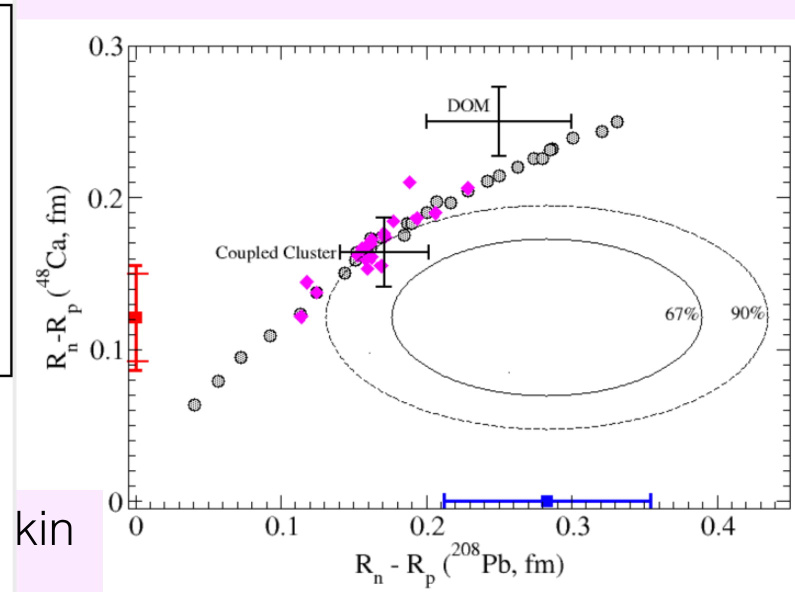
↓

Higher value of L — Stiffer EOS



kin

Lower value of L



D. Adhikari *et al*., PRL 128 (2022)142501

^{48}Ca neutron skin

Dipole Polarizability
Reaction Cross Section
CREX
} Agree

Rare isotopes with thicker skins will be more sensitive constraints on '*L*'

Summary

High energy reactions produce rare isotopes

Reactions of rare isotopes reveal new features - changing the conventional knowledge

- Few-body correlations emerge in many-body neutron-proton asymmetric nuclei.

  Nuclear Halos - Core + halo neutron correlation

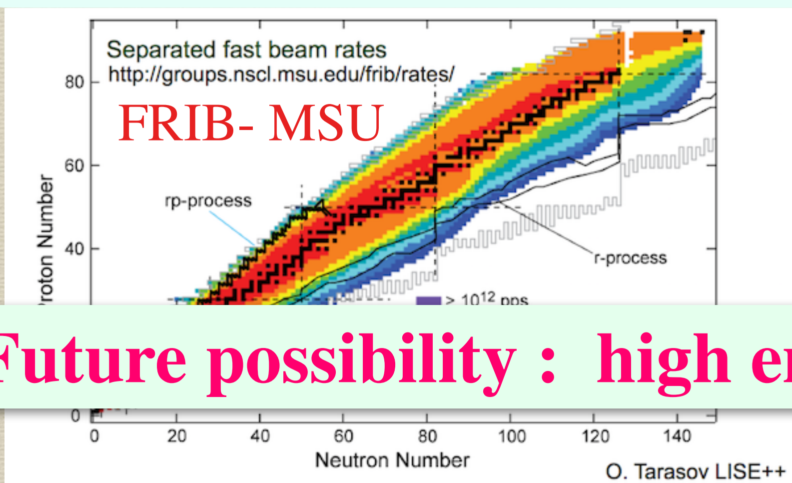
- Nuclear shells changes are related to these new structures.

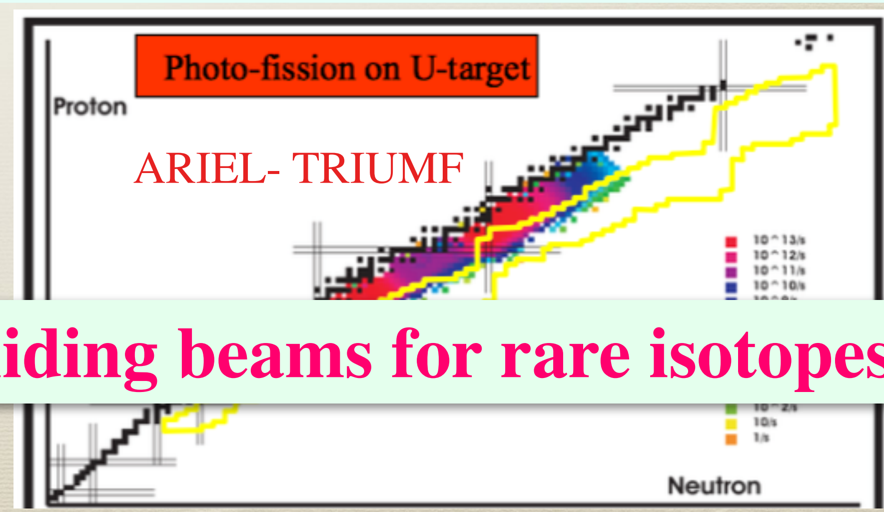
  Known shells @ N = 8, 20, 28 disappear *New Shells appear @ N = 16*

- Nuclear force needs to be better understood

  Rare isotope scattering shows strong sensitivity to various three-nucleon forces

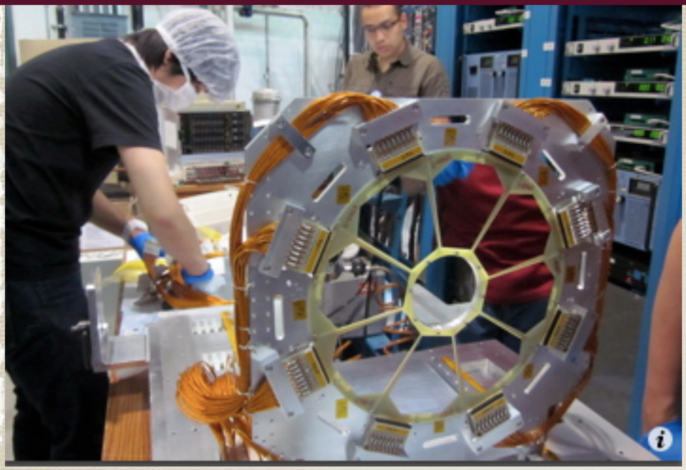
New generation facilities bring access to exotic high mass rare isotopes

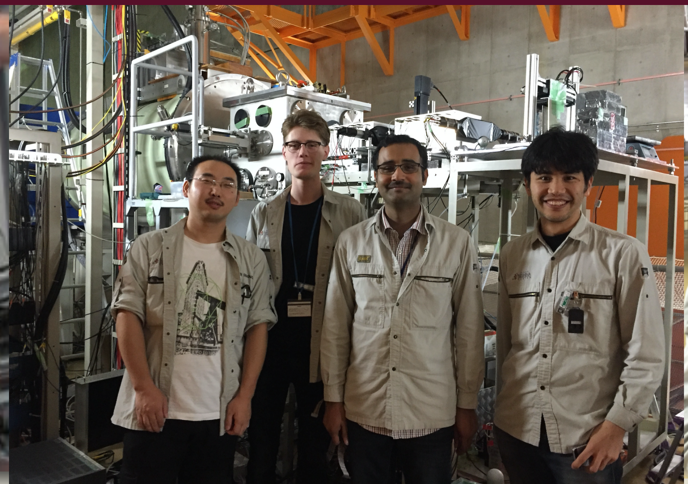
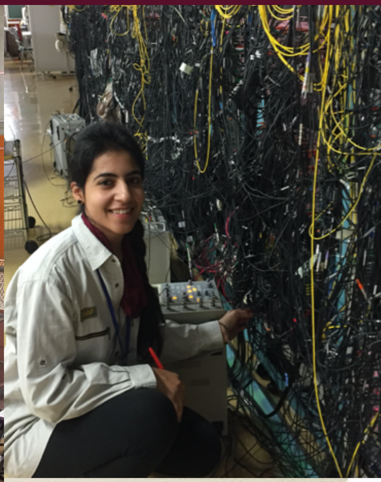




Future possibility : high energy colliding beams for rare isotopes?

Our Team



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