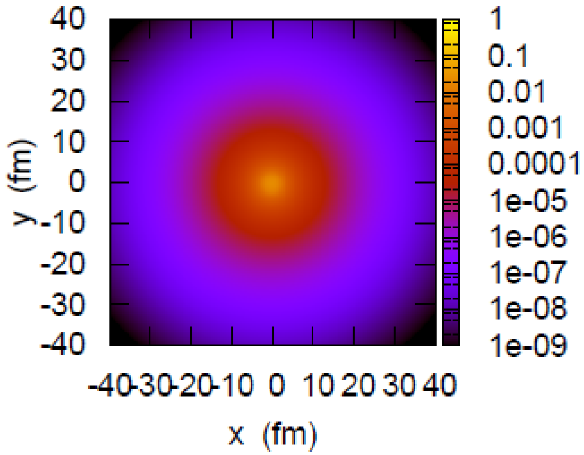
Pairing correlations and odd-even staggering in reaction cross sections of weakly-bound nuclei



K. Hagino (Tohoku U.)

H. Sagawa (U. of Aizu)

- PRC84('11)011303(R)
- PRC85('12)014303
- arXiv:1202.2725 [nucl-th]

1. Introduction: odd-even staggerings in atomic nuclei

2. Odd-even staggering of reaction cross sections (σ_R)

3. Pairing correlation in weakly-bound nuclei and σ_R

4. Staggering parameter

5. Summary

Introduction: odd-even staggering in atomic nuclei

➢ isotope shifts: smaller charge radius for odd-A nuclei

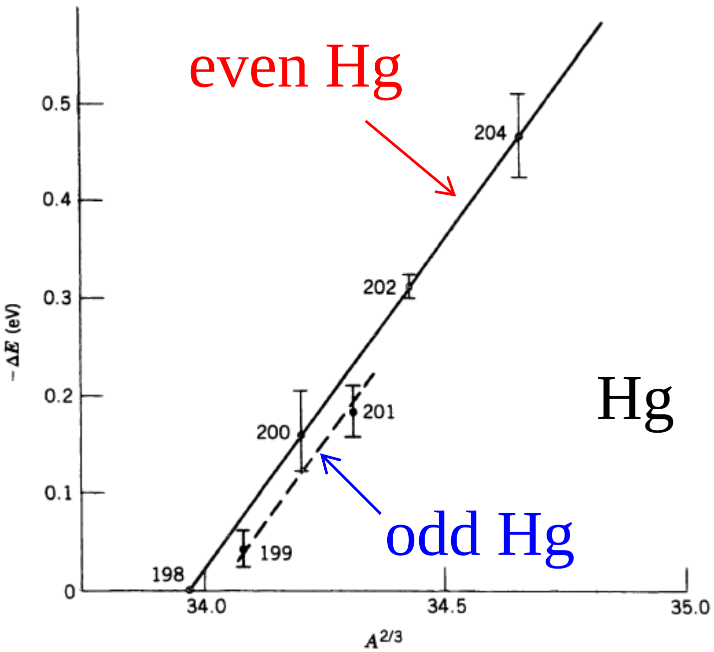


Figure 3.6 K X-ray isotope shifts in Hg. The energy of the K X ray in Hg is about 100 keV, so the relative isotope shift is of the order of 10^{-6}. The data show the

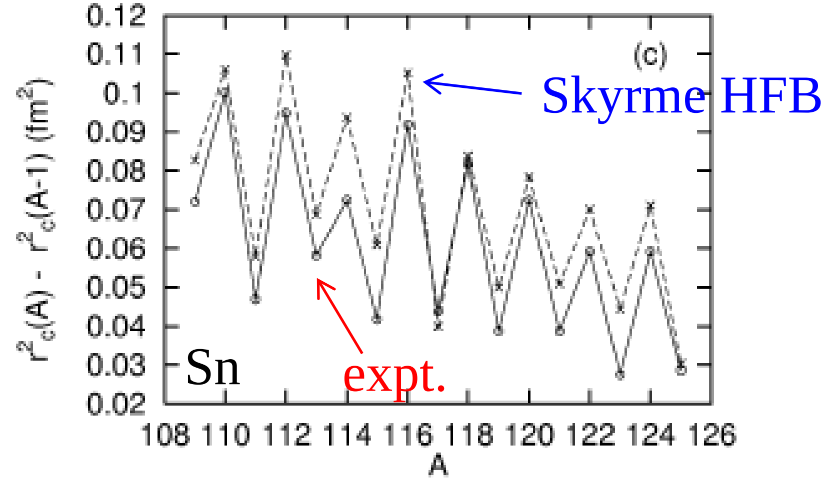
K.S. Krane, "Introductory Nuclear Physics"

$$\Delta E \sim -\frac{2}{5}\frac{Z^4e^2}{a_0^3}\left(\langle r^2\rangle_A - \langle r^2\rangle_{A'}\right)$$

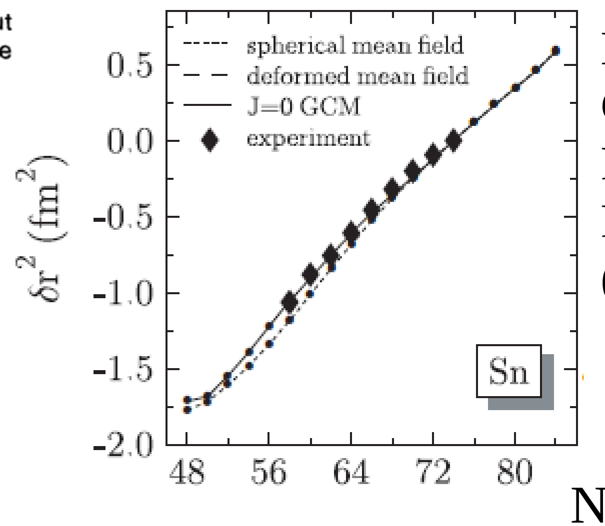
cf. Bohr-Mottelson, eq. (2.85)

$$\gamma \equiv \frac{\langle r^2\rangle_{A+1} - \langle r^2\rangle_A}{\langle r^2\rangle_{A+2} - \langle r^2\rangle_A}$$

- deformation effect? -pairing effect?

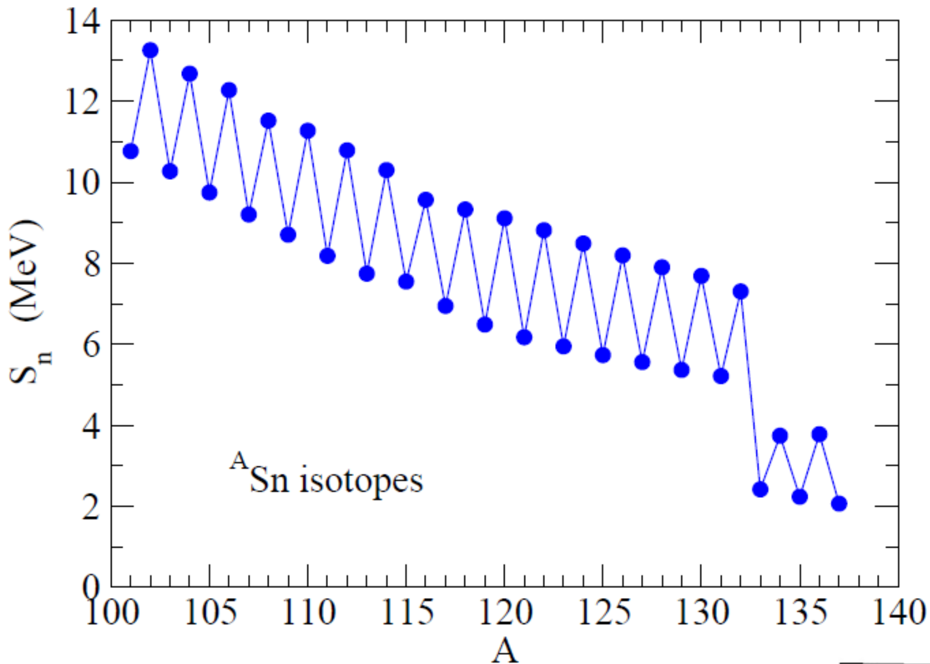


S. Sakakihara and Y. Tanaka, NPA691('01)649



M.Bender, G.F. Bertsch, P.-H. Heenen, PRC73('06)034322 (even-even only)

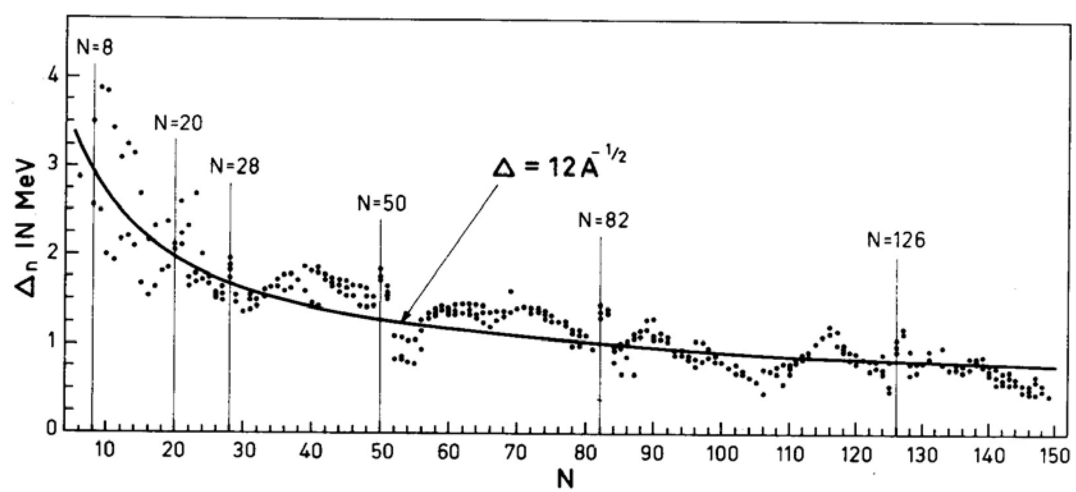
➢binding energy



pairing gap parameter

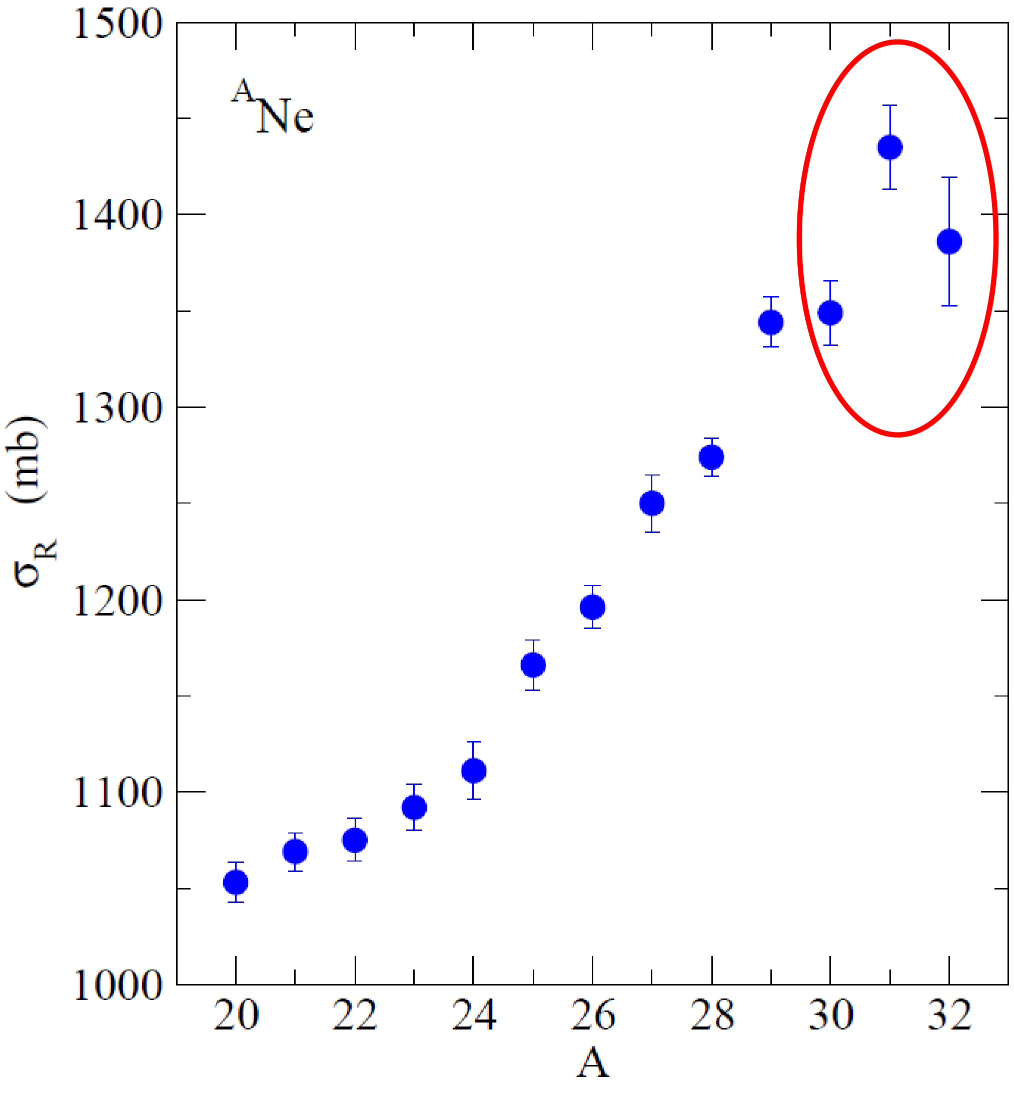
$$\Delta(N) = \frac{(-)^N}{2}(B(N-1) - 2B(N) + B(N+1)) = \frac{(-)^N}{2}(S_n(N-1) - S_n(N))$$

$S_n\,(N) = B(N) - B(N\text{-}1)$



Odd-even staggering of interaction cross sections

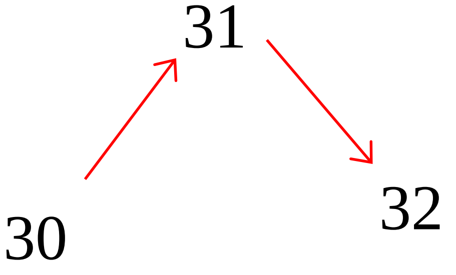
σ_I of unstable nuclei: often show a large odd-even staggering



Typical example:

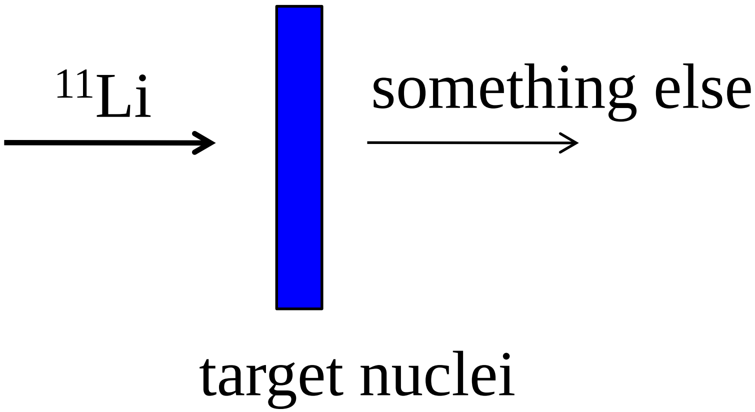
Recent experimental data on Ne isotopes

M. Takechi et al., Phys. Lett. B707 ('12) 357

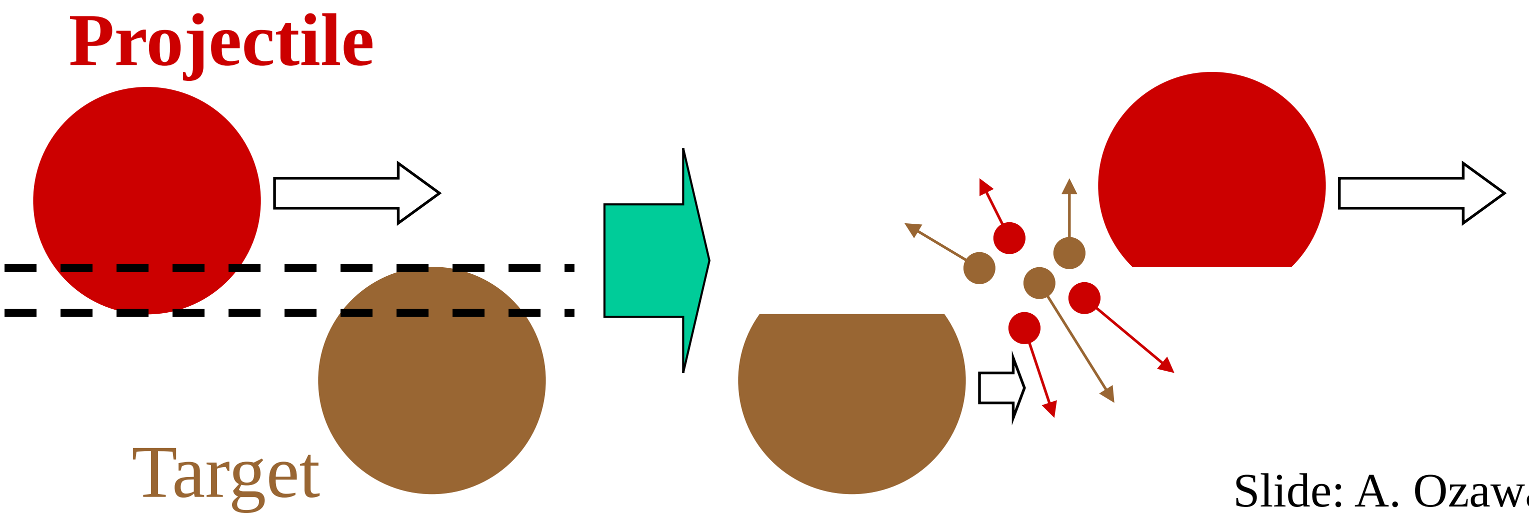


clear odd-even effect

Introduction: interaction cross section



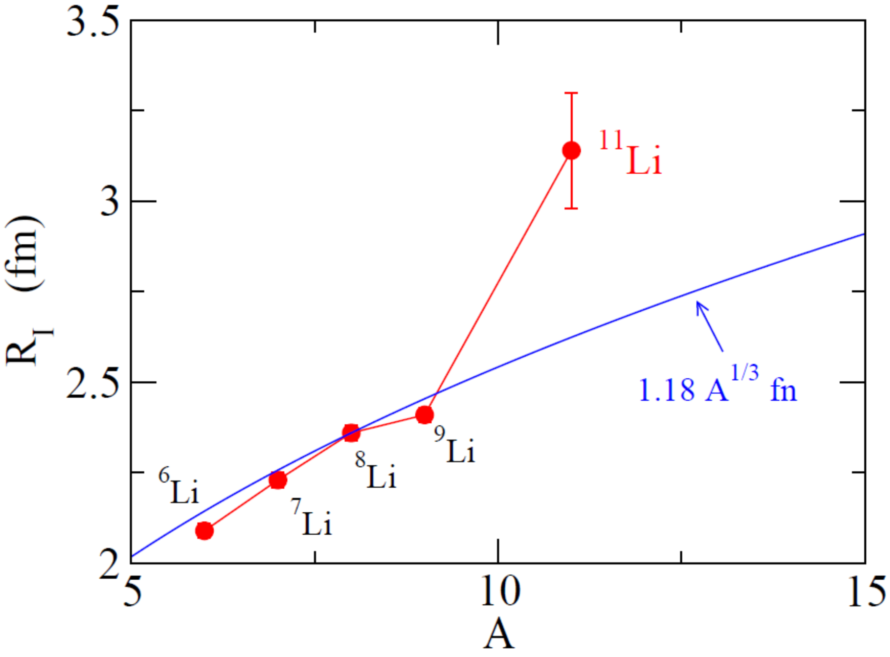
interaction cross section σ_I
= cross section for the change
of Z a/o N in the incident nucleus

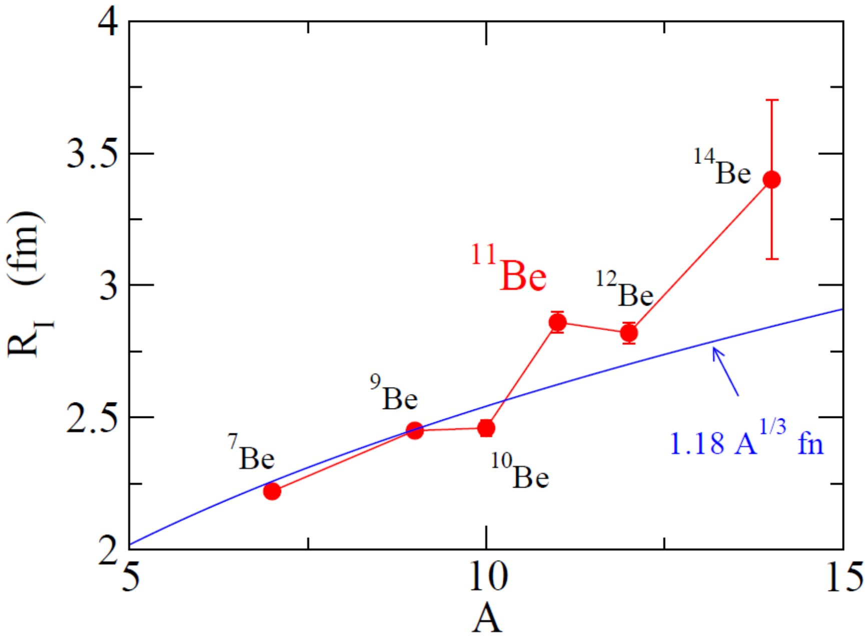


Slide: A. Ozawa

$$\boxed{\sigma_I \sim \pi[R_I(P) + R_I(T)]^2} \longrightarrow R_I(P)$$

Discovery of **halo nuclei**

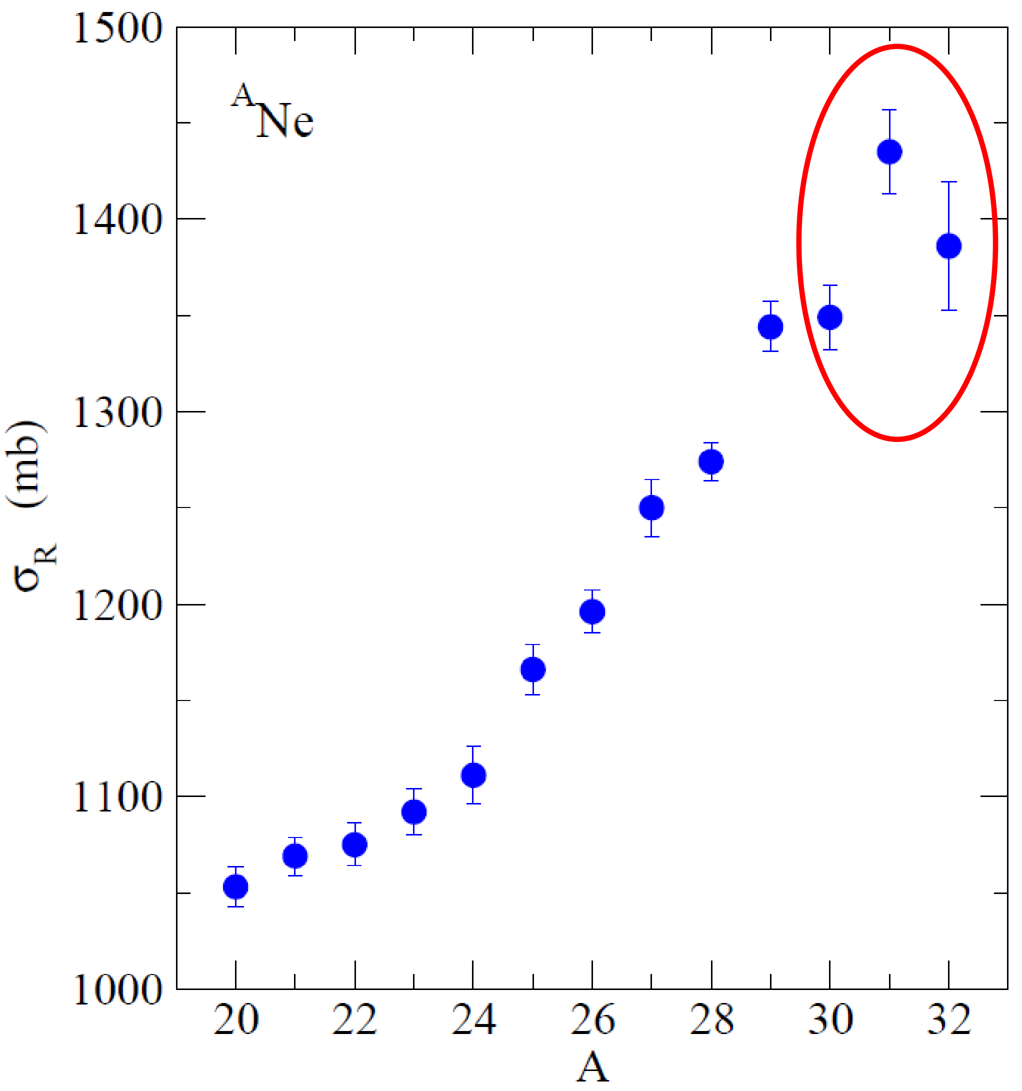




I. Tanihata, T. Kobayashi et al.,
PRL55('85)2676; PLB206('88)592

Odd-even staggering of interaction cross sections

σ_I of unstable nuclei: often show a large odd-even staggering



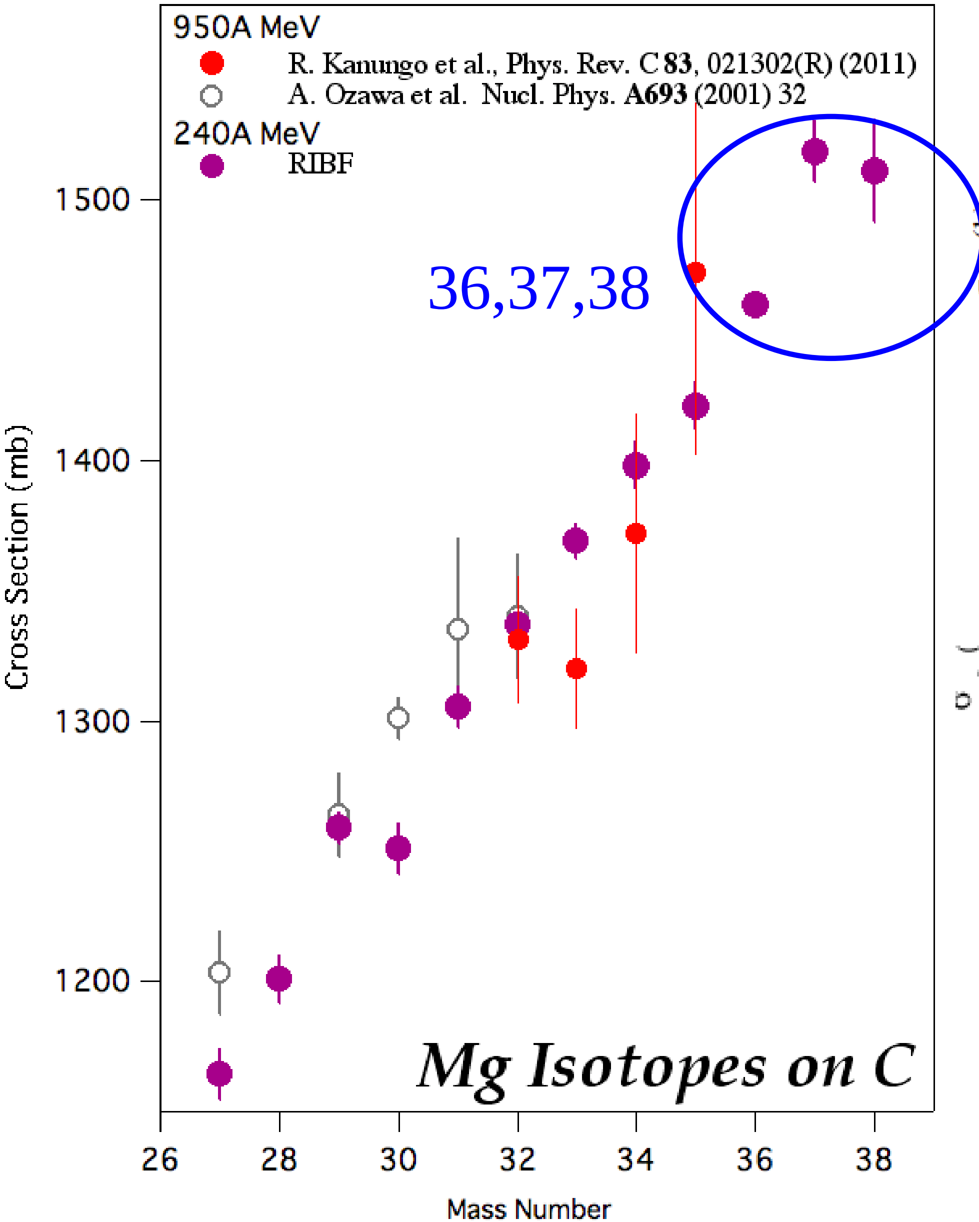
Typical example:
Recent experimental data on Ne isotopes
M. Takechi et al.,
Phys. Lett. B707 (‘12) 357

31

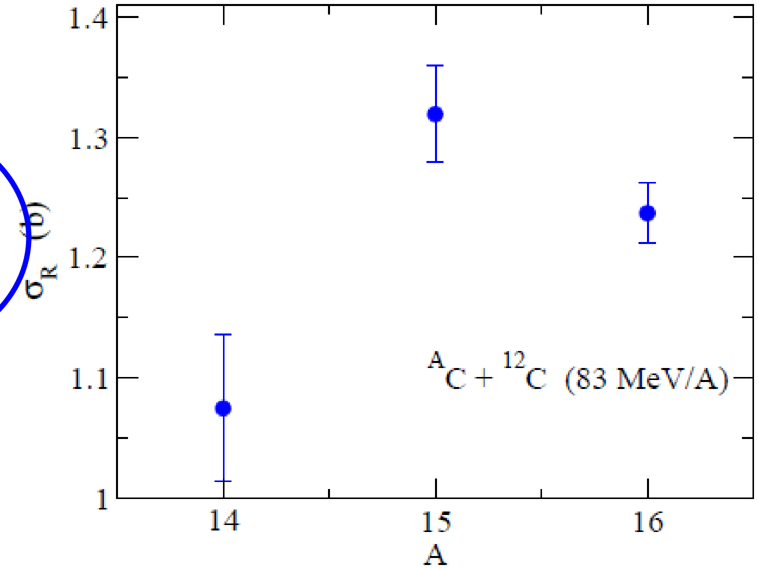
30 32

clear odd-even effect

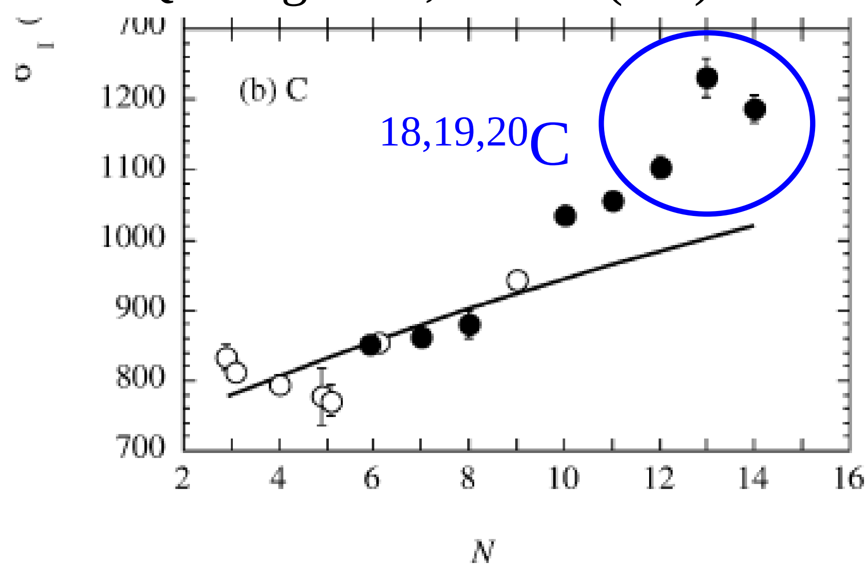
Other systems



M. Takechi, private communications



D.Q. Fang et al., PRC69('04)034613



A. Ozawa et al., NPA691('01)599

Our motivation:

Relation between the odd-mass staggering (OES) of σ_R and pairing (anti-halo) effect?

- pairing anti-halo effect

K. Bennaceur, J. Dobaczewski, and M. Ploszajczak, PLB496('00)154

pairing

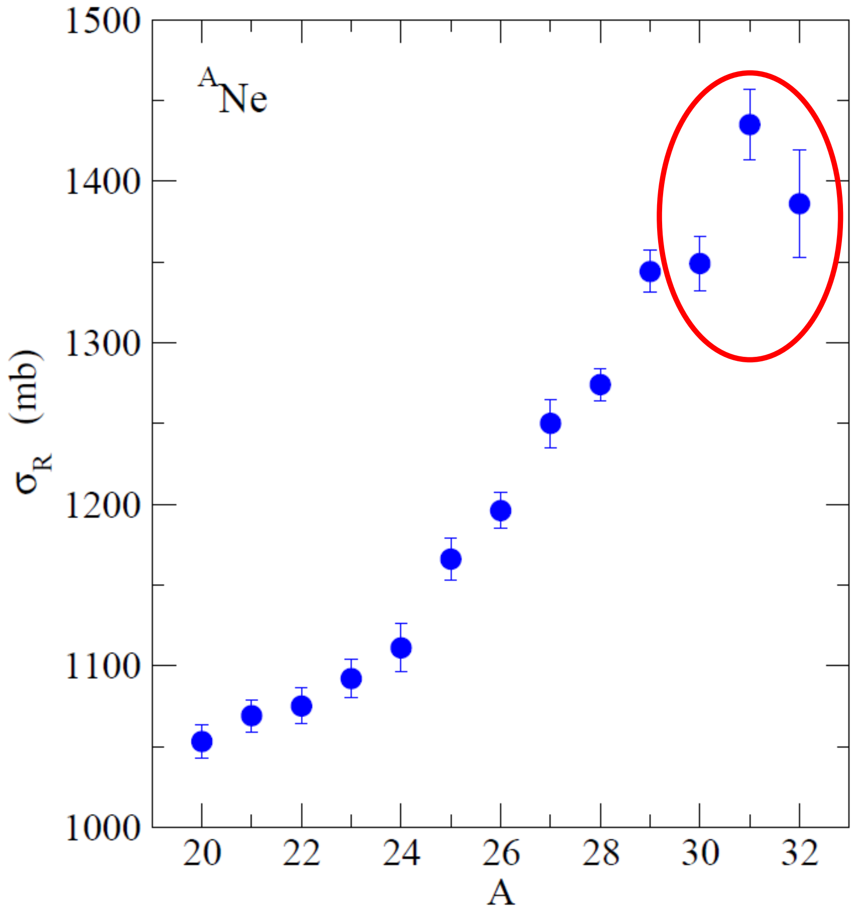
↓

asymptotic behavior of s.p. wave functions

↓

suppression of density distribution

- odd-even staggering of σ_R



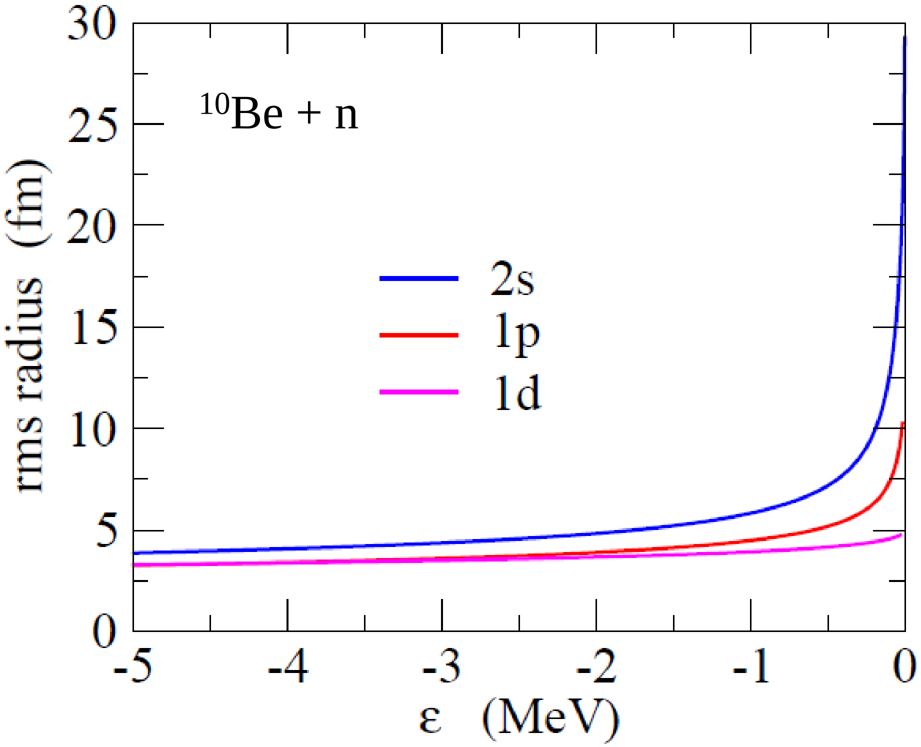
First experimental evidence for the anti-halo effect?

Effect of pairing on radius of a weakly-bound orbit

asymptotic behavior of a s.p. wave function for s-wave:

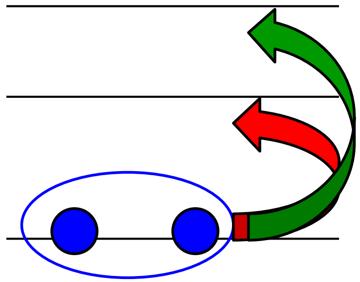
$$\psi(r) \sim \exp(-\kappa r) \qquad \kappa = \sqrt{\frac{2m|\epsilon|}{\hbar^2}}$$

$$\boxed{\langle r^2 \rangle_{\rm HF} = \frac{\int r^2 |\psi(r)|^2 dr}{\int |\psi(r)|^2 dr} \propto \frac{1}{\kappa^2} = \frac{\hbar^2}{2m|\epsilon|} \to \infty}$$



$$\langle r^2 \rangle \propto \begin{cases} \dfrac{1}{|\epsilon|} & (l=0) \\ \dfrac{1}{\sqrt{|\epsilon|}} & (l=1) \\ \text{const.} & (l=2) \end{cases}$$

For even-mass system:



Cooper pair

Hartree-Fock-Bogoliubov (HFB) equations:

$$\begin{pmatrix} \hat{h}-\lambda & \Delta(r) \\ \Delta(r) & -\hat{h}+\lambda \end{pmatrix} \begin{pmatrix} U_k(r) \\ V_k(r) \end{pmatrix} = E_k \begin{pmatrix} U_k(r) \\ V_k(r) \end{pmatrix}$$

Δ(r): pair potential
λ: chemical potential

density: $$\rho(\boldsymbol{r}) = \sum_k |V_k(\boldsymbol{r})|^2$$

Asymptotic form of $V_k(r)$:

$$V_k(r) \sim \exp(-\beta_k r)$$

$$\beta_k = \sqrt{\frac{2m(E_k-\lambda)}{\hbar^2}} \sim \sqrt{\frac{2m\Delta}{\hbar^2}}$$

$$\uparrow$$

$$E_k \sim \sqrt{(\epsilon-\lambda)^2+\Delta^2} \sim \Delta$$

$$(\epsilon, \lambda \to 0)$$

$$\boxed{\langle r^2 \rangle_{\mathrm{HFB}} \propto \frac{\hbar^2}{2m\Delta}}$$

"pairing anti-halo effect"

K. Bennaceur, J. Dobaczewski, and M. Ploszajczak, PLB496('00)154

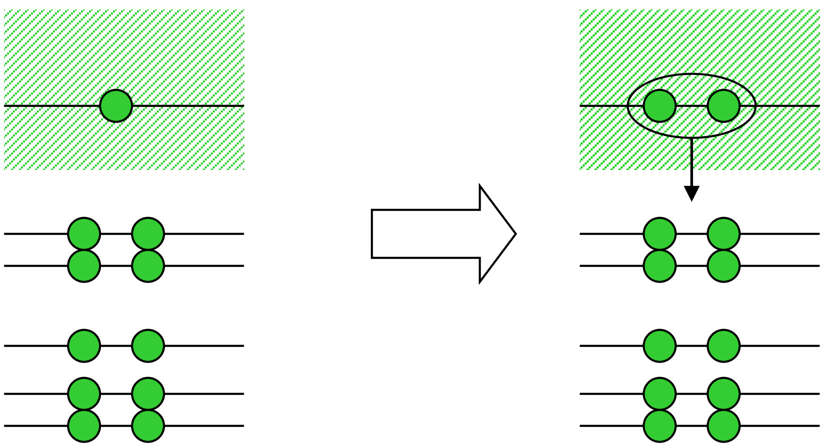
Pairing correlation in weakly-bound nuclei

$$\langle r^2\rangle_{\mathrm{HFB}} \propto \frac{\hbar^2}{2m\Delta}$$

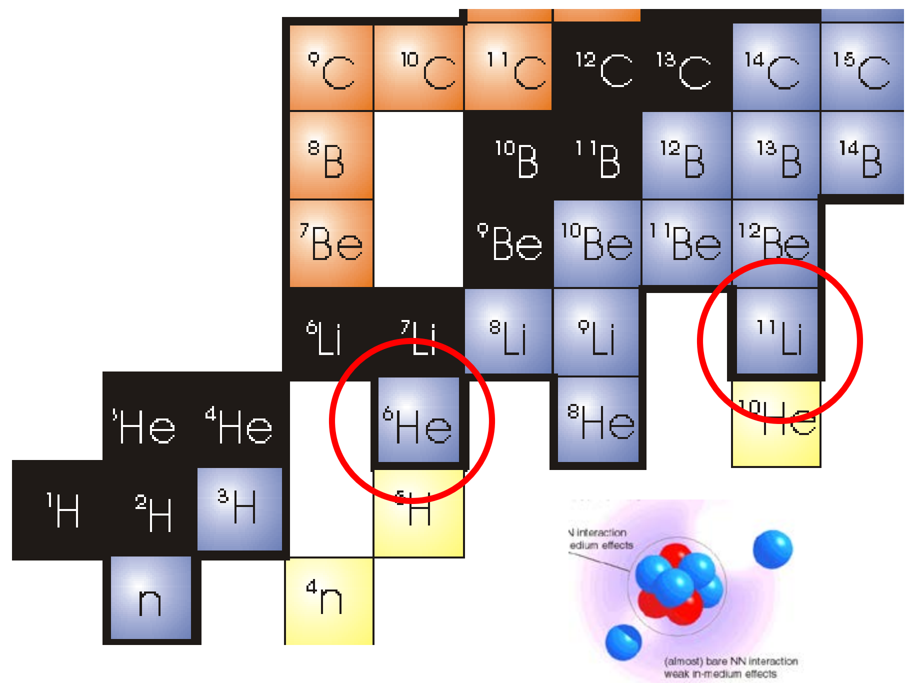
"pairing anti-halo effect"

$$\boxed{\Delta \neq 0 \quad \text{as } \epsilon, \lambda \to 0?}$$

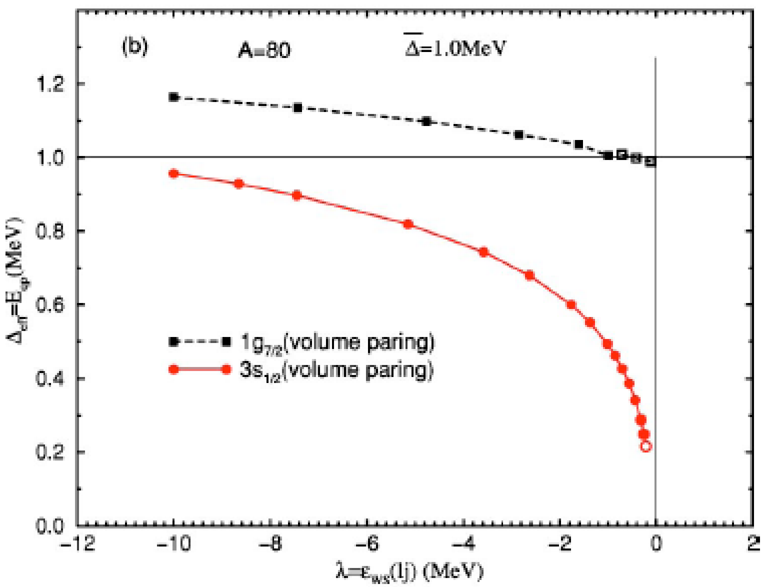
cf. for light neutron-rich nuclei (Borromean nuclei)



unbound bound



For heavier nuclei: controvertial arguments based on HFB



I. Hamamoto and H. Sagawa, PRC70('04)034317

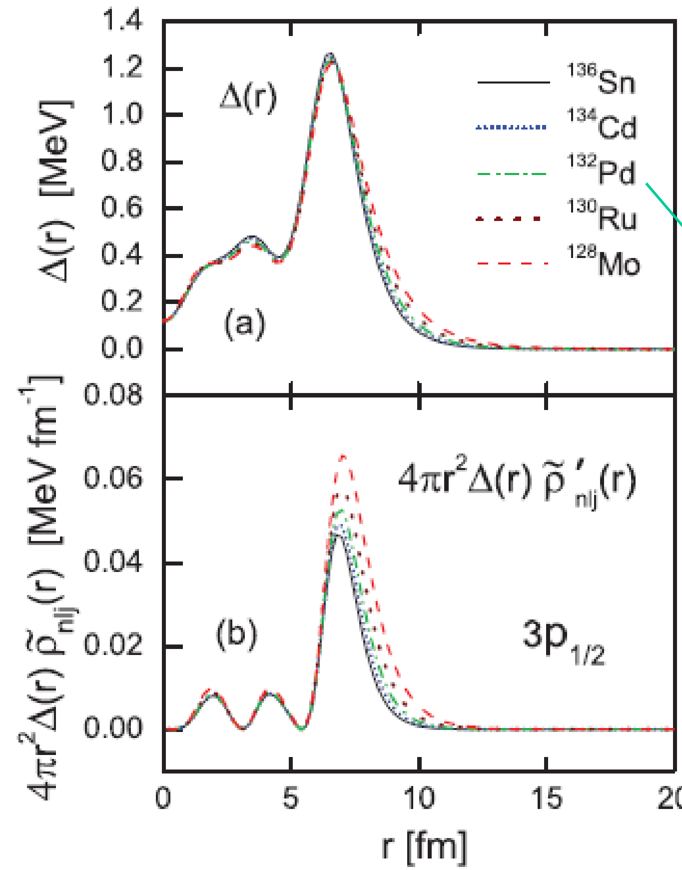
■simplified HFB model

✓$\Delta(r)$: prefixed

✓set $\lambda = \varepsilon_{HF}$

✓define Δ_{eff} = lowest E_{qp}

$$\Longrightarrow \Delta_{eff} \to 0 \quad (\epsilon \to 0)$$



e.g.

ε=-0.01 (MeV)

Δ = 0.57 (MeV)

$(3p_{3/2})$

Y. Zhang, M. Matsuo, J. Meng, PRC83('11)054301

■self-consistent HFB

$$\Delta_{eff} \neq 0 \quad (\epsilon \to 0)$$

see also M. Yamagami, PRC72('05)064308

Model HFB with a Woods-Saxon mean-field potential

$$\begin{pmatrix} \hat{h}-\lambda & \Delta(r) \\ \Delta(r) & -\hat{h}+\lambda \end{pmatrix} \begin{pmatrix} U_k(r) \\ V_k(r) \end{pmatrix} = E_k \begin{pmatrix} U_k(r) \\ V_k(r) \end{pmatrix}$$

$$\hat{h} = -\frac{\hbar^2}{2m}\nabla^2 + V_{\mathrm{WS}}(r)$$

$\uparrow$

${}^{76}_{24}\mathrm{Cr}_{52}$

-0.05 MeV $2d_{5/2}$

-0.26 MeV $3s_{1/2}$

50

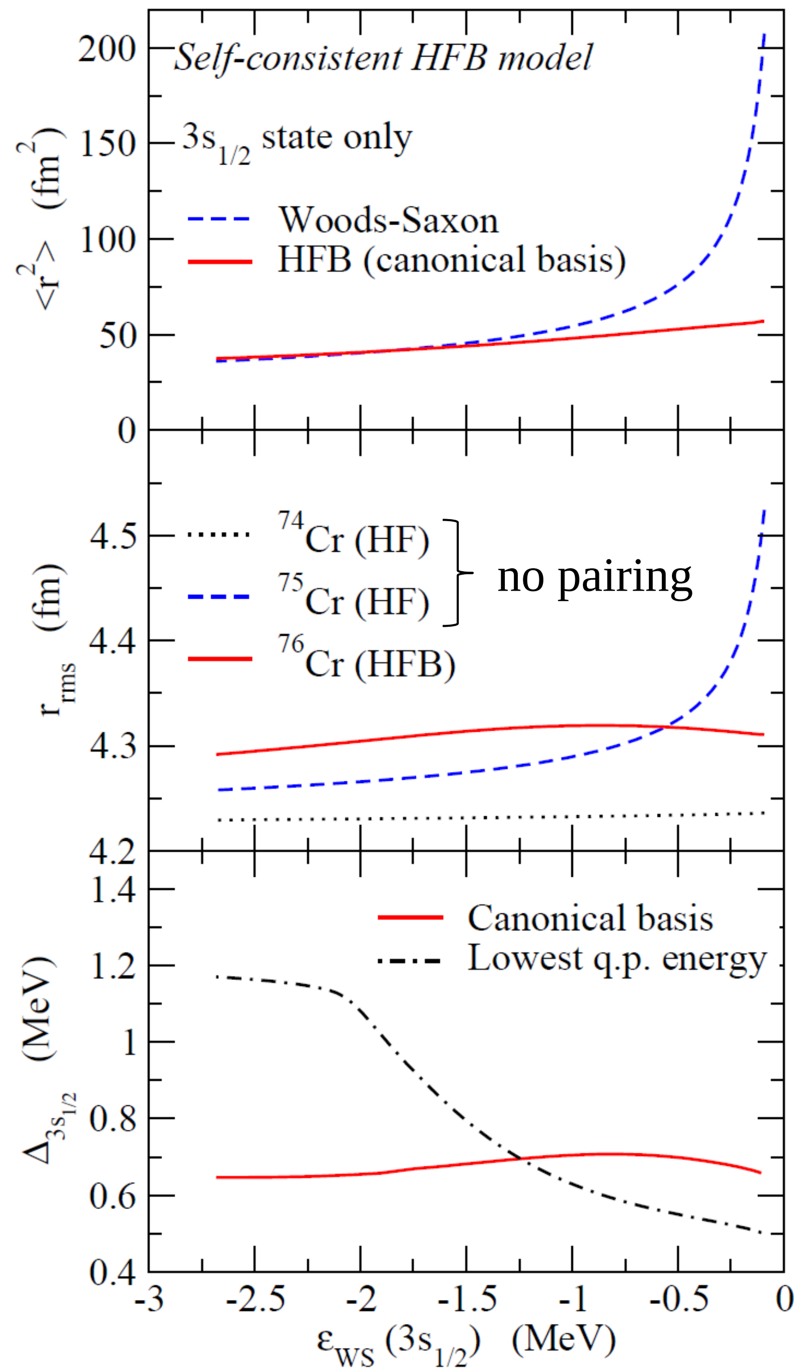
$$\Delta(r) = \frac{V_{\mathrm{pair}}}{2}\left(1 - \frac{\rho(r)}{\rho_0}\right)\tilde{\rho}_n(r) \qquad V_{\mathrm{pair}} \leftarrow \bar{\Delta} = 1.0 \ \mathrm{MeV}$$

$$\tilde{\rho}_n(r) \;=\; -\sum_{k=n} U_k^*(\boldsymbol{r})V_k(\boldsymbol{r})$$

✓λ: self-consistently determined so that N=52

✓E_{cut} = 50 MeV above λ

✓R_{box}=60 fm

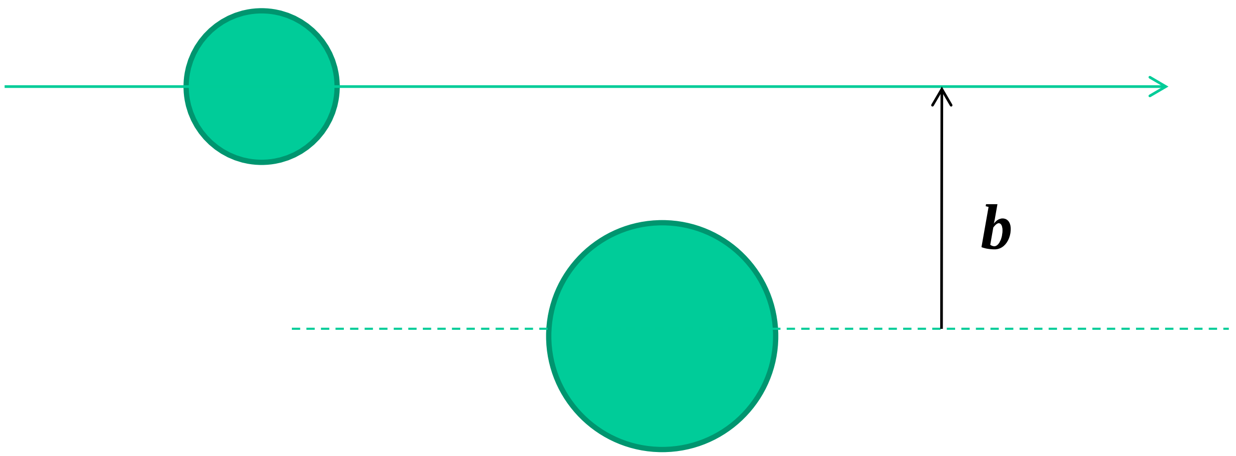


suppression of the radius

the effective pairing gap persists for both the definitions (agreement with Zhang-Matsuo-Meng)

K. H. and H. Sagawa, PRC85('12)014303

Reaction cross sections



Glauber theory (optical limit approximation:OLA)

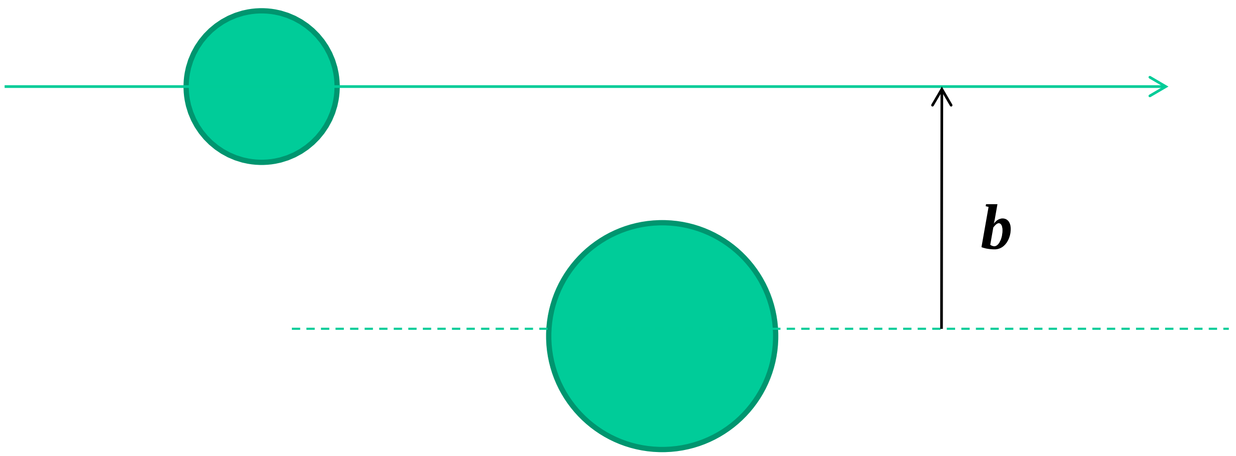
$$\sigma_{\mathrm{R}} = \int d^2b \left(1 - |e^{i\chi(b)}|^2\right)$$

$$e^{i\chi(b)} = \exp\left[-\int d\boldsymbol{r}_P \boldsymbol{r}_T \rho_P(\boldsymbol{r}_P)\rho_T(\boldsymbol{r}_T)\Gamma(\boldsymbol{b} + \boldsymbol{s}_P - \boldsymbol{s}_T)\right]$$

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

- straight-line trajectory
- adiabatic approximation
- simplified treatment for multiple scattering: $(1 - x)^N \to e^{-Nx}$

Reaction cross sections



Glauber theory (optical limit approximation:OLA)

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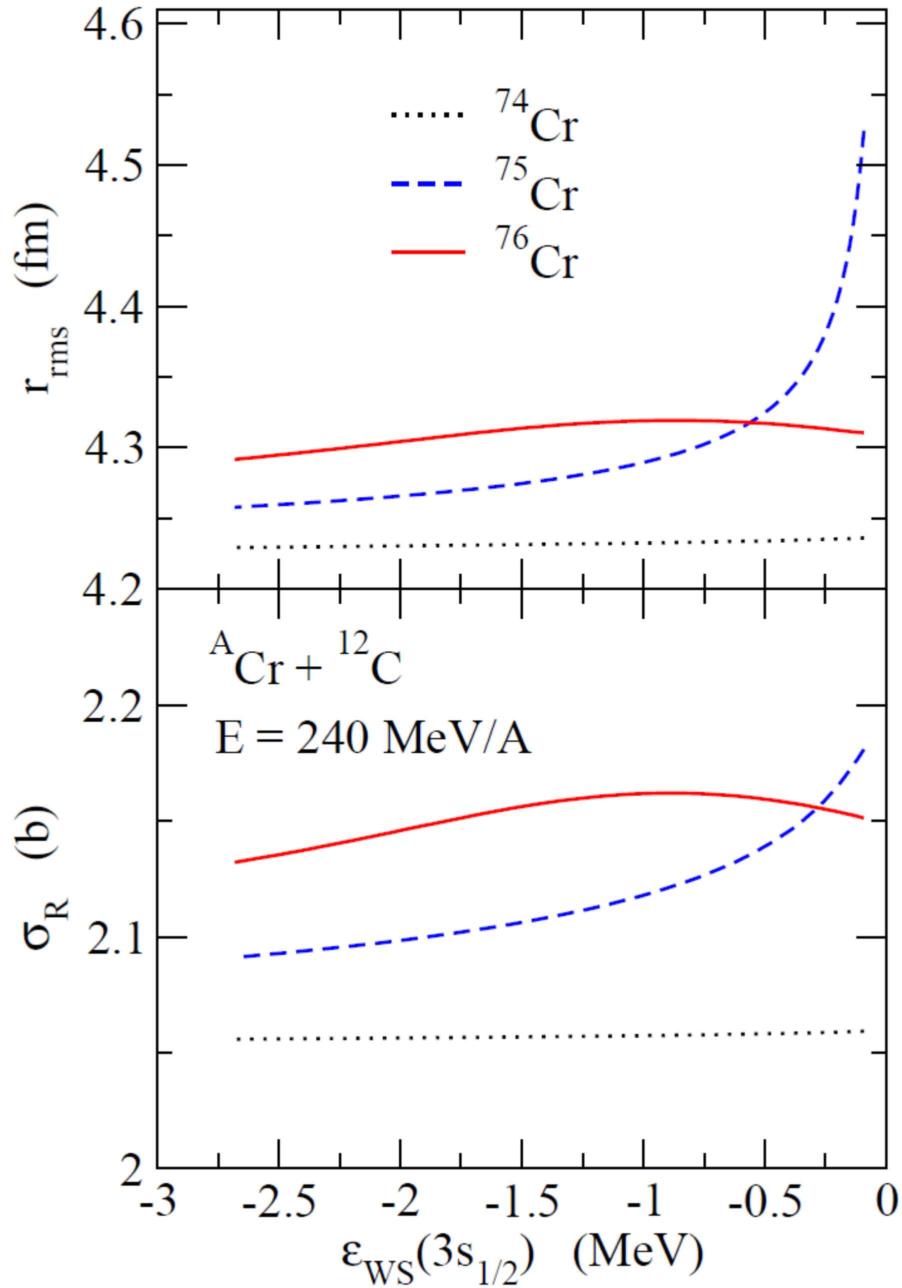
$$e^{i\chi(b)} \;=\; \exp\left[-\int d\boldsymbol{r}_P\boldsymbol{r}_T\rho_P(\boldsymbol{r}_P)\rho_T(\boldsymbol{r}_T)\Gamma(\boldsymbol{b}+\boldsymbol{s}_P-\boldsymbol{s}_T)\right]$$

- Correction to the OLA

B. Abu-Ibrahim and Y. Suzuki, PRC61('00)051601(R)

$$i\chi(b) \to -\int d\boldsymbol{r}_P\,\rho_P(\boldsymbol{r}_P)\left[1 - e^{-\int \boldsymbol{r}_T\rho_T(\boldsymbol{r}_T)\Gamma(\boldsymbol{b}+\boldsymbol{s}_P-\boldsymbol{s}_T)}\right]$$

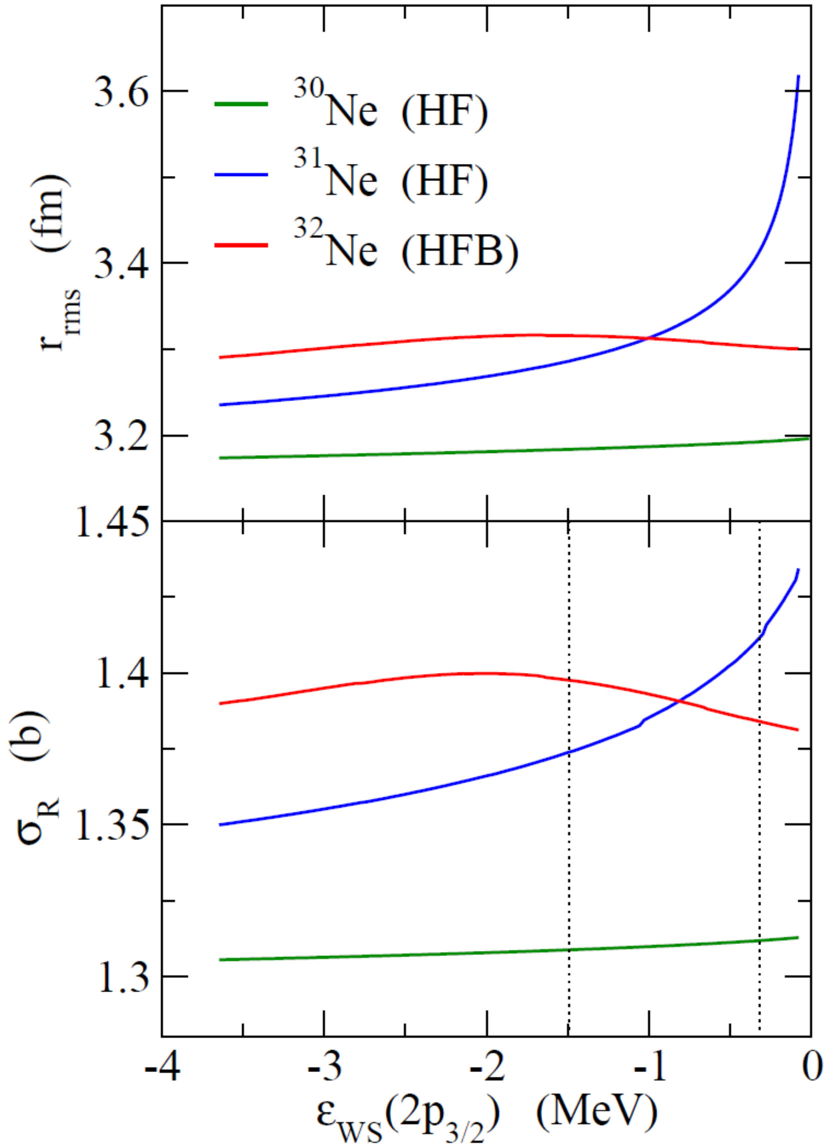


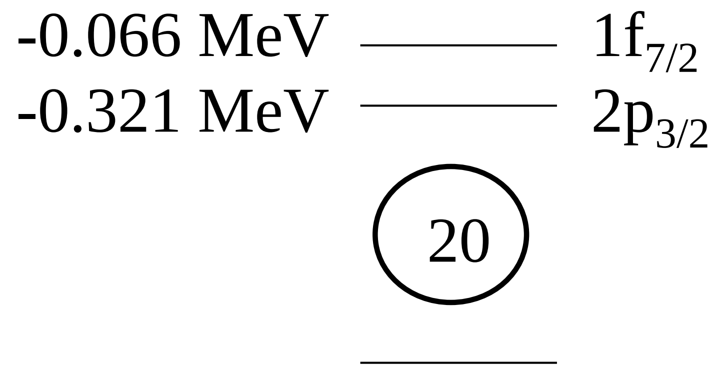
^{74,75,76}Cr + ^{12}C reactions
at E=240 MeV/A

density of ^{74,75,76}Cr : HFB
density of ^{12}C : Gaussian

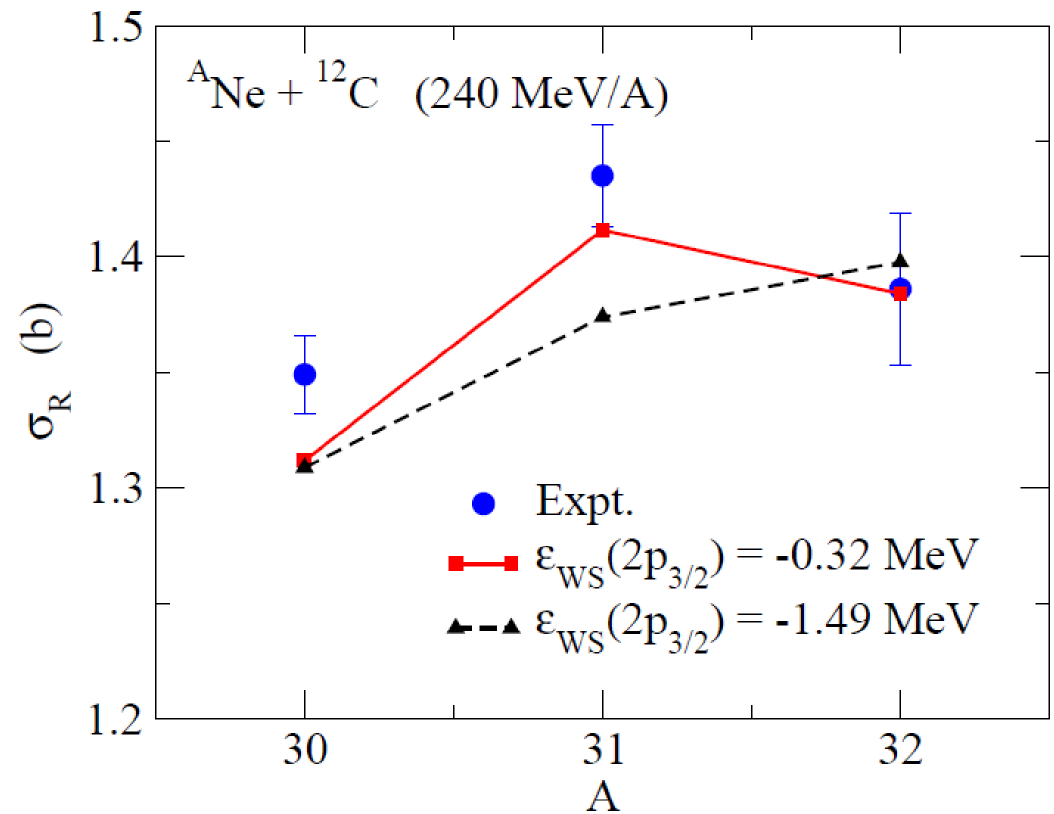
Other system: ^{30,31,32}Ne

HFB with a spherical Woods-Saxon





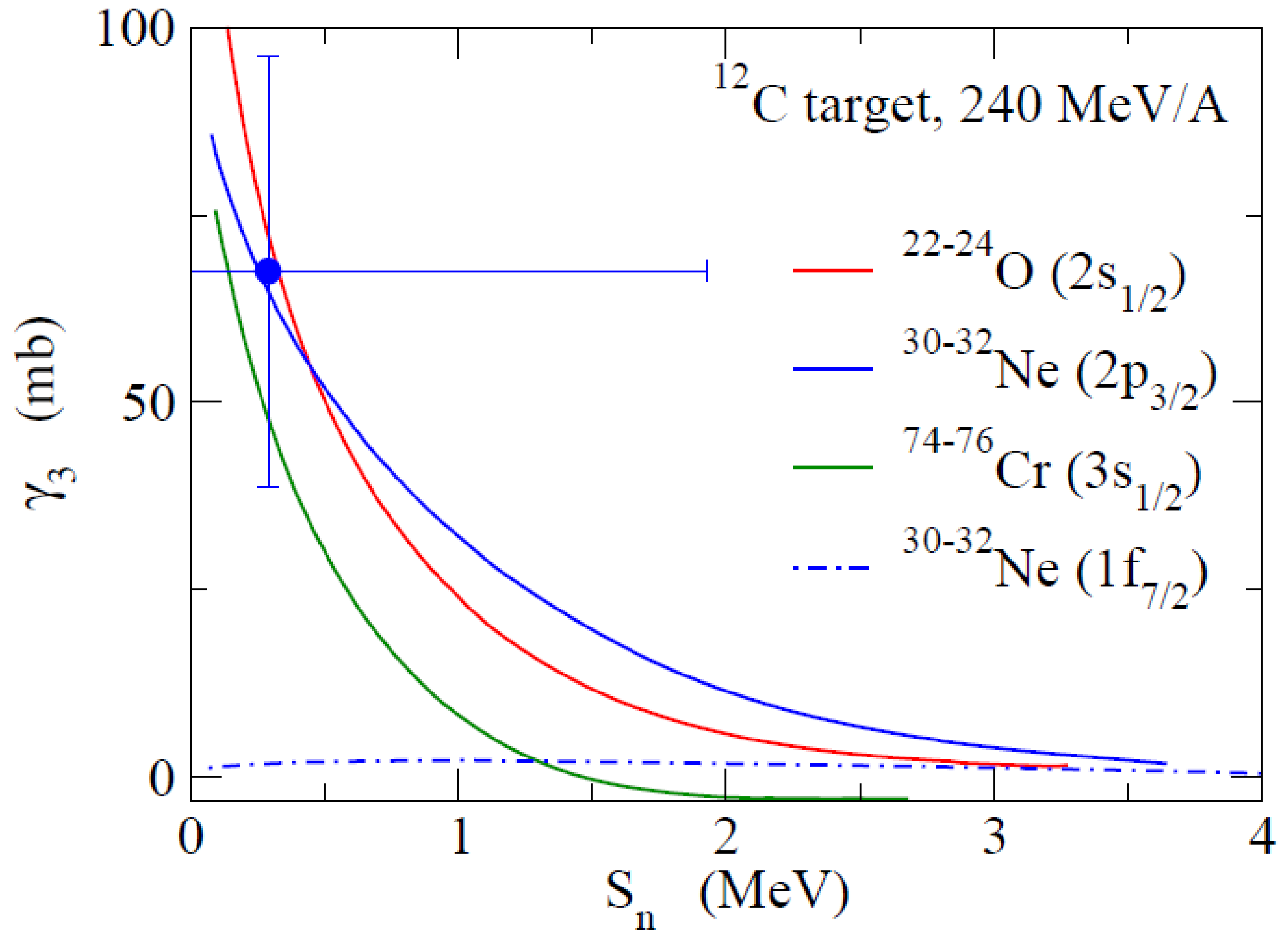
^{31}Ne (a =0.75 fm)



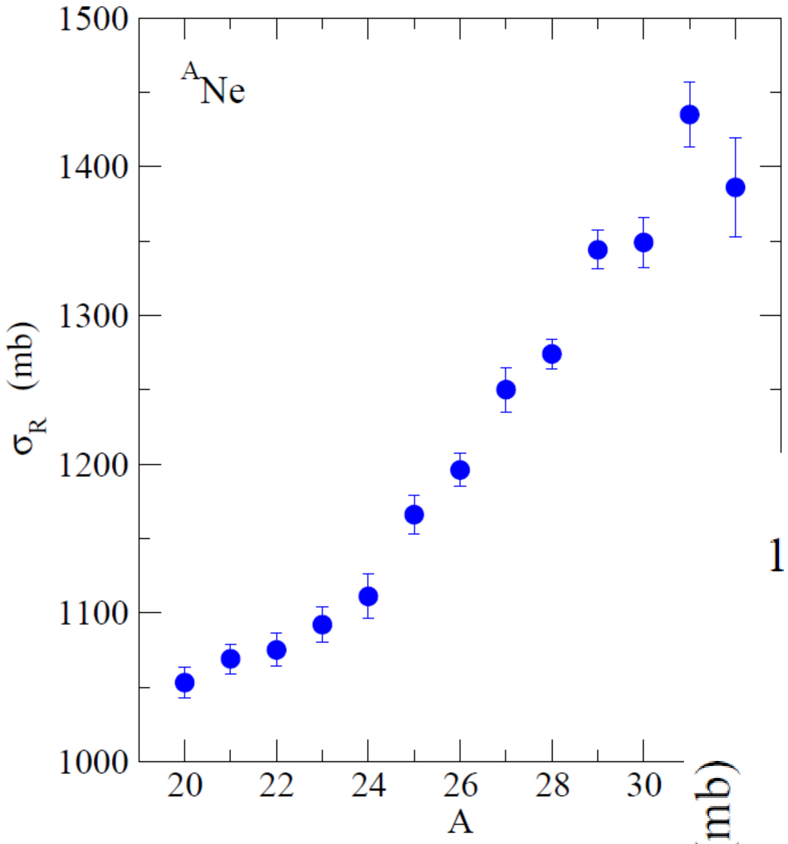
K. H. and H. Sagawa, PRC84('11)011303(R)

Systematic study: OES parameter

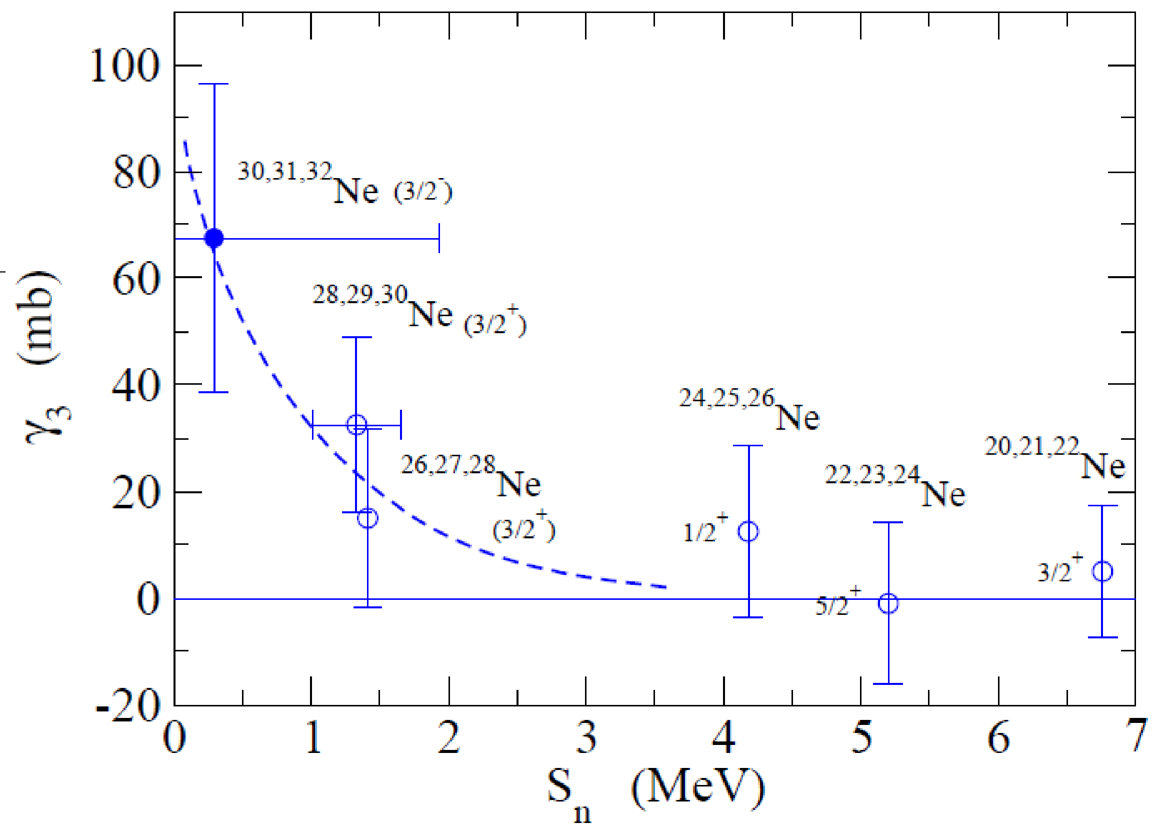
$$\gamma_3 \equiv -\frac{1}{2}[\sigma_R(A+2) - 2\sigma_R(A+1) + \sigma_R(A)]$$



K. H. and H. Sagawa, PRC85('12)014303

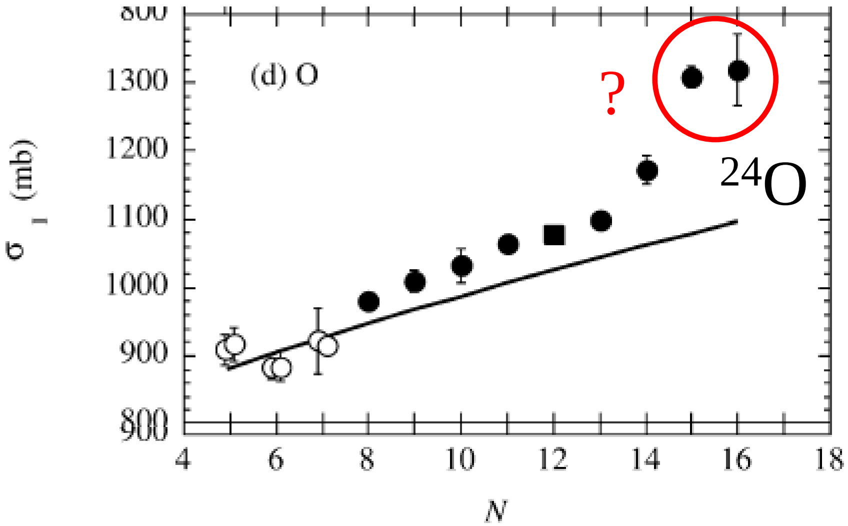


systematics

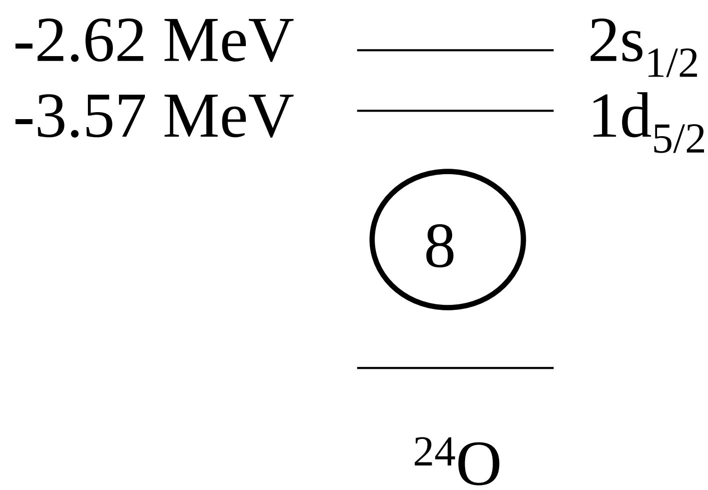


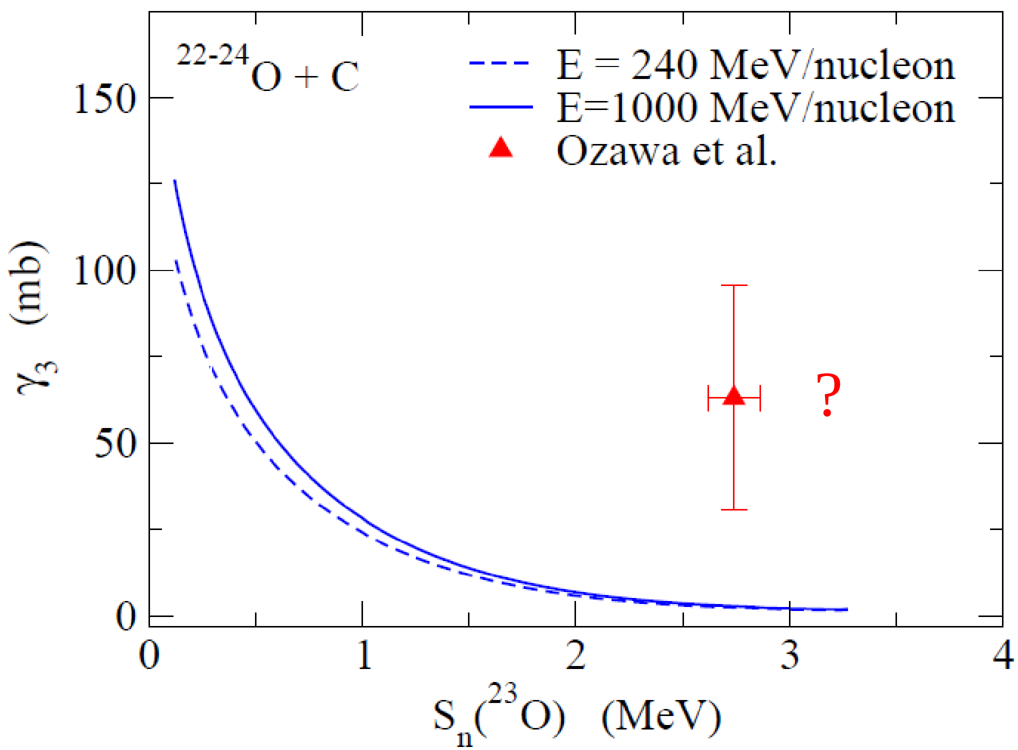
K. H. and H. Sagawa, PRC85('12)014303

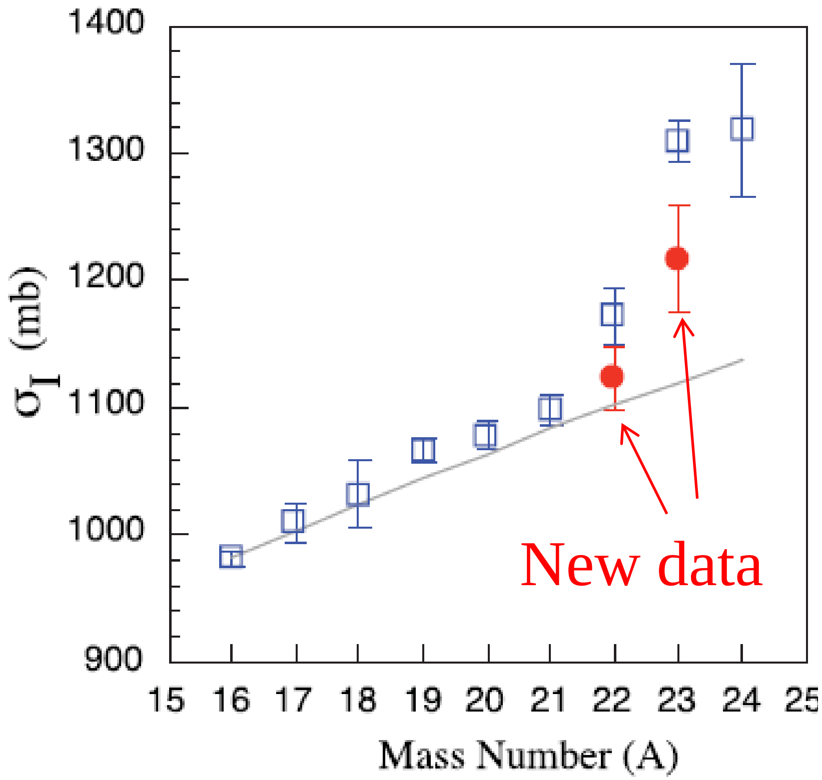
$^{22,23,24}O + ^{12}C$ @ 950 MeV/A



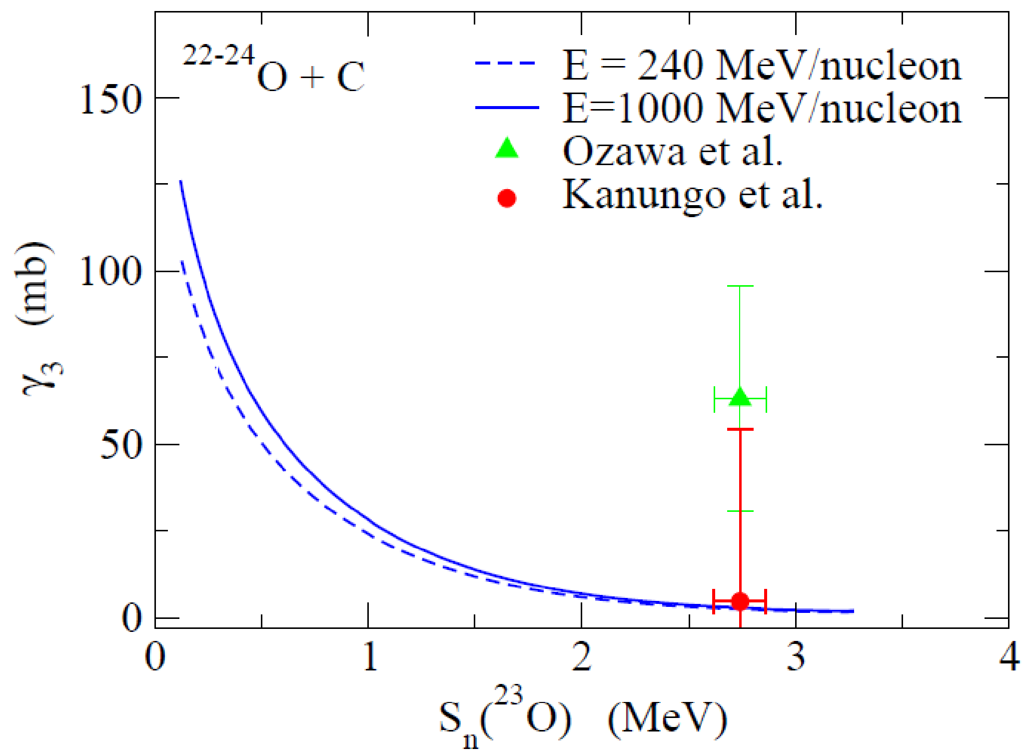
A. Ozawa et al.,NPA691('01)599







R. Kanungo et al.,
PRC84(‘11)061304(R)



K.H. and H. Sagawa,
arXiv:1202.2725 [nucl-th]

Summary

- Analyses of σ_R with HFB + Glauber

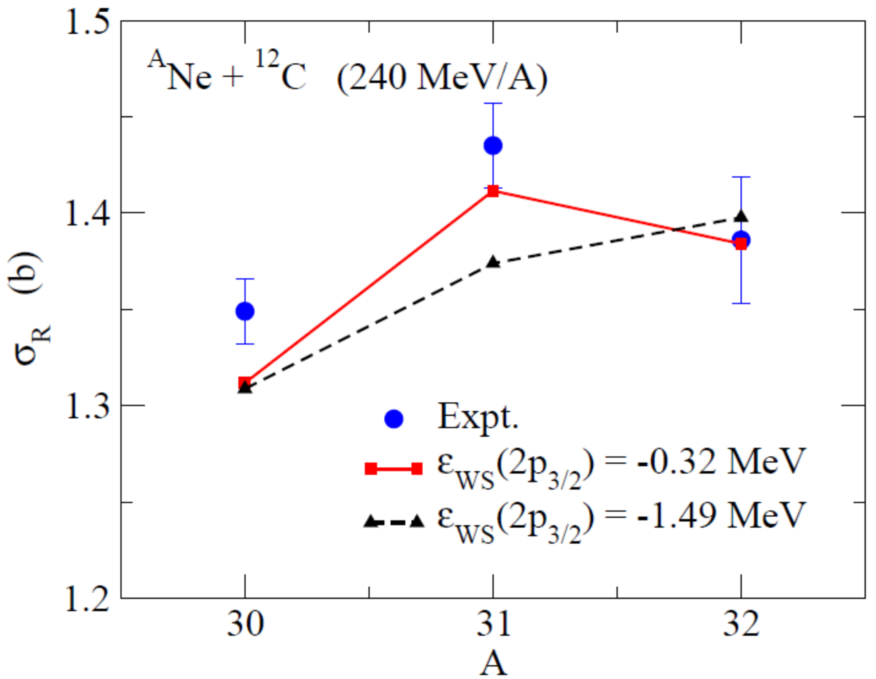
weakly-bound even-even nuclei:
✓the pairing correlation persists even at the drip
✓suppression of the radius due to *the pairing correlation* (l = 0, 1)

⇒ reduction of σ_R

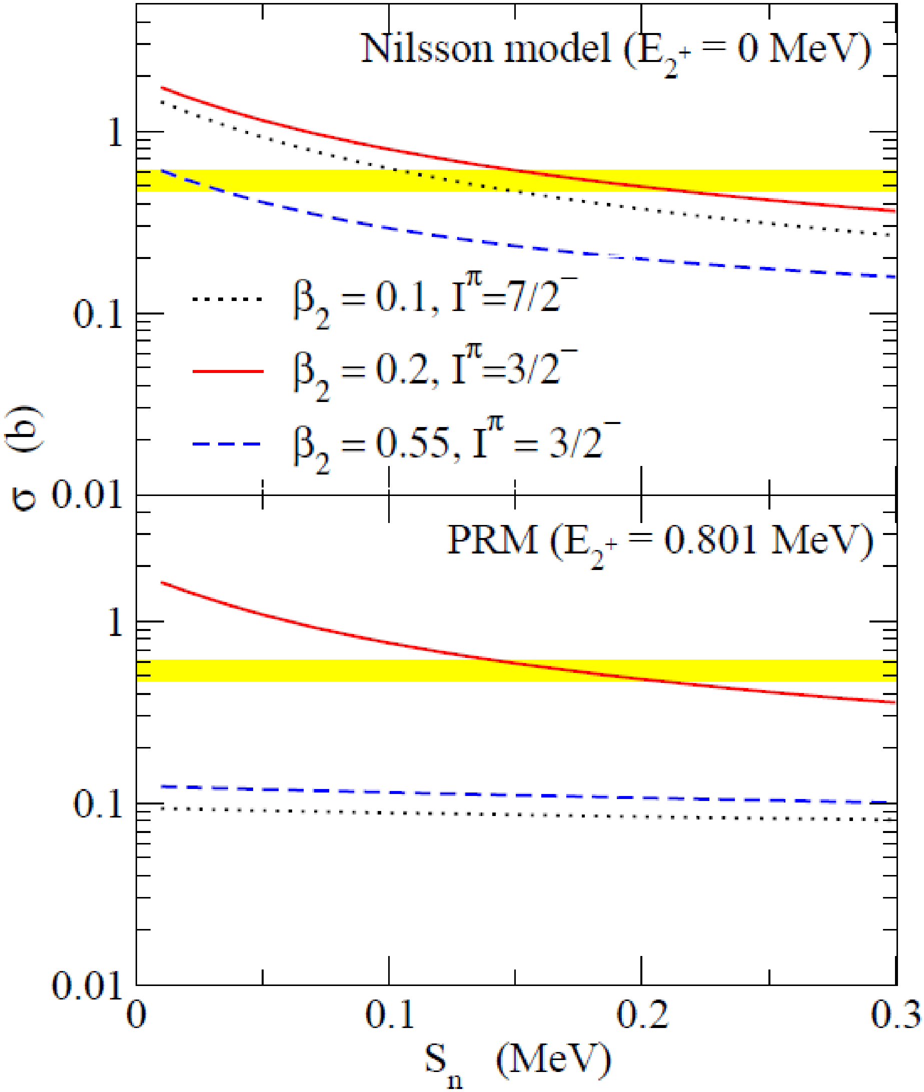
Odd-even staggering of σ_R

- Odd-even staggering parameter
  a good tool to investigate the pairing correlation in weakly bound nuclei

- Work in progress: deformation effects

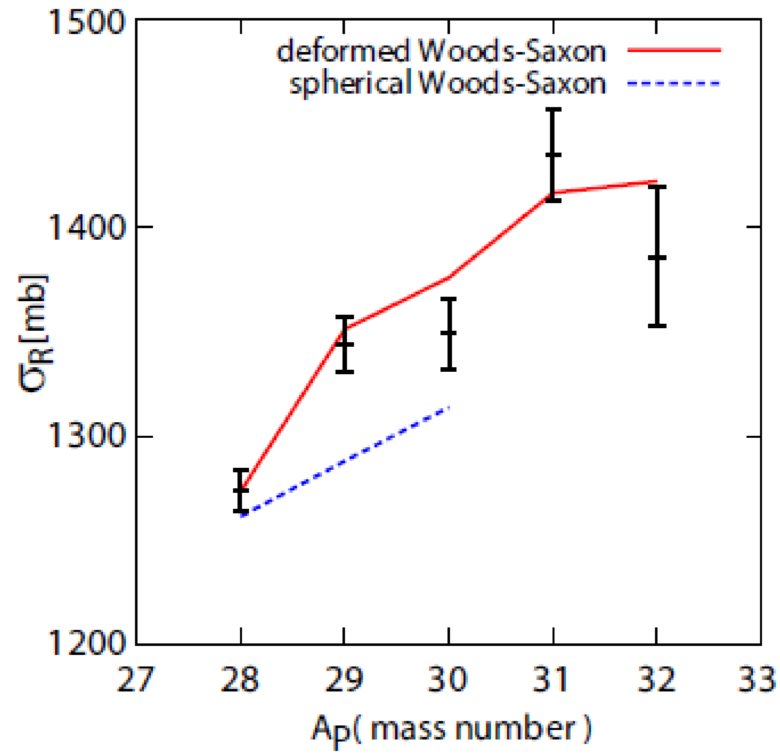


Deformation of ^{31}Ne



Coulomb breakup cross sections

Y. Urata, K.H., H. Sagawa,
PRC83('11)041303(R)



K. Minomo et al.,
PRC84('11)034602
PRL108('12)052503