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Low energy reactions of halo nuclei

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Low energy reactions of Halo nuclei

Halo nuclei present common structural properties:

- Rather inert core plus one or two barely unbound extra neutrons.
- Often form 3-body borromean systems: ^{6,8}He, ^{11}Li.
- Extended neutron distribution, large “radius”.→ “halo” .
- Low binding energy.
- Few bound excited states.

Coulomb barrier energies are interesting to study halo dynamics

- Important correlation between relative motion and internal degrees of freedom.
- Strong couplings effects between elastic channel and inelastic, transfer, breakup and fusion channels.
- Good energy range to study influence of halo on reaction dynamics.
- Probe of theoretical models for few body systems and nucleon correlations.

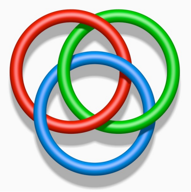
Elastic Cross Sections

- Large yields at Coulomb barrier.
- Useful to get first information with low intensity RIBs > 5 10^3 pps.
- Peripheral process, it probes the tail of the nuclear wave function.

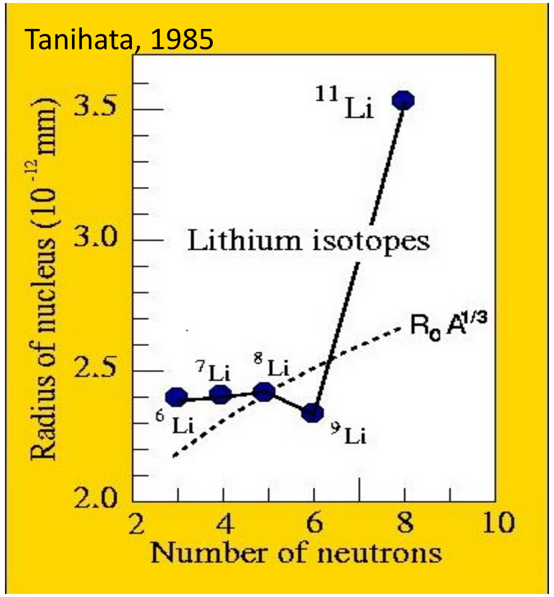
Weak binding + extended neutron distribution

- Large coupling to continuum states.
- Soft dipole modes.
- Coulomb dipole polarizability.
- Large breakup yields.

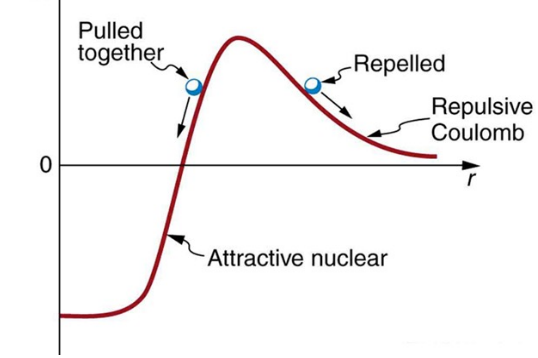
^{11}Li

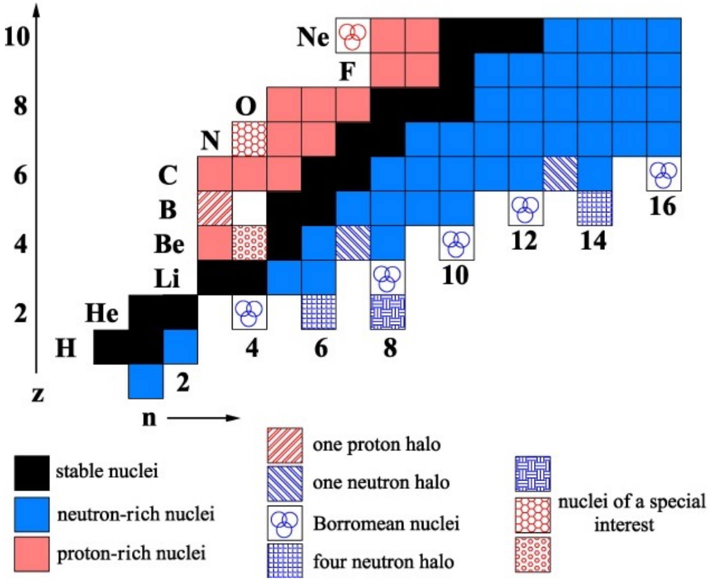


Borromean



Coulomb Barrier

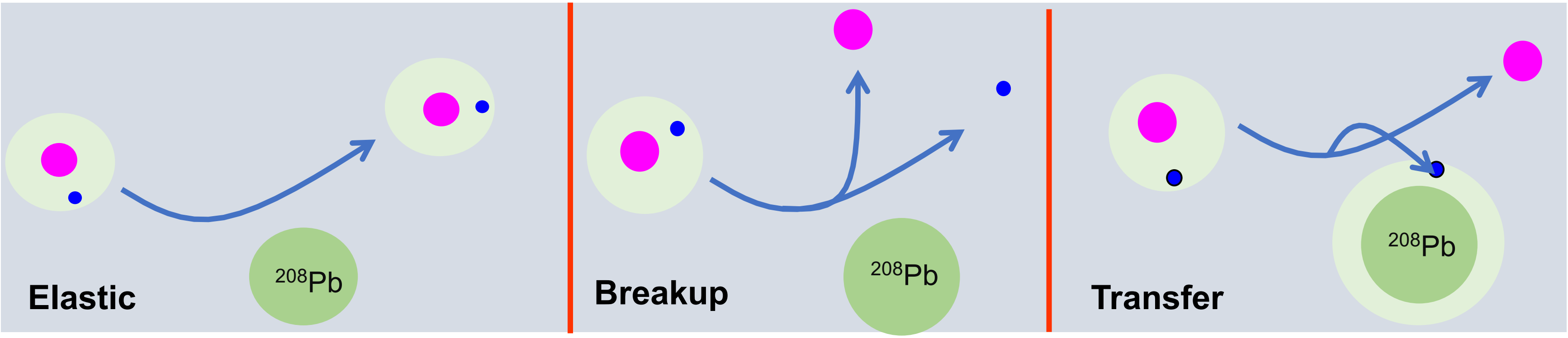




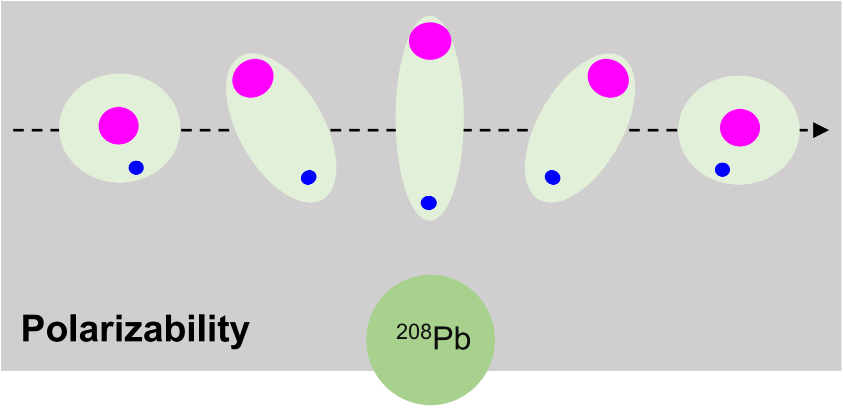
Coulomb barrier scattering of halo nuclei

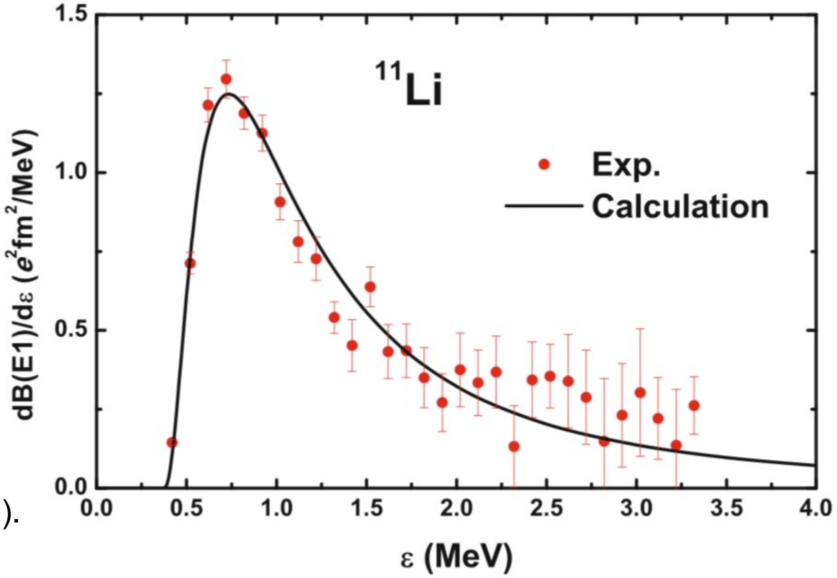
- Coupling between relative motion and internal degrees of freedom

  elastic – inelastic – transfer – breakup – fusion + effects of the continuum
- Strong absorption in elastic channel
- Large cross section for fragmentation



- They are easily polarizable: distortion of structure in the vicinity of target → Coulomb dip. polarizability





T. Nakamura et al., Phys. Rev. Lett. 96, 252502 (2006).
T. H. Kim et al., Jour. Kor. Phys. Soc. 73 (2018) 553.

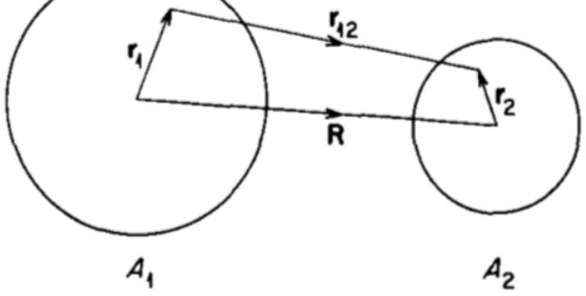
Reaction models at Coulomb barrier energies

A large part of the cross section comes from direct nuclear reactions: sort of “fast” reaction procesess in which there is no time to formation of a compound nucleus, and the cross section dependends on the initial and final states of the interacting nuclei.

Optical model (OM)

Describes (only) the elastic scattering between two nuclei by solving a one-body Srodinger equation

$$\boldsymbol{r}_{12} = \boldsymbol{R} - \boldsymbol{r}_1 + \boldsymbol{r}_2.$$



$$\left[-\frac{\hbar^2}{2\mu_\alpha}\nabla^2 + U(\boldsymbol{R})\right]\chi(\boldsymbol{R}) = E\,\chi(\boldsymbol{R}),$$

U(**R**) = U(**R**) + i Im U(**R**) ← Absorption of flux to non-elastic channels

Real + imaginary Woods-Saxon

$$V(r) = \frac{V_0}{1+\exp\left(\left(r-R_V\right)/a_V\right)} + \frac{iW_0}{1+\exp\left(\left(r-R_W\right)/a_W\right)}$$

$$R_V = r_V(A_p^{1/3} + A_B^{1/3}),\ R_W = r_W(A_p^{1/3} + A_B^{1/3})$$

$r_{V,W}$~ 1.1-1.3 fm $a_{V,W}$~ 0.5-0.7 fm

Double folding potential

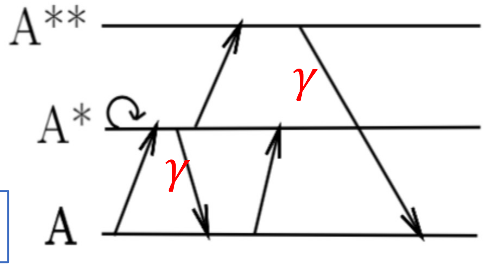
$$U_F(\boldsymbol{R}) = \int d\boldsymbol{r}_1 \int d\boldsymbol{r}_2\, \rho_1(\boldsymbol{r}_1)\,\rho_2(\boldsymbol{r}_2)\, v(\boldsymbol{r}_{12} = \boldsymbol{R} + \boldsymbol{r}_2 - \boldsymbol{r}_1).$$

VERY successful describing the elastic scattering of stable nuclei (50’s-80’s)
Global optical model potentials for the elastic scattering,
J. Cook, Nuclear Physics A388 (1982) pp.153-172

Coupled channels models

Coupled Channel calculations (CC) ~ include the coupling to excited states (bound)

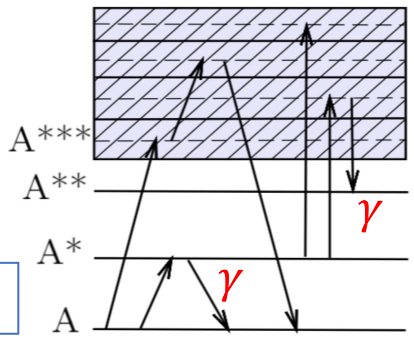
$$\Psi_\alpha = \sum_n \chi_n(\mathbf{R}_\alpha)\phi_n(\alpha)$$



A (a, a) A*

$$[E - \epsilon_\alpha - K_\alpha - \langle n|V_\alpha|n'\rangle]\,\chi_n(\mathbf{R}_\alpha) = \sum_{n'\neq n} \langle n'|V_\alpha|n\rangle\,\chi_{n'}(\mathbf{R}_\alpha)$$

Continuum-Discretized Coupled Channels calculations (CDCC) ~ include the effect of the coupling to the continuum states (breakup)



Continuum A*

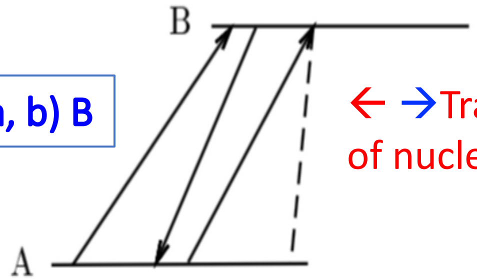
→ Breakup fragments

A (a, a) A*

Binning of the continuum w.f.

$$R^{bin}_{i,l}(r) = \sqrt{\frac{2}{\pi N}}\int_{k_1}^{k_2} \omega(k) R_{l,k}(r)\,dk$$

Coupled Reaction Channel calculations (CRC) ~ include rearrangement reactions, like nucleon transfer



A (a, b) B

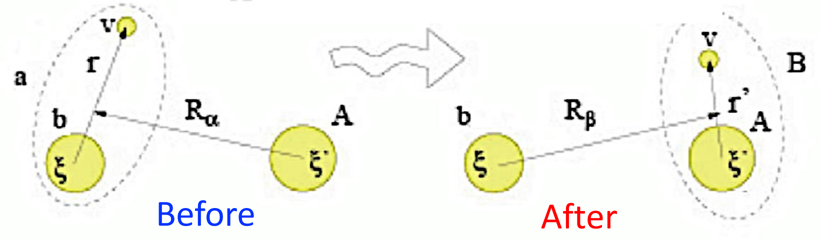
← →Transfer of nucleons

$$H = H_\alpha + k_\alpha + V_\alpha = H_\beta + k_\beta + V_\beta$$

$$\Psi = \chi_\alpha(\mathbf{R}_\alpha)\phi_\alpha(\alpha) + \chi_\beta(\mathbf{R}_\beta)\phi_\beta(\beta)$$

$$[E - \epsilon_\alpha - k_\alpha - \langle\alpha|V_\alpha|\alpha\rangle]\,\chi_\alpha(\mathbf{R}_\alpha) = \langle\phi_\alpha|(H-E)|\chi_\beta\phi_\beta\rangle$$

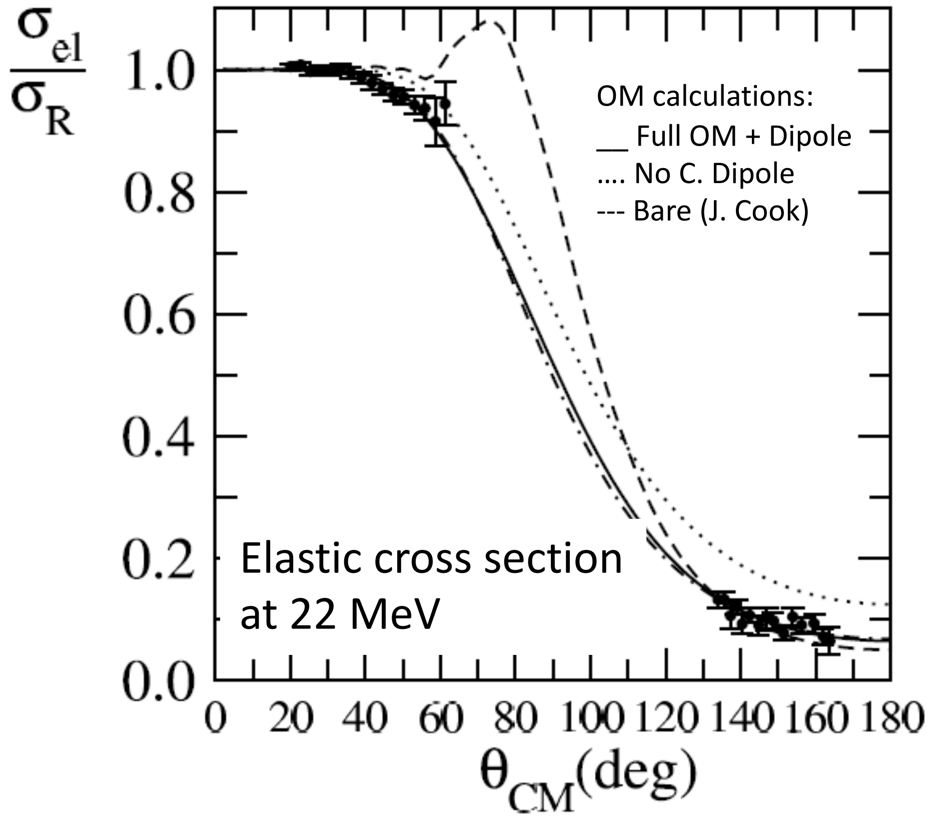
$$[E - \epsilon_\beta - k_\beta - \langle\beta|V_\beta|\beta\rangle]\,\chi_\beta(\mathbf{R}_\beta) = \langle\phi_\beta|(H-E)|\chi_\alpha\phi_\alpha\rangle$$



Scattering of ^{6}He

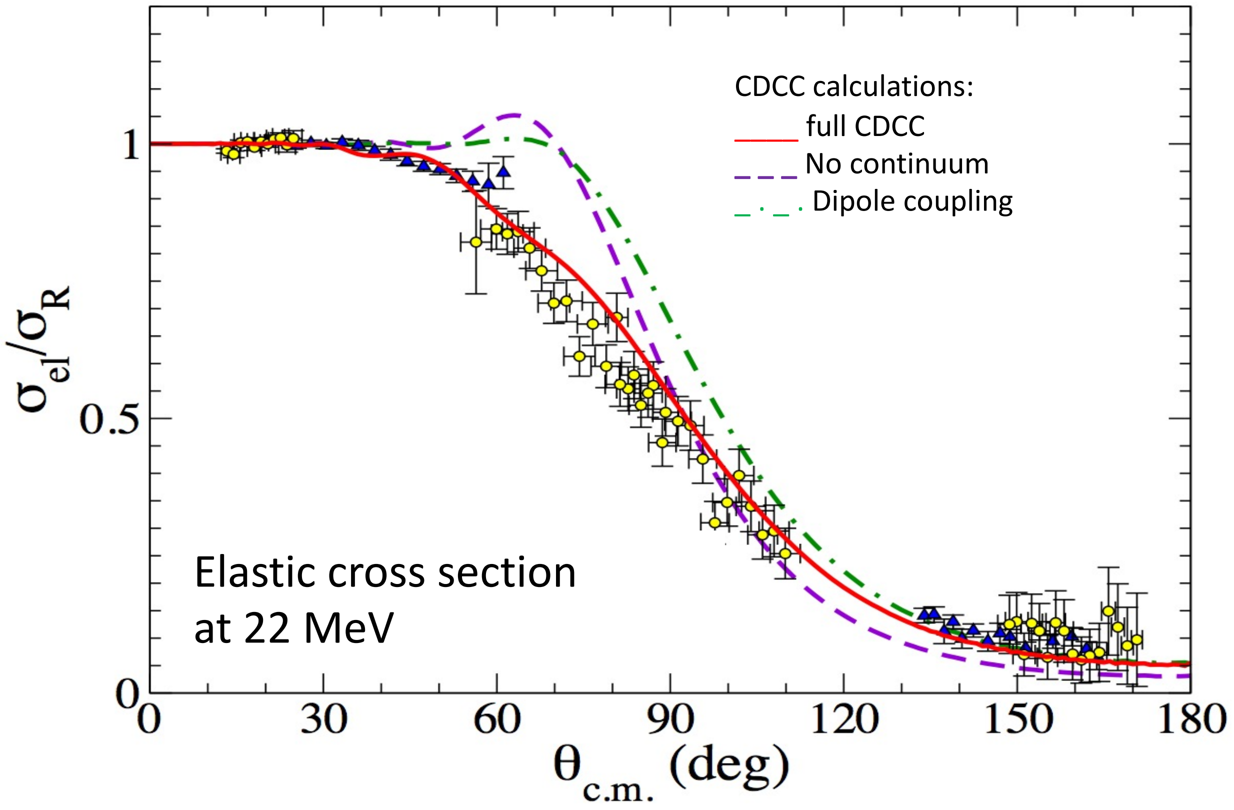
- Halo nucleus with Borromean structure: (4He + n + n); no bound states.
- Most investigated halo nucleus at Coulomb barrier energies (~ 50 data sets-EXFOR).
- ^{6}He+^{208}Pb @ 14,16,18, 22 MeV at CRC (Louvain-la-Neuve, Belgium).

A.M. Sánchez-Benítez, et al. NPA 803, 30 (2008)



- Strong absorption up to small scattering angles, rainbow dissapears.
- Large diffusivity of the OM imaginary potential ~ 1.8 fm
- Long range reaction mechanisms → Strong dipole Coulomb couplings

L. Acosta et al., PRC 84(2011) 044604.

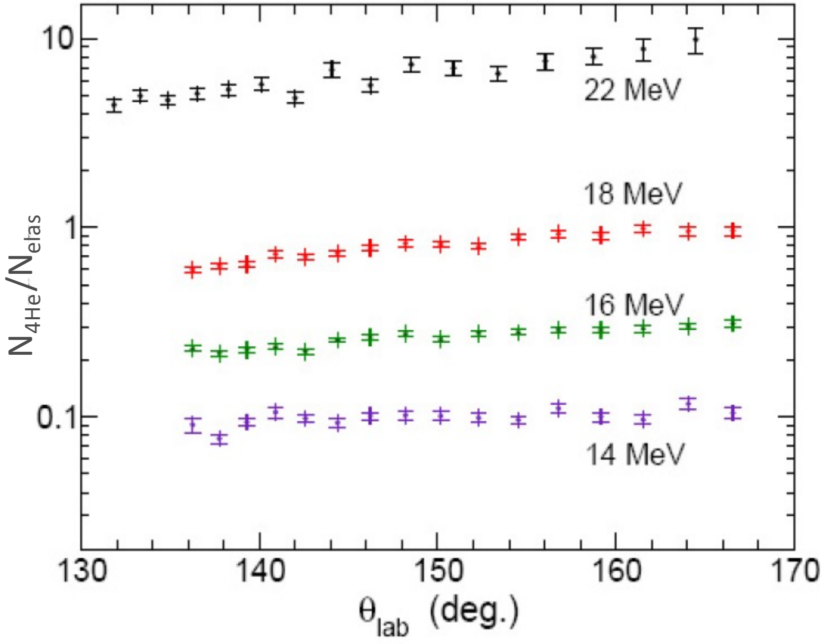


- CDCC calculations describe the data (2n-model)
- Scattering process dominated by:
- Dipole couplings (coulomb + nuclear)
- Coupling to continuum
- Strong Coulomb couplings due to the high target Z

N. Keeley et al., PRC 68, 054601 (2003)
K. Rusek et al., PRC 72, 037603 (2005).

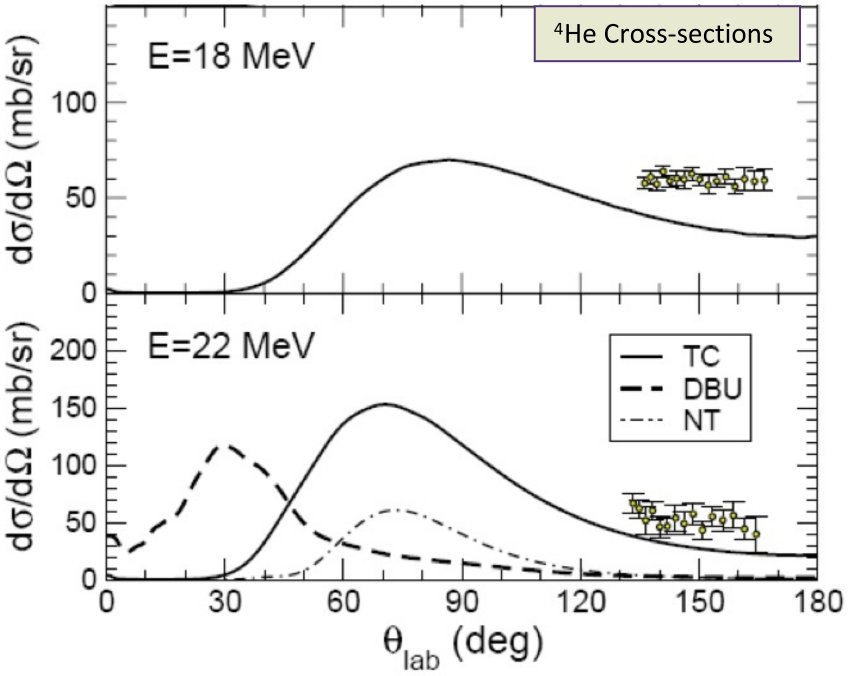
Scattering of ^{6}He

^{4}He Yield vs ϑlab (normalized to elastic)

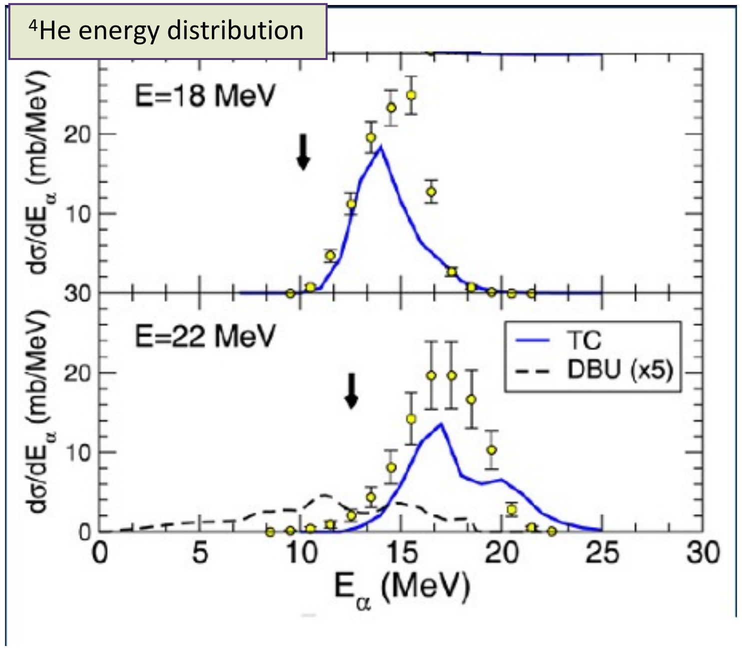


D. Escrig et al, NPA 792 (2007), L. Acosta et al., PRC 84(2011) 044604.

^{4}He Cross-sections



^{4}He energy distribution



- Large alpha yields even at sub-barrier energies (14 MeV, 10% of elastic)
- Large deviation from Rutherford scatt. well below the barrier.
- Forward angles dominated by direct breakup: CDCC calculations (DBU).
- Backward angles dominated by neutron transfer. DWBA calculations:
  → 1n – transfer (NT) gives small contribution.
  → 2n- transfer to the continuum (TC) gives main contribution.

- 2n-transfer describes properly the energy distribution.
- Strong coupling to breakup and transfer channels.
- Testbench for improving dynamic polarization potentials (breakup), polarizability, di-neutron and four body models.

R.S. Machintosh and N. Keley, Phys. Rev. C.79 (2009) 014611
N. Keeley, K.W. Kemper, K. Rusek. Phys. Rev. C.88.017602
A.M. Moro, et al, Phys. Rev. C 75, 064607 (2007)
M. Rodríguez-Gallardo et al., PRC 80, 051601(R)(2009)
V. Morcelle et al, PLB 732, 2014, 228

Scattering of ^{6}He

Vast amount of data: systematics of low energy ^{6}He scattering: reaction cross sections

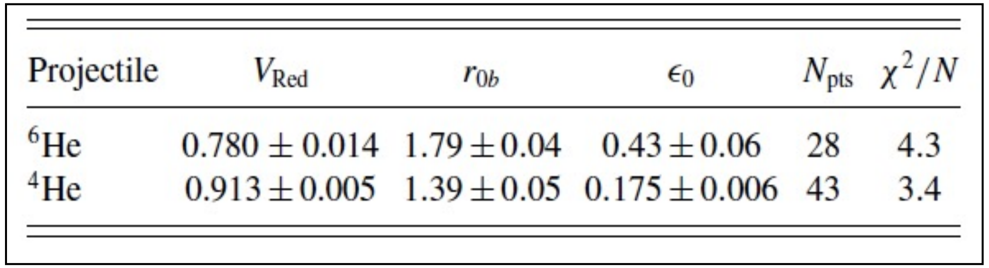
A systematic behavior can be found in reactions with several targets and energies by using scaling parameters for energy and radius:

Radius scaling factor: $(Ap^{1/3}+At^{1/3})$ ~ size
Energy scaling factor: $Zp\,Zt/(Ap^{1/3}+At^{1/3})$ ~ coulomb barrier → $E_{reduced}$
Xsection scaling factor: $R^2 \sim (Ap^{1/3}+At^{1/3})^2$ → $\sigma_{reduced}$

Fit data with Wong's formula:

$$\sigma^{W}_{\text{Red}} = \frac{\epsilon_0 r_{0b}^2}{2E_{\text{Red}}} \ln\left\{1+\exp\left[\frac{2\pi}{\epsilon_0}(E_{\text{Red}} - V_{\text{Red}})\right]\right\}$$

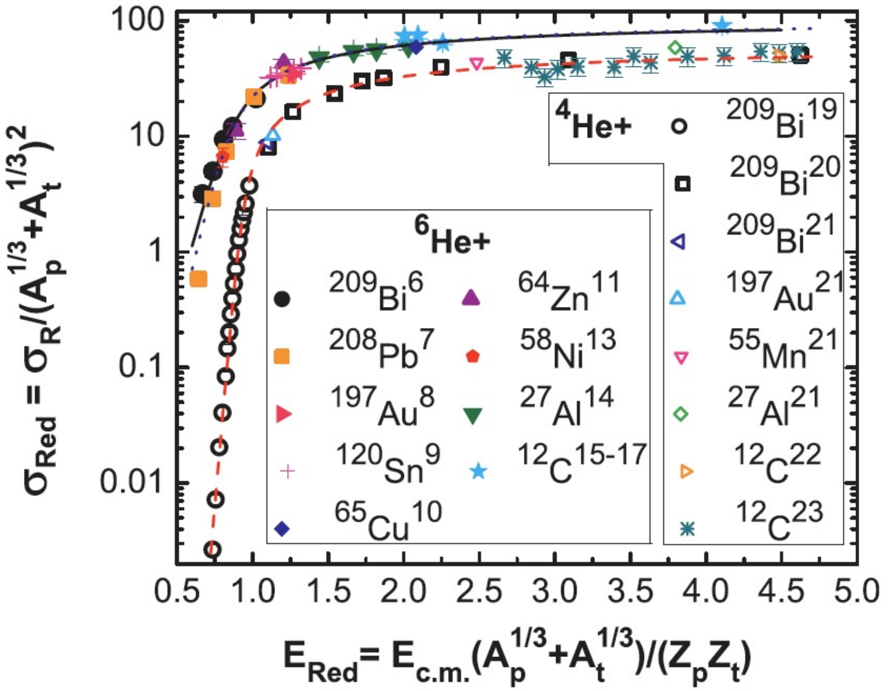
Results:



Projectile	V_{Red}	r_{0b}	ϵ_0	N_{pts}	χ^2/N
^{6}He	0.780 ± 0.014	1.79 ± 0.04	0.43 ± 0.06	28	4.3
^{4}He	0.913 ± 0.005	1.39 ± 0.05	0.175 ± 0.006	43	3.4

E.F. Aguilera et al., PRC 83, 021601(R) (2011)

Reaction cross sections for ^{6}He and ^{4}He at several energies and targets



Conclusions:

- Halo effects → Reaction barrier becomes lower and narrower → increase of reaction Xsection
- "Universal" function for ^{6}He reactions
- Core + halo decoupling: Xreac = Xcore + Xhalo
- Classification of light nuclei: normal, weakly bound, halo

J.J. Kolata and E.F. Aguilera et al., PRC 83, 027603 (2009)

Scattering of ^{6}He

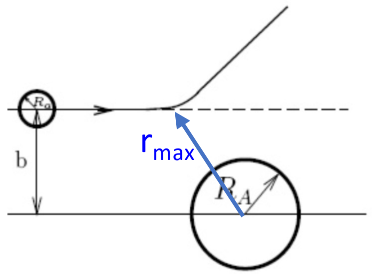
Systematics of Elastic scattering angular distributions

The scattering of halo nuclei at low energy system ^{6}He+^{208}Pb also exhibits interesting regularities in the angular distributions of elastic and alpha production cross sections.

Scaling parameters:

- Cross section: → Rutherford cross section
- Angle → distance of closest approach in coulomb trajectory

$$r_{max}(\theta) = e^2 (Zp\, Zt/2E)(1+1/\sin(\theta/2))$$



→ Semiclassical picture of the reaction process

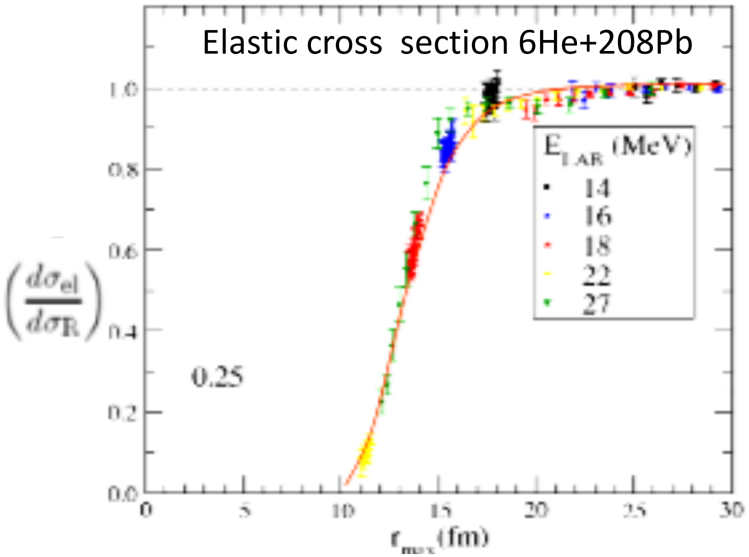
Survival probability $\dfrac{d\sigma_{el}}{d\sigma_R} = P_{el} = \exp\left[-\dfrac{2}{\hbar}\displaystyle\int_{-\infty}^{\infty} W(r(t))dt\right]$

- Proximity potential + Coulomb trajectories $W(r) = -W_0 \exp -\left(\dfrac{r-R}{a}\right)$

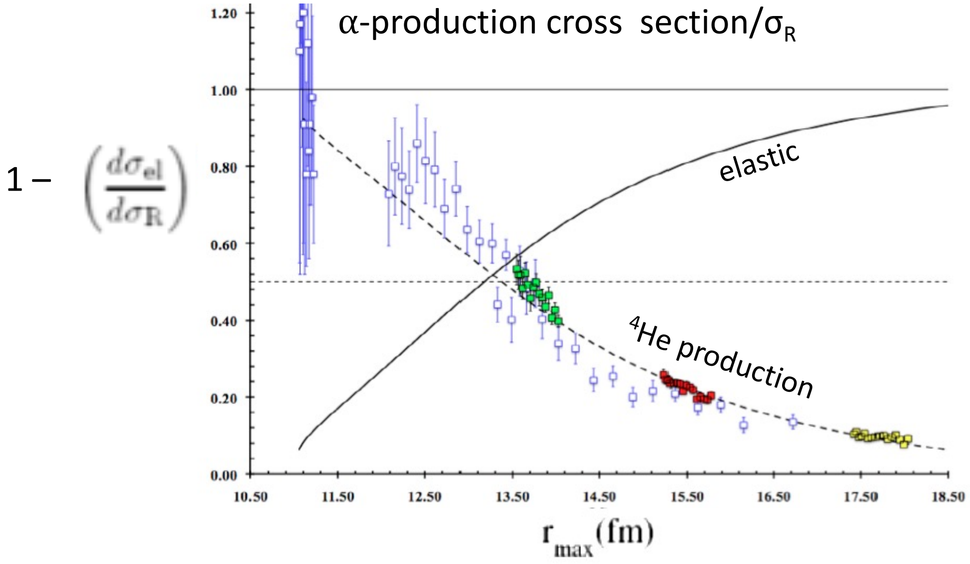
- Analytic result: $\log\left(\dfrac{d\sigma_{el}}{d\sigma_R}\right) = -4W_0\dfrac{a_0}{\hbar v}\exp\left(\dfrac{R-a_0}{a}\right)\left[K_0\left(\dfrac{a_0}{a}\epsilon\right) + \epsilon K_1\left(\dfrac{a_0}{a}\epsilon\right)\right]$

- Systematics → Reaction, Elastic and ^{4}He yield
- Reaction dominated by alpha production channels (n-transfer, breakup…)
- Semi-classical picture: reactions produced at distance of closest approach
- “Universal” function for ^{6}He scattering

A.M. Sánchez-Benítez et al., Acta Phys. Pol. B 37 (2006) 1



I. Martel, et al. Eur. Phys. Jour. (2011)

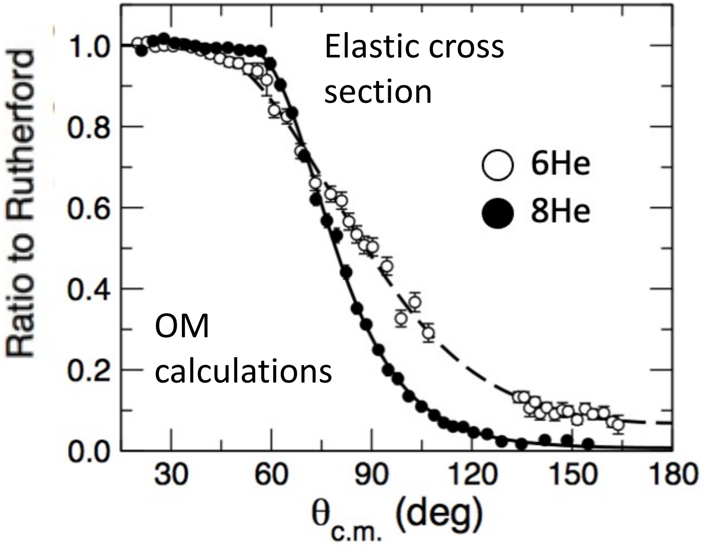


Scattering of ^{8}He

- ^{8}He is the most neutron-rich particle-stable nucleus with N/Z = 3→ Borromean & neutron skin (^{4}He+ n+n+n+n).
- ^{8}He + ^{208}Pb @ 22 MeV at SPIRAL1/GANIL (Caen, France)

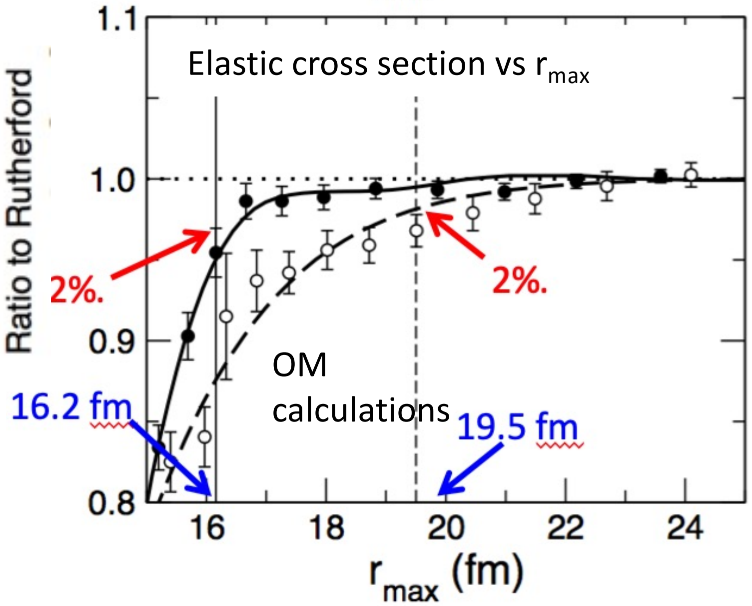
G. Marquínez-Durán et al., PRC 94, 064618 (2016), PRC 95 (2018)024602

I. Martel et al., PRC 102 (2020) 34609



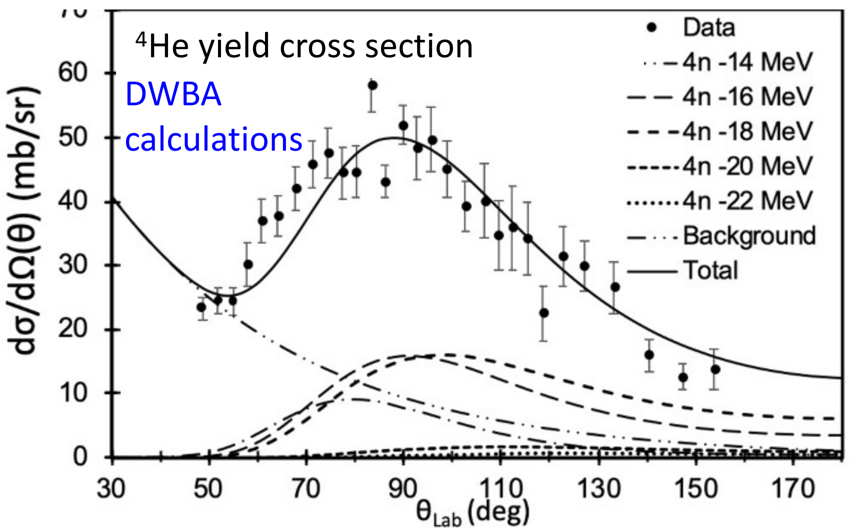
Elastic cross sections show clear structural effects due to difference between skin and halo

- Suppression of the Coulomb rainbow
- For 8He (skin): sharp fall-off of the elastic Xsection with with angle; but for 6He (halo): larger suppression of the Coulomb rainbow, smooth fall-off of elastic Xsec.
- Similar reaction cross sections for 6He,8He (1500/1400 mb).
- 8He OP has larger radius and smaller imaginary diffusivity → neutron transfer; 6He: dipole coupling to continuum and breakup.



Semi-classical plot using distance of closest approach in Coulomb trajectories

- Large absorption for 6He/8He at radii well beyond the strong absorption radius, but for 6He has a much longer range than for 8He
- Absorption for 8He has an abrupt decrease with distance whereas for 6He is very smooth
- 8He: dominated by neutron stripping at the proximity of the target. 6He: dipole coupling to continuum and breakup at large distances to the target.



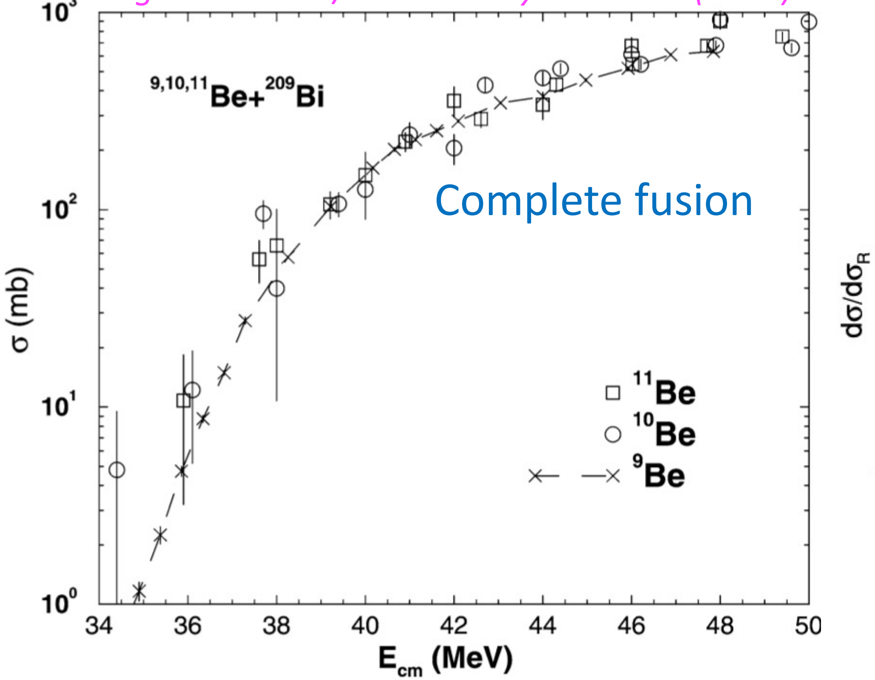
6He & 4He yields

- Large cross section for 6He, 4He production (900/400 mb) → little room for complete fusion.
- Angular distributions consistent with n transfer.
- ^{6}He yield (DWBA): Dominated by 1n transfer to excited states in 209Pb at Ex ~ 4 MeV, small contribution of direct 2n transfer.
- ^{4}He yield (DWBA): Can be described by direct 4n transfer at Ex ~ 18 MeV. → tetraneutron transfer

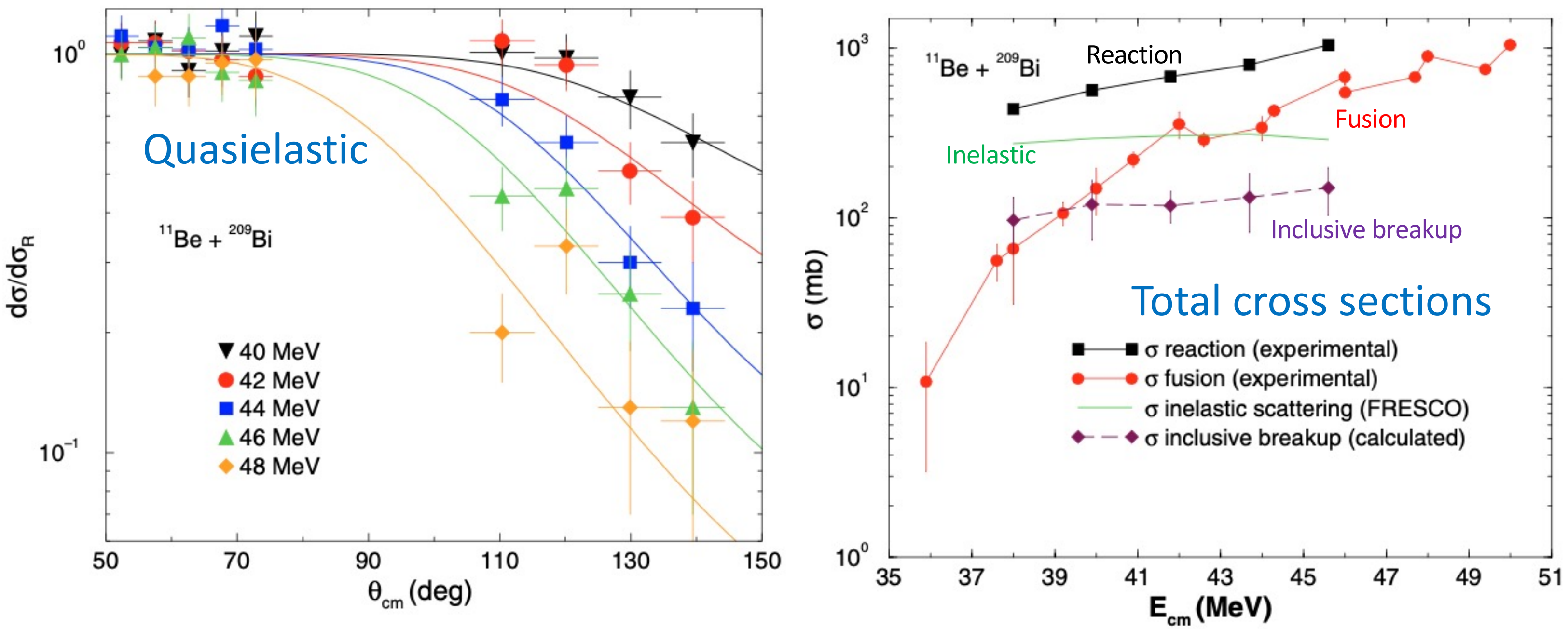
Scattering of ^{11}Be

- ^{11}Be: 1n halo (^{10}Be+n), one bound excited state (1/2-,320 keV), largest known B(E1) (ex → gs) → first halo discovered
- ^{11}Be+^{209}Bi @ 35 - 50 MeV at RIKEN RIPS facility
- Inflight method + degraders → beam energy event by event via Time-Of-Flight (TOF).

C. Signorini et al. / Nuclear Physics A 735 (2004) 32



M. Mazzocco et al., Eur. Phys. J. A 28, 295 (2006)



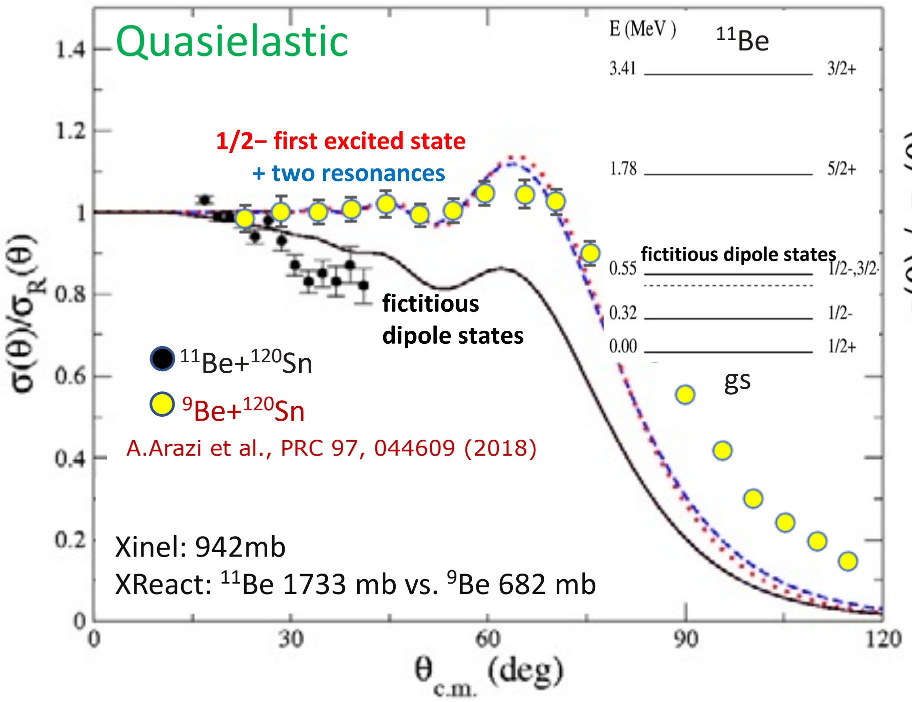
- Puzzling result: very similar data for ^{9,10,11}Be.
- Reproduced by CCFULL, CDCC calculations.
- No sub-barrier hindrance for ^{11}Be due (expected from halo).
- No sub-barrier hindrance ^{10}Be (coupling to 1st ex. state, large β_2).
- ^{11}Be → competition halo (hindrance) – breakup.
- Similar effects to ^{6}He fusion. R. Wolski et al., EJPA 111 (2011)

- Data well described by OM, DWBA and Coupled-Channel formalism with deformation from B(E1). Strong absorption ~ no Coulomb rainbow
- Calculated inelastic cross sections.
- Reaction cross section ~ 10 x fusion cross section.
- Derived inclusive breakup cross sections ~ 100-150 mb ~ relatively small.
- Slightly larger fusion cross sections for ^{11}Be than ^{9}Be below the barrier → halo effects.

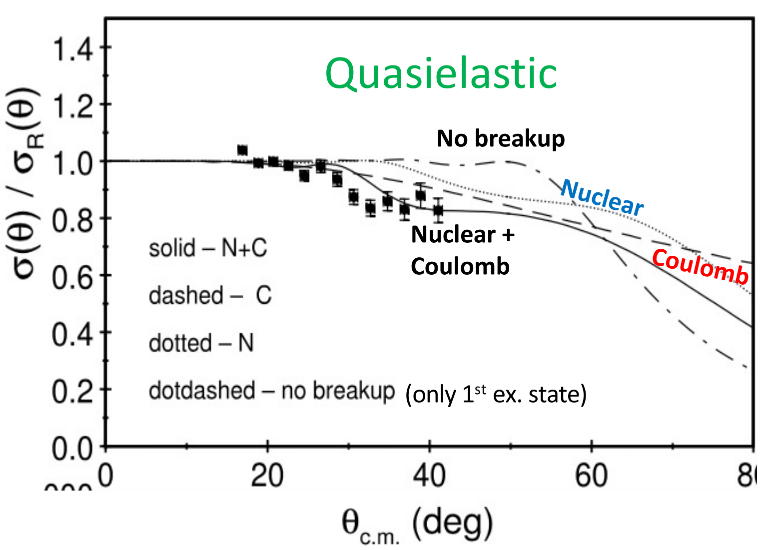
Scattering of ^{11}Be

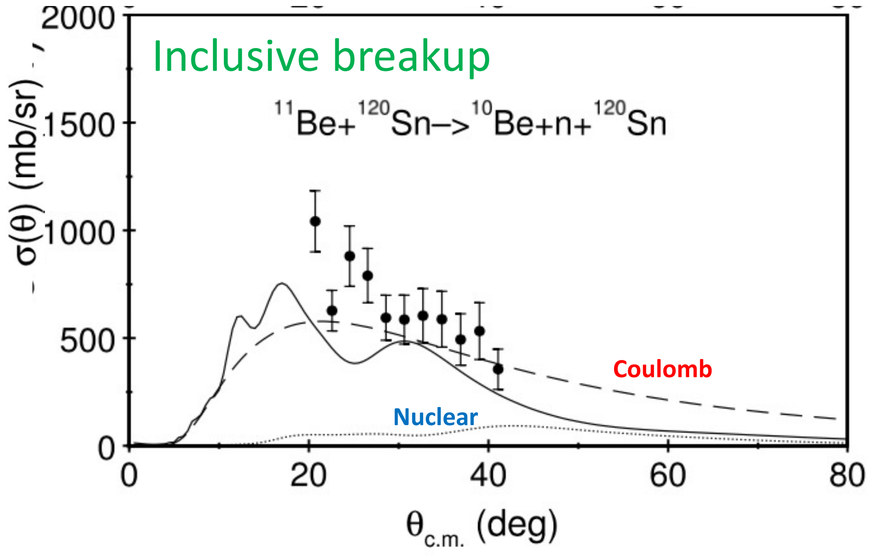
^{11}Be+^{120}Sn @ 32 MeV (REX-ISOLDE/CERN) → ^{11}Be quasielastic and ^{10}Be fragments (breakup)

L. Acosta et al., Eur. Phys. J. A 42, 461 (2009).



K. Rusek et al. 43 (2012) ACTA PHYSICA POLONICA B





- Coulomb-nuclear interference is strongly damped.
- Deviation from Coulomb ~30° cm → long range reaction mechanism
- (CC) calculations: simple vibrational model + Inert target.
- Deformation length from B(E1).
- Two resonant states at 1.78MeV and 3.41MeV.
- Coupling to ^{10}Be + n. continuum→ two fictitious dipole states.
- Most important effect is the coupling to the (dipole) continuum.
- No effect of ½- state on elastic despite relative large cross section.
- Small effect of resonances.

- CDCC calculations: weak dependence on n + ^{10}Be potentials
- Large breakup yield ~ 50% total.
- Strong Coulomb-nuclear interference effect: competition of BOTH Coulomb and **nuclear contributions;** for ^{11}Be 1st exited state ~ destructive interference.
- Important for BOTH quasielastic and breakup.
- Coulomb post-acceleration: the whole Coulomb potential energy of ^{11}Be is taken by ^{10}Be: larger kinetic energy than predicted from kinematics by ~ 1.8 MeV

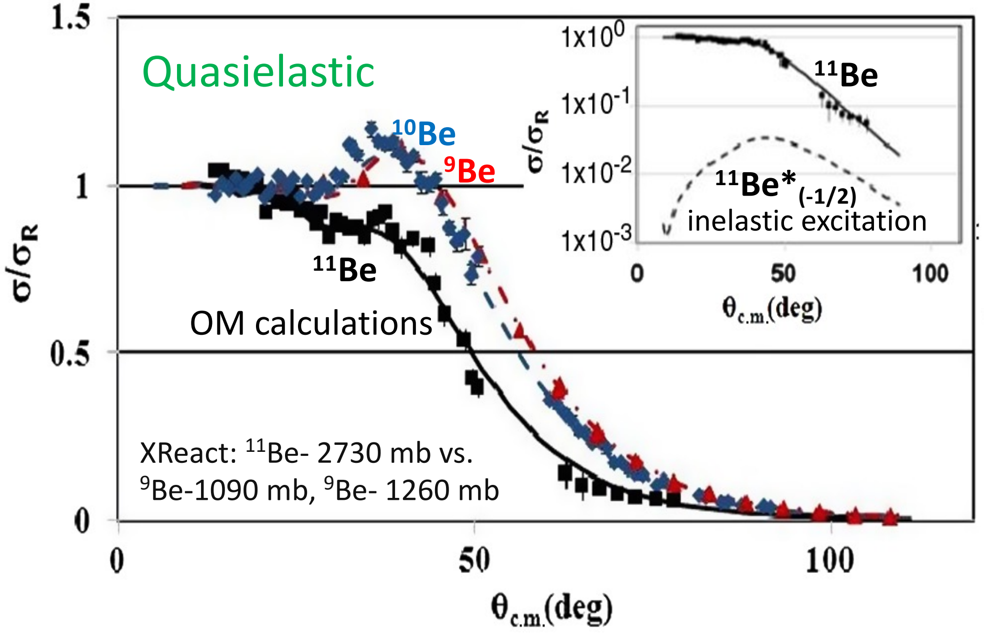
$$\Delta E = \frac{m_n}{m_n + m_c}\,\frac{Z_c Z_t e^2}{R_{bu}},$$

→ ^{11}Be breaks at about ~ 20 fm from the target
→ Much larger than strong absorption radius
→ large Coulomb effect on breakup

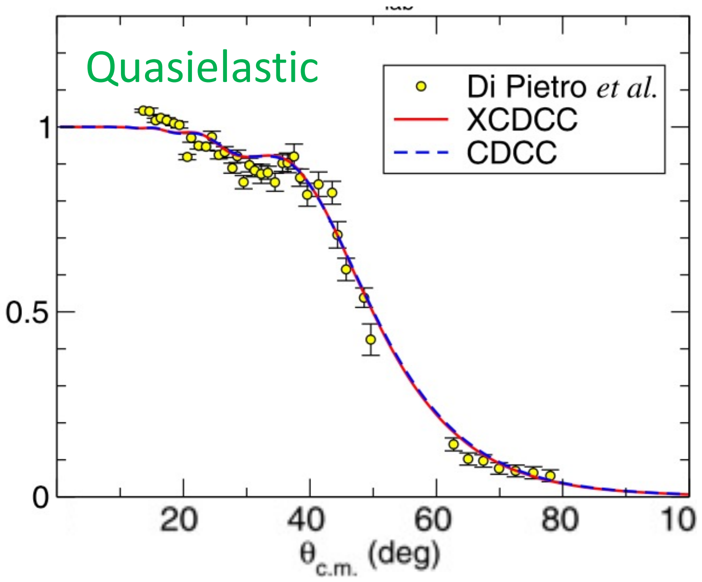
Scattering of ^{11}Be

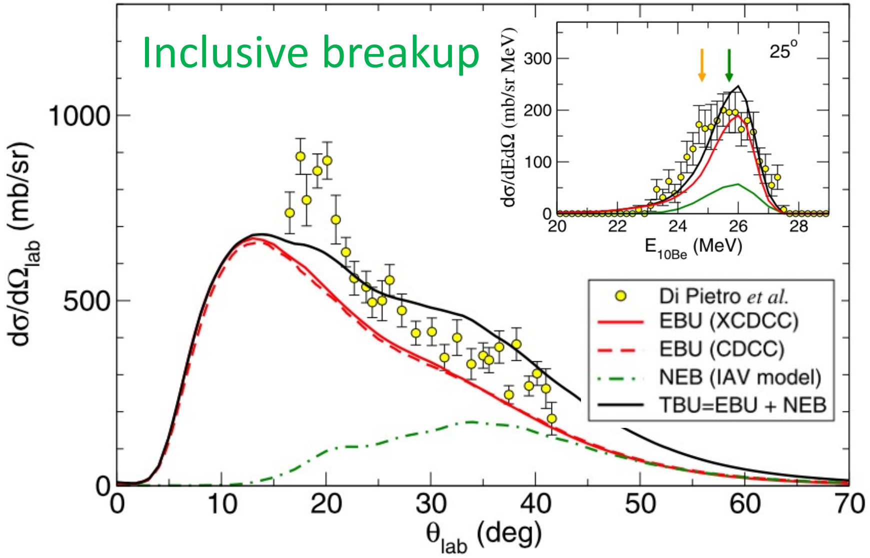
^{11}Be+ ^{64}Zn @ 28.7 MeV (REX-ISOLDE/CERN) → ^{11}Be quasielastic and ^{10}Be fragments (breakup)

A. Di Pietro et al., Physics Letters B 798 (2019) 134954



A. Di Pietro et al., Physics Letters B 798 (2019) 134954





- ^{11}Be → Coulomb-nuclear interference is strongly damped.
- Deviation from Coulomb ~30° cm → long range reaction mechanism.
- Low Z target (Z=30): Coulomb breakup not too strong → strong absorption associated with the halo structure.
- Small inelastic contribution ~ COULEX using B(E1).
- ^{11}Be: OM calculations with large imaginary surface term ~ polarization potential to account for the strong reduction of the Coulomb-nuclear interference (ai=3.5 fm) → diffuse halo structure → long range absorption ~ dynamic polarizability.
- Large transfer/breakup cross section ~ 40% of the reaction cross sections. ~ factor 2 x ^{9,10}Be.

- Elastic and non-elastic BU calculations (EBU, NEB)
- EBU: XCDCC calculations ~ effect of core excitation→ 10Be deformation.
- n-10Be system particle-plus-rotor model + deformed central potential (^{10}Be ex.)
- Standard CDCC with same parameter to compare effects
- NEB: participant-spectator IAV model (M. Ichimura, N. Austern, C.M. Vincent, PRC32 (1985)431)
- Both XCDCC and CDCC reproduce the Quasielastic cross sections, but the inelastic cross sections differ by ~ 50% (940mb/450 mb) could only be tested by measuring inelastic.
- Both XCDCC and CDCC underpredict the inclusive BU 20%, the NEB makes an important contribution.
- EBU+NEB consistent with angular and **energy distributions** of ^{10}Be fragments.
- Coulomb post-acceleration: larger kinetic energy ~ 1 MeV ~ 15 fm angle-independent, consistent with the result of ^{120}Sn scatt. → included in EBU+NEB formulation.

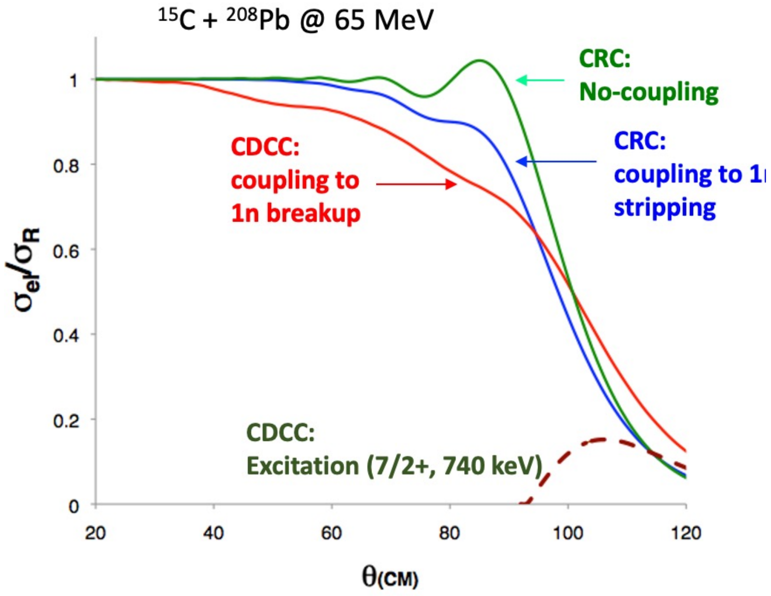
Scattering of ^{15}C

- ^{15}C: 1n-halo (^{14}C+n). **Unique ground** state characterized by $2s_{1/2}$ single-particle configuration. First excited state (E= 740 keV).
- Coulomb barrier scattering of ^{15}C + ^{208}Pb @ 65 MeV
- Recent experiment at HIE-ISOLDE (CERN)

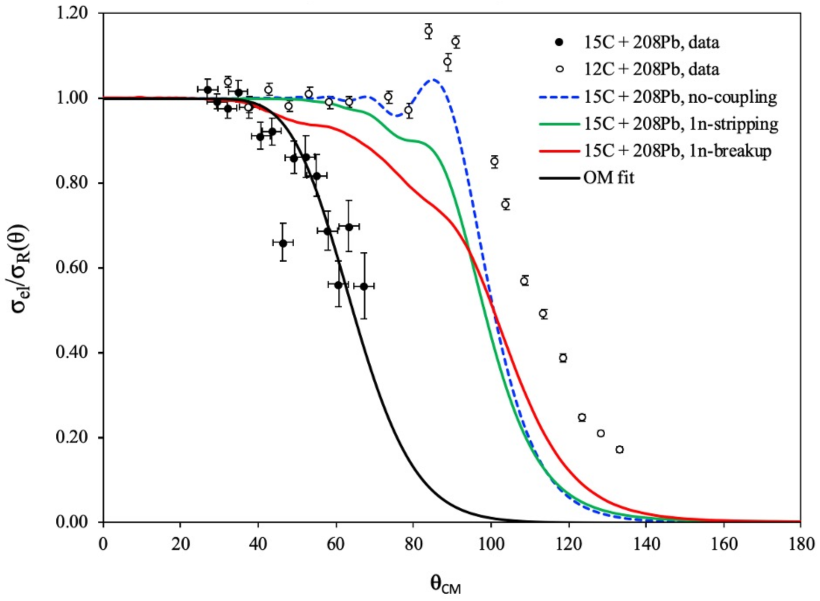
Theoretical studies for the system ^{15}C+^{208}Pb at Coulomb barrier ~ E= 65 MeV.

- 1n-stripping channel: Coupled Reaction Channel calculations (CRC).
- Breakup: Continuum Discretized Coupled Channel Calculations (CDCC).
- Inelastic (7/2+, 740 keV): CDCC.

N. Keeley et al., Phys. Rev. C 75 (2007) 054610
N. Keeley et al., Eur. Phys. J. A 50 (2014) 145.



Preliminary results



Scattering dominated by the competition of one-neutron stripping and breakup.

CRC/ 1n stripping		CDCC/ direct breakup	
Total reaction (mb)	927	Total reaction (mb)	1379
1-n stripping (mb)	265	Breakup (mb)	462
		Excitation(5/2+,740keV) (mb)	45

OM parameters

^{15}C → a_w= 1.5 fm (!!)

- ✓ Stable: ^{12}C, a_w= 0.4 fm
- ✓ 1n-halo: ^{11}Be, a_w= 3.5 fm
- ✓ 2n-halo: ^{6}He, a_w= 2 fm

Reaction cross sections

$\sigma_{exp}(^{15}C)$ ~ 3000 mb → 8 x $\sigma_{exp}(^{12}C)$

- ✓ 3 x σ_{th}(1n-stripping)
- ✓ 2 x σ_{th}(1n-breakup)

Seems to be an extraordinary result, but:

- Data analysis suffered from low statistics ~ shift forward angular distribution ~20°
- Requesting more beam time to improve/review the measurement

Summary and conclusions

- Brief summary of relevant results involving Coulomb barrier scattering of ^{6}He (2n-halo), ^{8}He(2n/4n-skin) and ^{11}Be (1n-halo), ^{11}C (1n-halo).
- Larger reaction cross sections than stable nuclei, dipole polarizability and coupling to the continuum.
- Systematics of reaction cross sections, angular distributions of elastic and core-production cross sections.
- Difference between halo and skins.
- More neutrons do not produce much more fusion → breakup.
- Reaction dynamics depends on the particular halo system and target: for large target Z Coulomb effects are more important.
- Core deformation, elastic and inelastic breakup.
- Simpler 3 body models can describe gross properties, core deformation and 4 body models are needed for accurate descriptions.
- Good workbench to test few-body models and nucleon-nucleon correlations, leading to new interesting discoveries.