EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Proposal to the ISOLDE and Neutron Time-of-Flight Committee

Probing the halo structure of ^{15}C at energies around the coulomb barrier (P-446)

Spokespersons: I. Martel, O. Tengblad

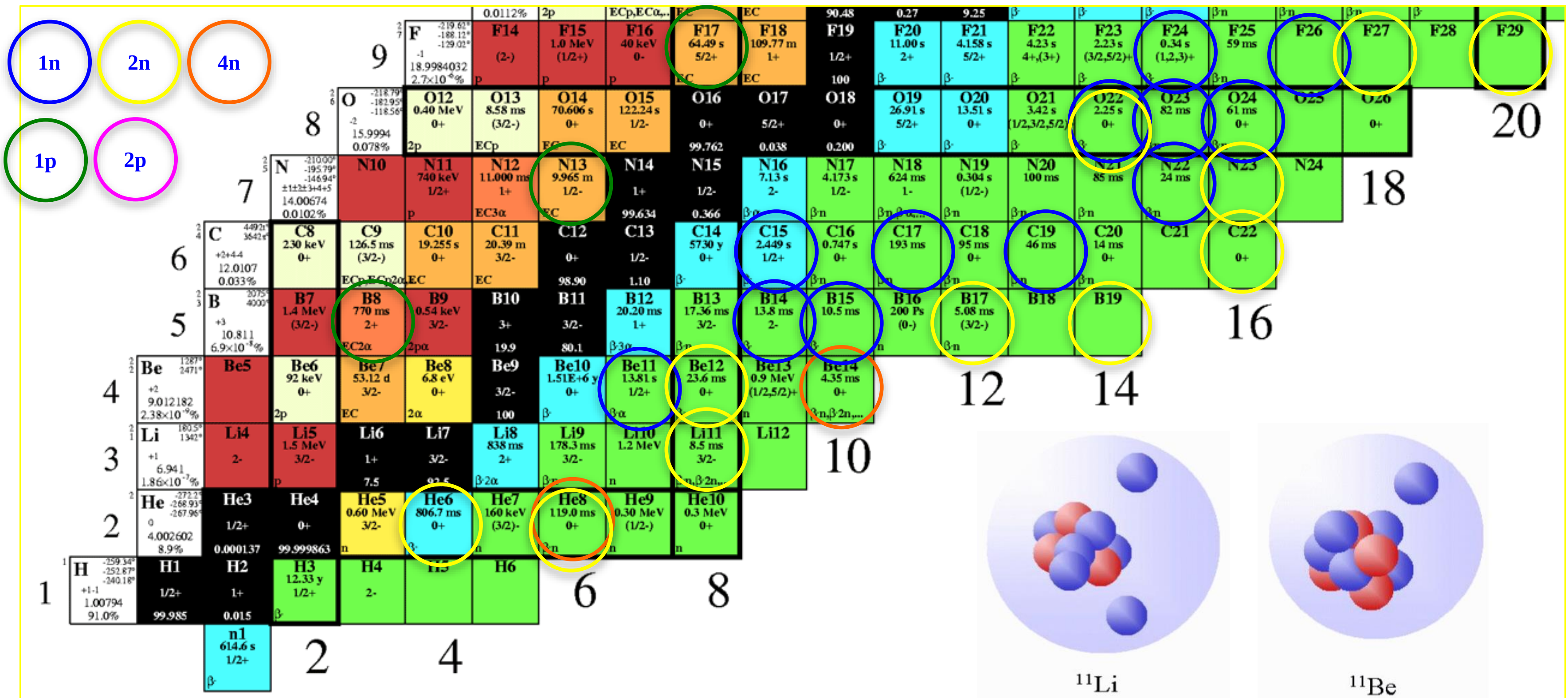
Local contact: Miguel Madurga

Motivation

The occurrence of nuclear halos is within the most striking properties of light exotic nuclei.

Threshold effect:

- States having loosely bound nuclei, S_{1n} or S_{2n} << 2 MeV (or proton!)
- Tunneling the nuclear potential → extended nuclear density distribution (~ "50% out")
- Two & three body correlation effects → often "borromean" systems
- Low lying dipole strength close to break-up threshold



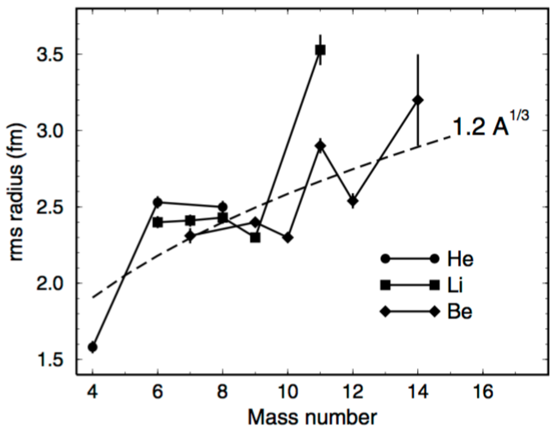
Gudveen Sawhney et al., J. Phys. G: Nucl. Part. Phys. 41 (2014) 055101 (13pp)

Experimental Evidences: high energy scattering

The first evidence of the existence of halo structure came in early 1980's from the measurement of the electric dipole transition between the first and gs. in ^{11}Be, that could only be explained by assuming an extended wave function arising from the weak binding.

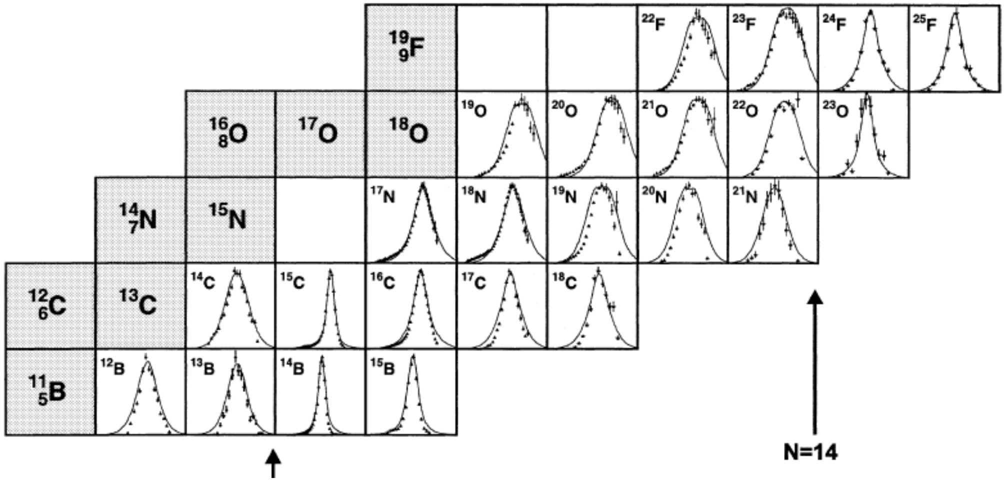
D.J. Millener, J.W. Olness, E.K. Warburton, S. Hanna, Phys. Rev. C 28, 497(1983).

Experiments at high beam energies ~100- 800 MeV/nucleon reveal very large total reaction cross sections and extremely narrow momentum distributions following nuclear breakup, which can be only explained by assuming a halo structure.



A plot of the matter radii of isotopes of He, Li and Be as predicted by reaction cross section measurements and deduced from Glauber model calculations

J.S. Al-Khalili, et al., Phys. Rev. Lett. 76 3903 (1996), Phys. Rev. C 54 1843 (1996).



The longitudinal momentum distributions for the core fragments following single neutron removal from a range of neutron-rich nuclides on a carbon target. The narrow the distribution, the larger the size of the nucleus.

E. Sauvan et al., Phys. Lett. B 491, 1 (2000)

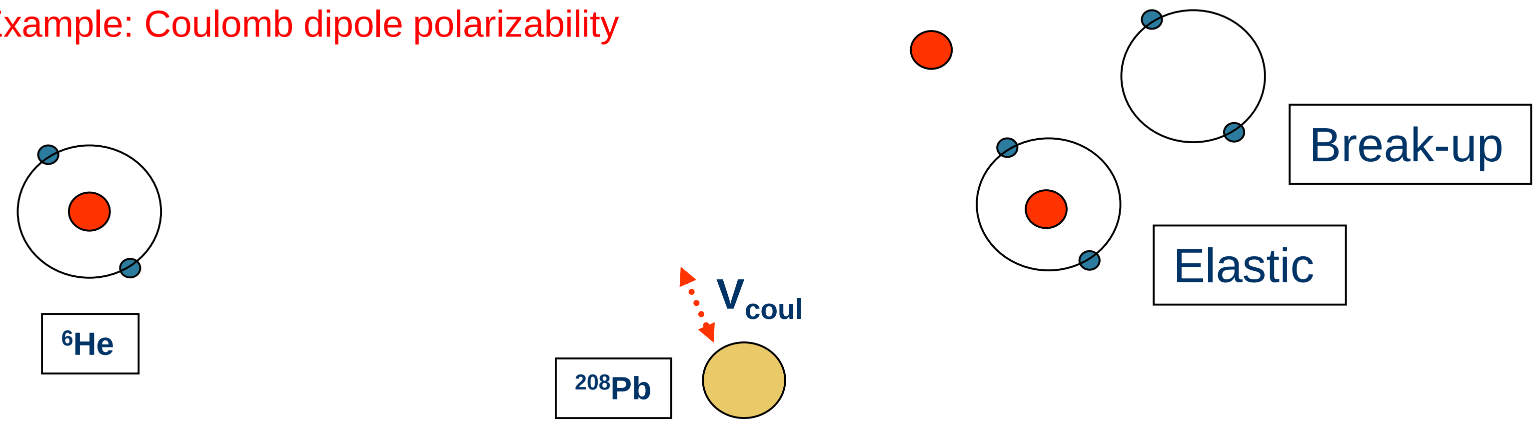
"An Introduction to Halo Nuclei", Jim Al-Khalili, Department of Physics, University of Surrey, UK, "The Euroschool Lectures on Physics with Exotic Beams, Vol. III", Lect. Notes Phys. 764, Springer 2009

Experimental Evidences: Low energy scattering

Coulomb barrier energies are interesting to study halo dynamics: important correlation between relative motion and internal degrees of freedom; provides strong couplings effects between elastic channel and inelastic, transfer, breakup and fusion channels

→ good scenario to study influence of halo and coupling to the continuum on reaction dynamics
→ probe of theoretical models for nuclear reactions and few body correlations

Example: Coulomb dipole polarizability



→ Strong absorption in elastic channel

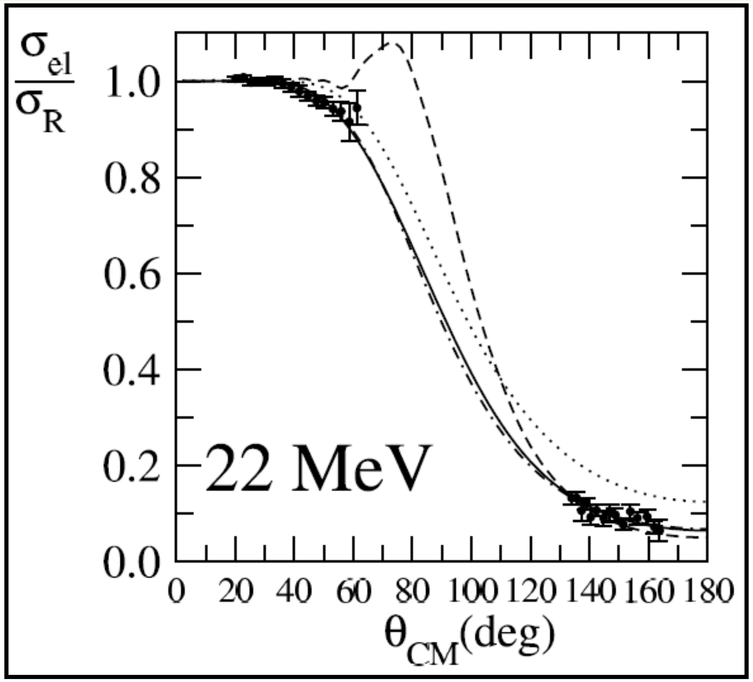
→ Large cross section for fragmentation

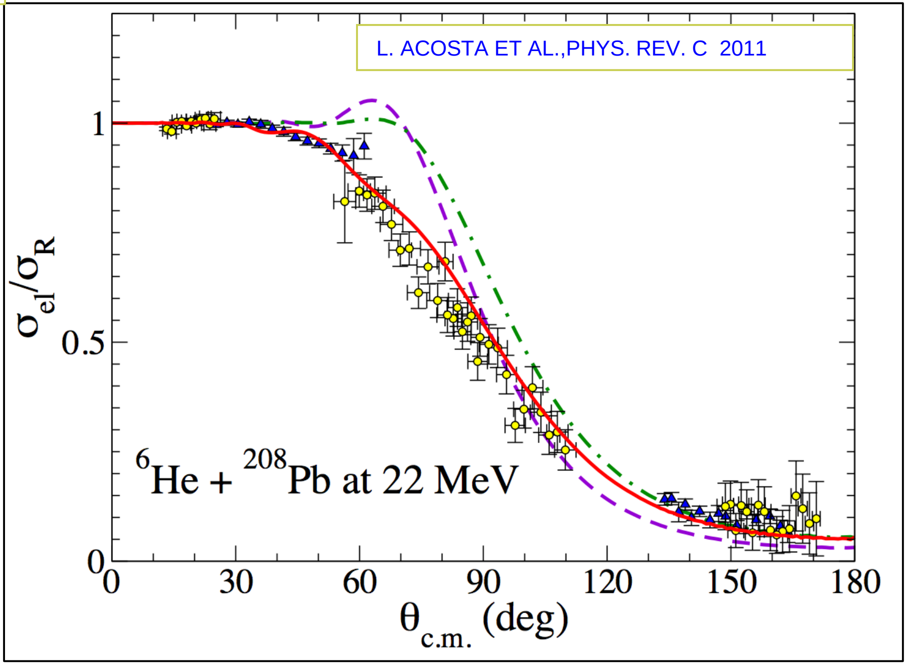
→ a very sensitive probe of a halo structure can be just the angular distribution of the elastic cross sections and fragment yields in reactions with heavy targets at Coulomb barrier energies

Elastic cross sections for ^{6}He + ^{208}Pb system at Coulomb barrier energies

CRC-Louvain la-Neuve (Belgium) Experiments PH189, PH215

A.M. SANCHEZ-BENITEZ, et al.   NUCLEAR PHYSICS A803, 30 (2008)





OM calculations:
— Full OM + Dipole   No C. Dipole   --- Bare (J. Cook)

CDCC calculations:
— full CDCC   — No continuum   — Dipole coupling

Strong absorption up to small scattering angles, rainbow dissapears. → Long range reaction mechanisms → Strong dipole Coulomb couplings

CDCC calculations describe the data (2n-model)

N. Keeley et al., Phys. Rev. C 68, 054601 (2003)

K. Rusek et al., Phys. Rev. C 72, 037603 (2005).

Scattering process dominated by:

- Dipole couplings (coulomb + nuclear)
- Coupling to continuum

Systematics of low energy ^{6}He scattering: angular distributions

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

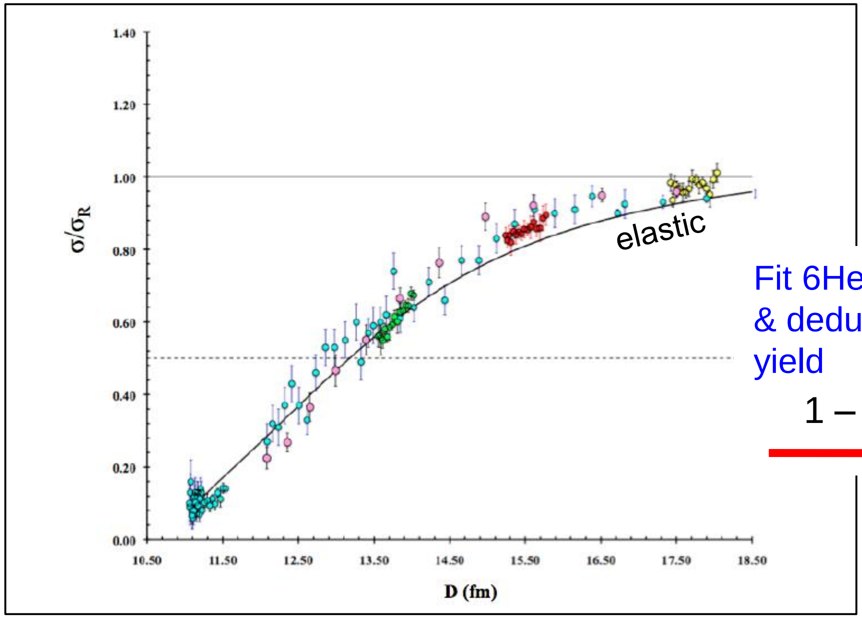
Scaling parameters:

- Cross section: → Rutherford cross section
- Angle → distance of closest approach in coulomb trajectory $D(\theta) = e^2 (ZpZt/2E)(1+1/\sin(\theta/2))$

→ Semiclassical picture of the reaction process

I. Martel, AIP Conf. Proc. 1423 (2011) 89.

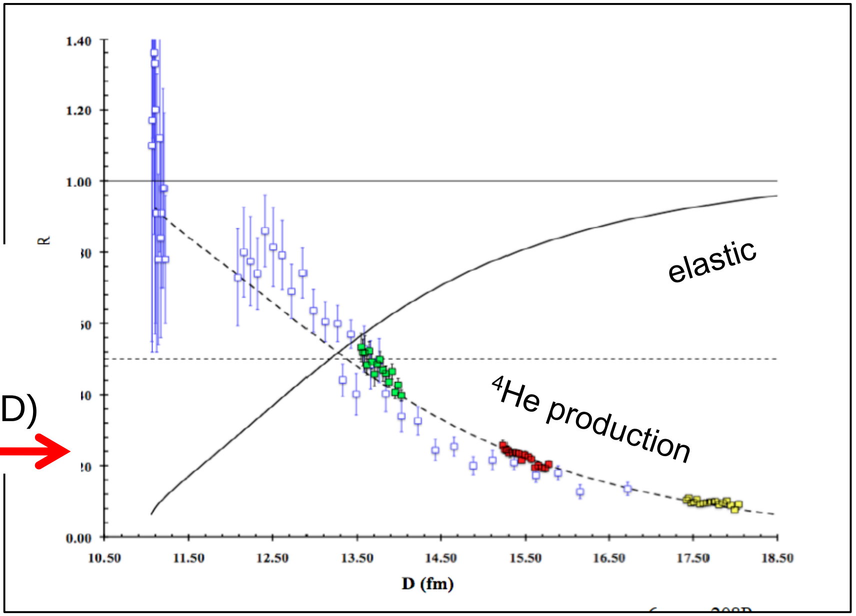
$^6He+^{208}Pb$, elastic (14, 16, 18, 22 MeV)



Fit 6He elastic & deduce 4He yield

1 – Xelas(D)

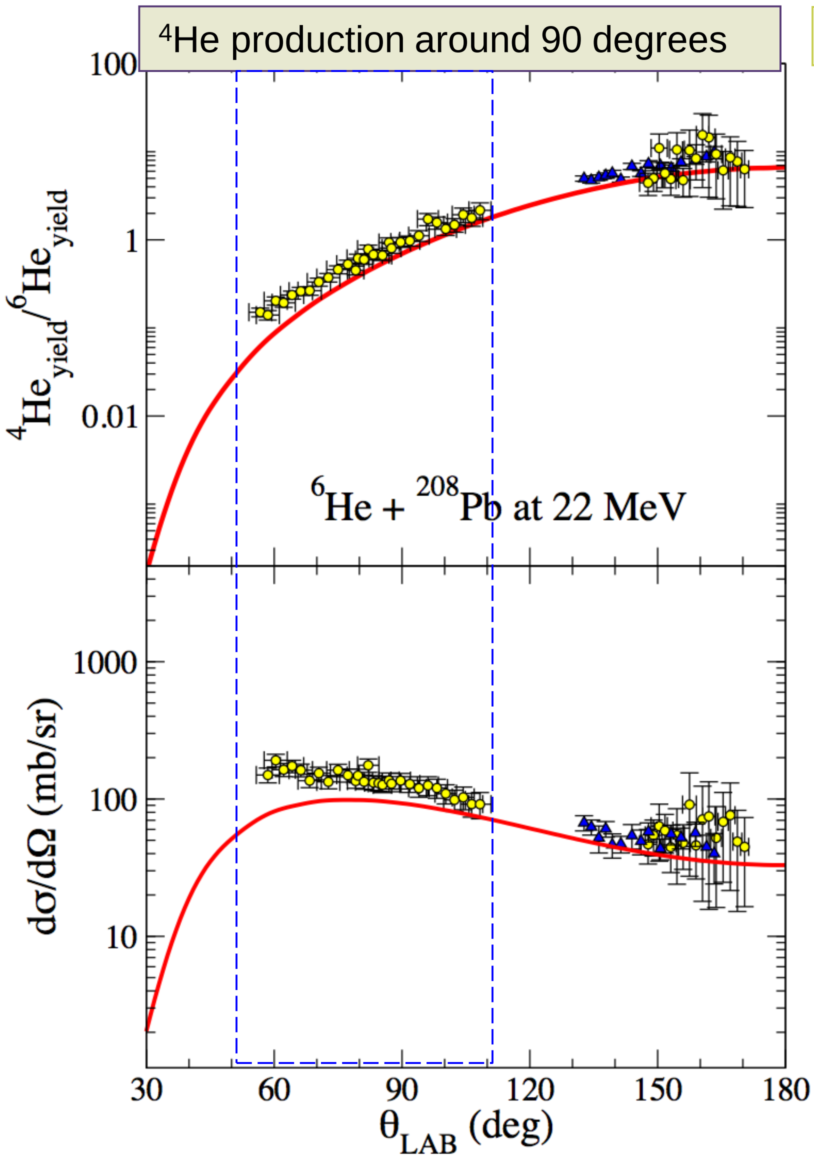
$^6He+^{208}Pb$, ^4He yield (14, 16, 18, 22 MeV)



- Characteristics reaction mechanisms at each given turning point!!
- Core/halo "decoupling"
- Only one energy needed (22 MeV) to predict angular distributions of Xel and Xreact at lower energies!!

→ Characteristic low-energy probe of "halo" systems.

The role of breakup/transfer channels

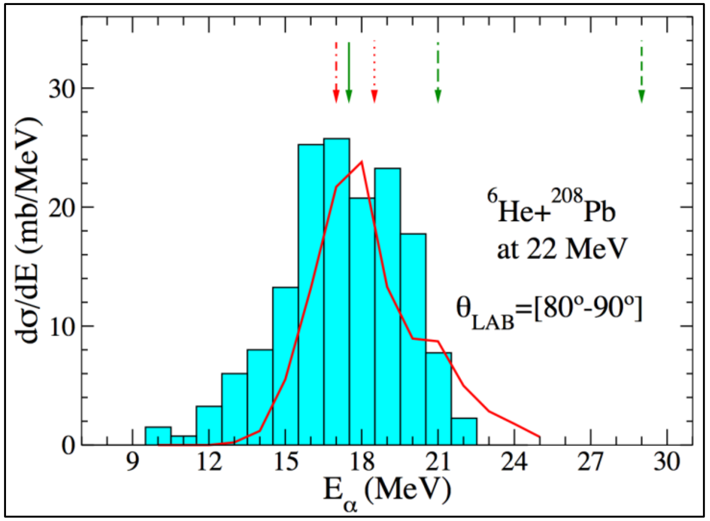


L. ACOSTA ET AL., PHYS. REV. C 2011

DWBA calculation

2n- transfer gives main contribution at backwards AND intermediate angles (red line).

→ Consistent with energy distribution.



Conclusion:
Breakup dominates at forward angles, but transfer reactions, and especially 2n transfer to neutron-unbound final states make the biggest contribution to the alpha-particle production cross section.

The case of the neutron rich nucleus ^{15}C

Measured reaction cross-sections and transverse momentum distribution for $^{14-17}$C at intermediate/high energies (20 A MeV - 1000 A MeV) at RIPS/RIKEN(Tokyo, Japan), GSI (Darmstadt, Germany), LBL (Berkeley, USA) and RIBLL (Lanzhou, China).

D. Bazin, et al. PRC 57(1998) 2156

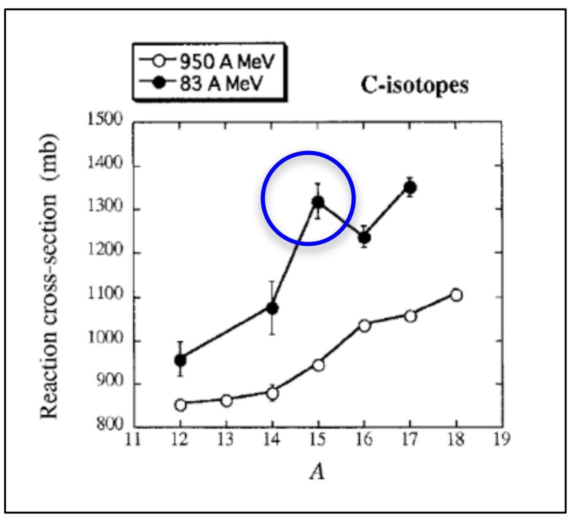
Nucleus	Be target	Ta target
^{14}B	57 ± 2 MeV/c	48 ± 3 MeV/c
^{15}C	67 ± 3 MeV/c	67 ± 1 MeV/c
^{17}C	145 ± 5 MeV/c	
^{19}C	42 ± 4 MeV/c	41 ± 3 MeV/c

Measured FWHM of the parallel momentum distributions expressed in the c.m. system.

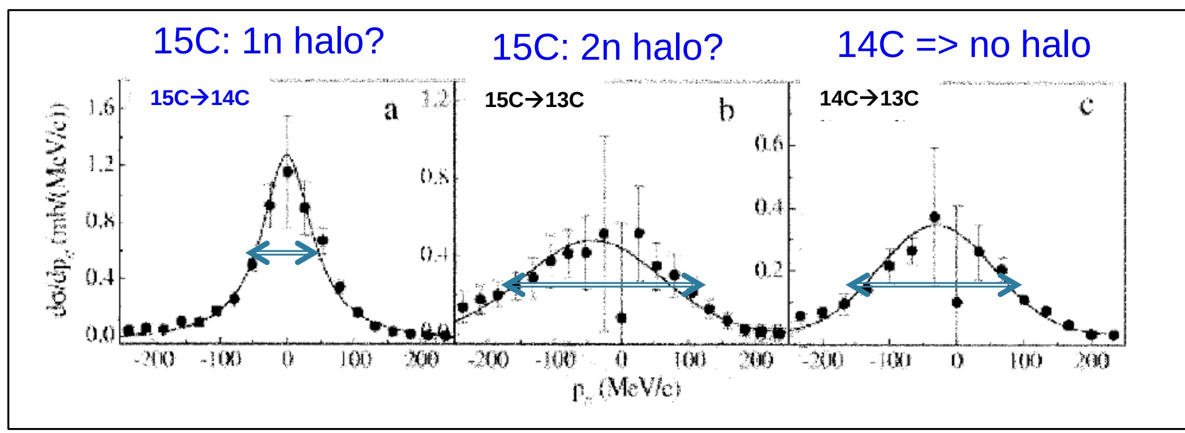
Halo nuclei

Nucleus	S_n	J^π g.s.	Valence neutron orbit
^{14}B	970 ±21 keV	2^- (expt.)	$1s_{1/2}$ (expt.)
^{15}C	1218.1 ±0.8 keV	$1/2^+$ (expt.)	$1s_{1/2}$ (expt.)
^{17}C	729 ±18 keV	$3/2^+$ (calc.)	$0d_{5/2}$ (calc.)
^{19}C	160 ±110 keV	$1/2^+$ (calc.)	$1s_{1/2}$ (calc.)

A. Ozawa, Nuclear Physics A738 (2004) 3844



Reaction cross sections for C isotopes an 83 A MeV and 950 A MeV on 12C target



Longitudinal momentum distributions for 14C from 15C, I3C from 15C, and 13C from 14C at 83 A MeV on 12C target.

→ Is 15C a Halo nucleus?

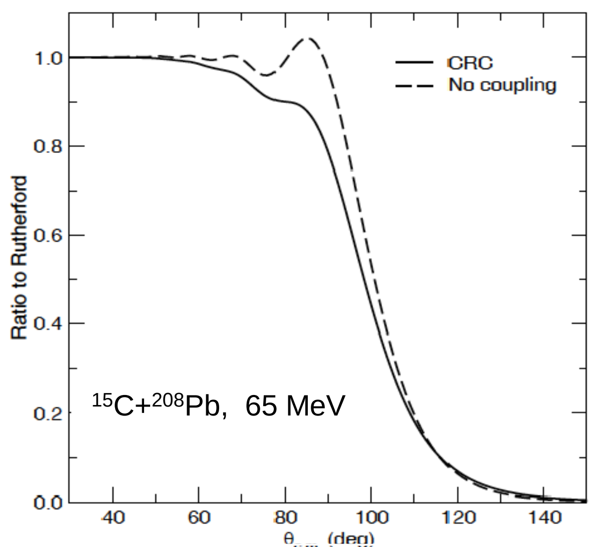
Nuclear reactions of ^{15}C at energies around the Coulomb barrier

A very important probe of the halo structure are particular signatures appearing in reactions at Coulomb barrier energies. In particular, the coupling of the system to the transfer and break-up channels should produce large effect in the elastic cross sections, leading to very peculiar effects:

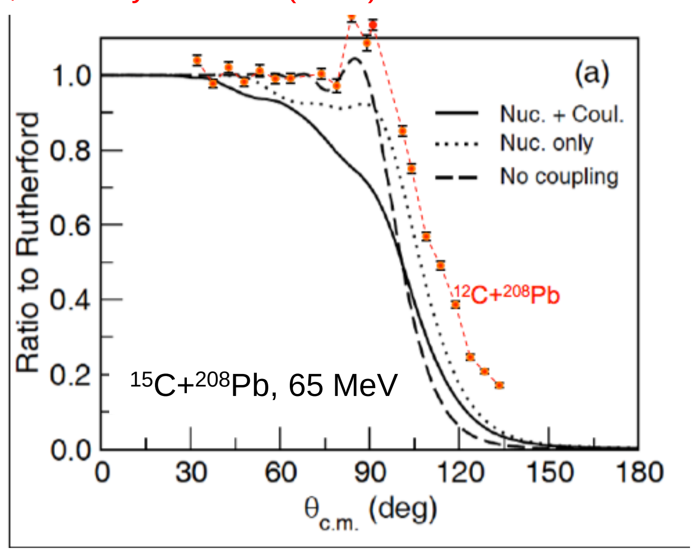
- Strong absorption from the elastic channel → long range reaction channels
- Suppression of the nuclear rainbow
- Strong coupling to transfer to transfer, break-up channels, even well below the Coulomb barrier
- Strong coupling to the continuum
- Systematic effects in angular distributions

To investigate this effects we have performed CRC and CDCC calculations for ^{15}C + ^{208}Pb

N. Keeley, K.W. Kemper and K. Rusek, Eur. Phys. J. A 50 (2014) 145.



CRC calculations. Dashed curve: bare optical model. Solid curve: coupling to the $^{208}Pb(^{15}C, ^{14}C)$209Pb single neutron transfer.



CDCC Calculations. Dashed curve: bare optical model calculation. Solid curve: coupling to the 14C + n continuum. Dotted curve: only nuclear coupling.

A. Shrivastava et al., Physical Review C64 (2001) 024602

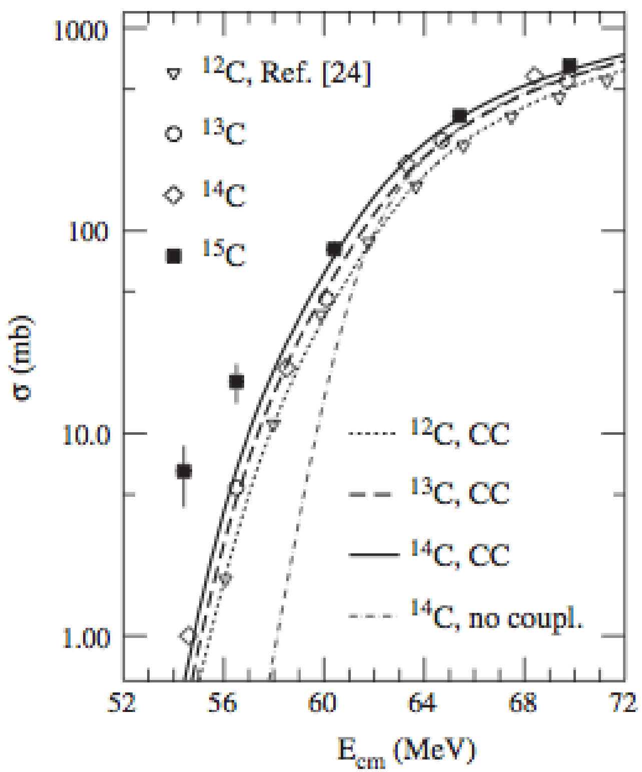
L.R. Gasques et al., Physical Review C65 (2002) 044314

^{15}C is a halo nucleus? ….Need to measure at Coulomb barrier energies!

Fusion Reactions

There is still at present no consensus on the behaviour of the low energy fusion cross sections induced by halo nuclei. The presence of the halo might increase the fusion yield → "Sub-barrier fusion enhancement". However coupling to break and transfer channels might play an important role.

M. Alcorta et al., Phys. Rev. Lett. 106 (2011) 172701



Cross section for fusion-fission reactions $^{13;14;15}$C + ^{232}Th vs c.m. energy. The lines are the result of coupled-channels calculations.

For understanding the role of the halo it is convenient the use of targets with well known nuclear structure.

Fusion measurements of the system ^{15}C+^{232}Th show large enhancement at energies well below the barrier. → Complicated target structure.

^{15}C+^{208}Pb fusion reaction at the Coulomb barrier

-^{208}Pb: doubly closed shell nucleus with simpler target structure.
- Measure at 65 MeV, just at the Coulomb barrier.
-Short lived products, alpha emitters (E~6-7 MeV) with reasonable yields (PACE4)

^{220}Ra (18 ms) - 62% - 157 mb
^{219}Ra (10 ms) - 10% - 26 mb
Fission: 27,5% 70 mb

Simultaneous measurement with elastic channel!!

Purpose of this experiment

Investigate the halo nature of ^{15}C and study the relevant reactions channels dominating the scattering with ^{208}Pb target of at energies around the Coulomb barrier.

Quantities to be measured

1. Angular distribution of 15C (elastic scattering)
2. Angular distribution of 14C fragments (1n transfer/breakup)
3. Alphas (fusion-evaporation)

Two energies: 65 MeV and 45 MeV (around the barrier).

^{208}Pb target, doubly closed-shell nucleus, with large Z=82, well known structure and large separation energy between ground and first excited states

Data analysis: CRC, CDCC and fusion evaporation calculations.

What can we learn from this experiment?

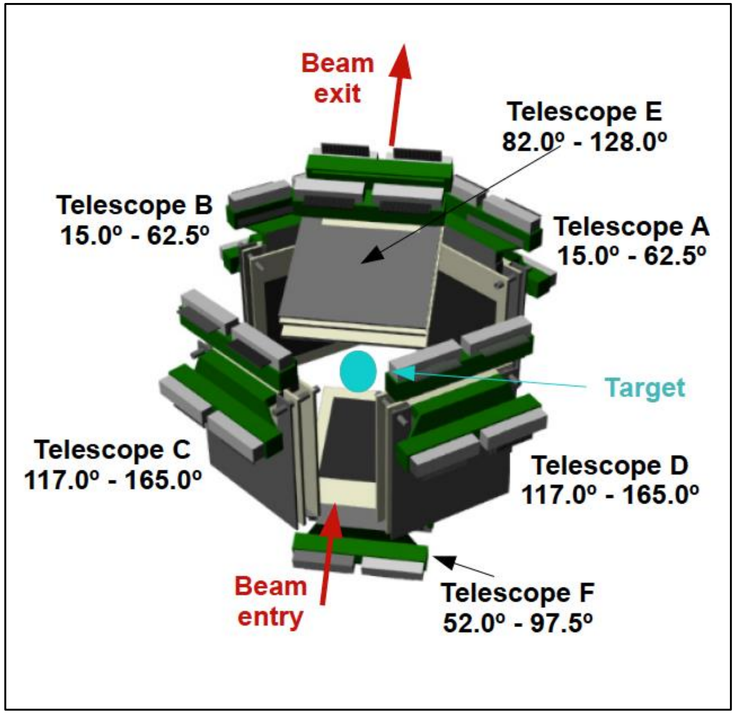
1. Is 15C a halo nucleus?
2. Long range absorption effects in near-barrier scattering
3. OM nuclear potentials and total reaction cross section
4. Coupling effects due to 1n-transfer channels, expected to be large
5. Coupling effects due to coulomb and nuclear potential
6. Mechanism of transfer to continuum vs direct breakup
7. Sistematics in elastic cross sections
8. Fusion cross section at the Coulomb barrier

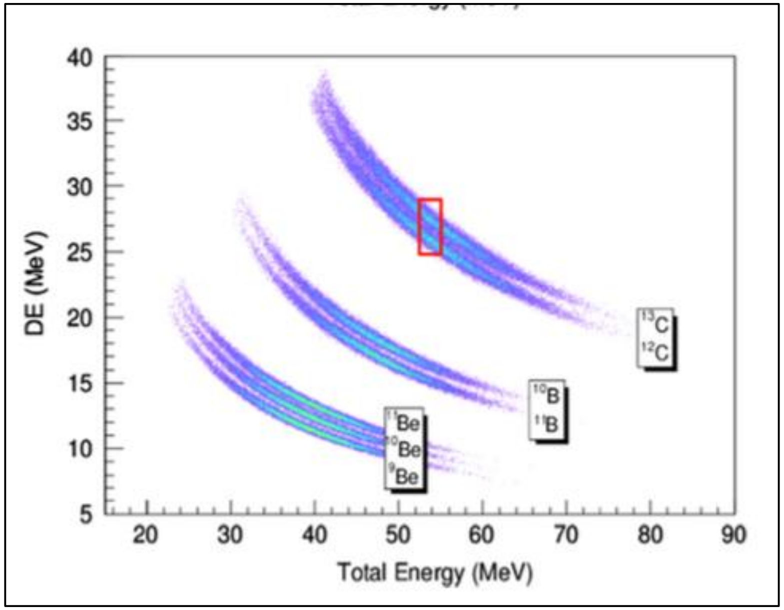
This would be the first dynamical study carried out so far for the halo nucleus ^{15}C at Coulomb barrier energies.

Experimental set-up at XT02

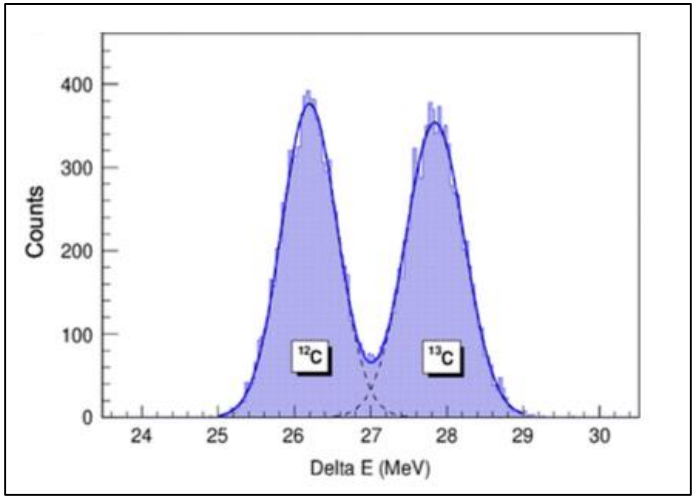
GLObal Reaction Array: GLORIA

G. Marquínez-Durán, Nucl. Inst. Meth. A755 (2014) 69.





- 6 DSSSD particle telescopes (40mm, 1mm).
- Overall solid angle of 26.1% of 4π.
-“Continuum” angular distributions between 15º-165º Lab.
- E_{res} ~30 keV



Montecarlo simulations for light ion detection

Beam-time request

We request 30 shifts on 15C (5+) with A/Q=2,5 at a beam energy of 65 MeV (4,3 MeV/u). If we obtain enough statistics after the first 24 shifts, then we would dedicate 6 shifts at 45 MeV (3 MeV/u) for normalization of the cross-sections, which should be Rutherford.

ISOLDE ^{15}C production (CaO target, 1.4 GeV) ~7.9 x 10^5 pps just after the GPS (Isolde Yields Data Base)

Transport- Charge breeding (REX-EBIS) → 4 x 10^4 pps at reaction target (2% efficiency)

→ Improved by using the new developed ion source (Thierry)

Contaminants:

$^{15}N(6+)$ at 4 x 10^6 → run with 15C(5+) + 2 strippers + 1 stripper (after IH) → 4 x 10^4 pps (aprox.)

In any case, 15N will be separated in silicon telescopes

But: Coulomb Barrier for ^{15}N + ^{208}Pb ~ 76 MeV → at 65 MeV should be Rutherford → data normalization

Also: Trigger with proton-pulse to measure TOF → use release curve to separate most of ^{15}N

Expected yields at 65 MeV:

GLORIA: 25% efficiency   Target: 1 mg/cm2 ^{208}Pb σ_{el} (80º Lab) =450 mb/sr σ_{tran}(80º Lab) = 50 mb/sr

Y_{el} = 12 cph Y_{tran} = 1.5 cph

Expected uncertainty in elastic cross sections ~4%
Expected fusion events ~ 6000 alphas

15C Collaboration:

CERN – Huelva (Spain) – Madrid (Spain) – Warsaw (Poland) – Belfast (UK) – Leuven (Belgium) – Catania (Italy) –Zagreb (Croatia) – Ioannina (Greece) – Mexico (Mexico) – Cracow (Poland) – Aarhus (Denmark)

I. Martel[1,2], X. Aslanoglou[10] , L. A. Acosta[11], L. Barrón-Palos[11], MJG. Borge[1,3], T. Cap[5], E. Chávez-Lomelí[11], A. Di Pietro[8], P. Figuera[8], JP. Fernández[8], H.O.U. Fynbo[13], A. Huerta-Hernandez[11], N. Keeley[5], R. Kotak[6], M. Madurga[1], G. Marquínez-Durán[2], A. Pakou[10], K. Rusek[4], A.K. Orduz[2], R. Raabe[7], K. Riisager[13], N. Soic[9], O. Sgouros[10], A.M. Sánchez-Benítez[2], V. Soukeras[10], O. Tengblad[3], A. Trzcinska[4], M. Wolinska-Cichocka[4], R. Wolski[12]

1 PH Department, CERN, CH-1211 Geneva 23, Switzerland
2 University of Huelva, Avda Fuerzas Armadas sn, 21971 Huelva, Spain
3 Instituto de Estructura de La Materia – CSIC. Serrano 113 bis, ES-28006 Madrid, Spain
4 Srodowiskowe Laboratorium Ciężkich Jonów, Uniwersytet Warszawski, Pasteura 5A, 02-093 Warszawa, Poland
5 National Centre for Nuclear Research, ul. Andrzeja Sołtana 7, 05-400 Otwock, Poland.
6 Astrophysics Research Centre, School of Mathematics and Physics, Queen's University Belfast, Belfast, County Antrim, BT7 1NN, United Kingdom
7 Instituut voor Kern- en Stralingsfysica, Celestijnenlaan 200d - bus 2418, B-3001 Heverlee, Belgium
8 INFN - Laboratori Nazionali del Sud, via S.Sofia 62, 95123 Catania, Italy
9 Rudjer Boskovic Institute, Bijenicka cesta 54, HR-10000 Zagreb, Croatia
10 Department of Physics and HINP, The University of Ioannina, Ioannina, Greece
11 Departamento de Física Experimental del Instituto de Física, Universidad Nacional Autónoma de México. Aptdo 20-364, México D. F. 01000, Mexico
12 Henryk Niewodniczanski Institute of Nuclear Physics PAS, Cracow, Poland
13 Department of Physics and Astronomy, University of Aarhus, DK-8000 Aarhus, Denmark.

THANKS FOR YOUR ATTENTION!

Table 1. The calculated 1n- and 2n-halo characteristics of some observed and theoretically possible light neutron-rich nuclei. The cluster-core configuration resulting from the PES is shown with respect to $\ell = 0$ case for both spherical and deformed choices of nuclei, along with the magic character of the core nucleus.

Structure	Nucleus	S_{1n} (KeV)	S_{2n} (KeV)	Spherical/Deformed Cluster	Core	Z	N	Possible magic number
1n-halo	^{11}Be	556.4	7343.6	1n	^{10}Be	4	6	$N=6$
	^{14}B	1019.7	5789.6	1n	^{13}B	5	8	$N=8$
	^{15}C	668.2	9207.8	1n	^{14}C	6	8	$N=8; Z=6$
	^{17}C	789.8	5623.2	1n	^{16}C	6	10	$Z=6$
	^{19}C	669.8	4526.3	1n	^{18}C	6	12	$Z=6; N=12$
	^{22}N	507.8	4571.3	1n	^{21}N	7	14	$N=14$
	^{22}O	6170	9979.7	1n/2n[b]	^{21}O/^{20}O[b]	8	13/12	$Z=8; N=12$
	^{23}O	4006.6	10176.6	1n	^{22}O	8	14	$Z=8$
	^{24}O	2831.1	6837.7	1n	^{23}O	8	15	$Z=8$
	^{24}F	4460.4	11213.9	1n	^{23}F	9	14	$N=14$
	^{26}F	− 390	4651.2	1n/2n[b]	^{25}F/^{24}F[b]	9	16/15	$N=16$
	^{29}Ne	2983.3	7443.5	1n	^{28}Ne	10	18	$N=18$
	^{31}Ne	− 2350	1149.9	1n	^{30}Ne	10	20	$N=20$
2n-halo	^{6}He	1966.3	1120	2n	^{4}He	2	2	$N=Z=2$
	^{8}He	2957.9	2072.8	2n	^{6}He	2	4	$Z=2$
	^{11}Li	355.5	323.7	2n	^{9}Li	3	6	$N=6$
	^{12}Be	3227.4	3783.8	2n	^{10}Be	4	6	$N=6$
	^{14}Be	1857.7	1351.1	2n	^{12}Be	4	8	$N=8$
	^{17}B	1480.7	1431.6	2n/1n[a]	^{15}B/^{16}B[a]	5	10/11	Neighboring $Z=6$ and $N=12$
	^{19}B	955	438.6	2n	^{17}B	5	12	Neighboring $Z=6; N=12$
	^{22}C	2471	1925.3	2n/4n[a]	^{20}C/^{18}C[a]	6	14/12	$N=14$ or $12; Z=6$
	^{23}N	3100.9	3608.7	2n	^{21}N	7	14	$N=14$
	^{27}F	2015.4	1625.4	2n/1n[b]	^{25}F/^{26}F[b]	9	16/17	$N=16$
	^{29}F	1978.2	875.7	2n	^{27}F	9	18	$N=18$

[a] β_2 deformed case.
[b] β_2-β_4 deformed case.

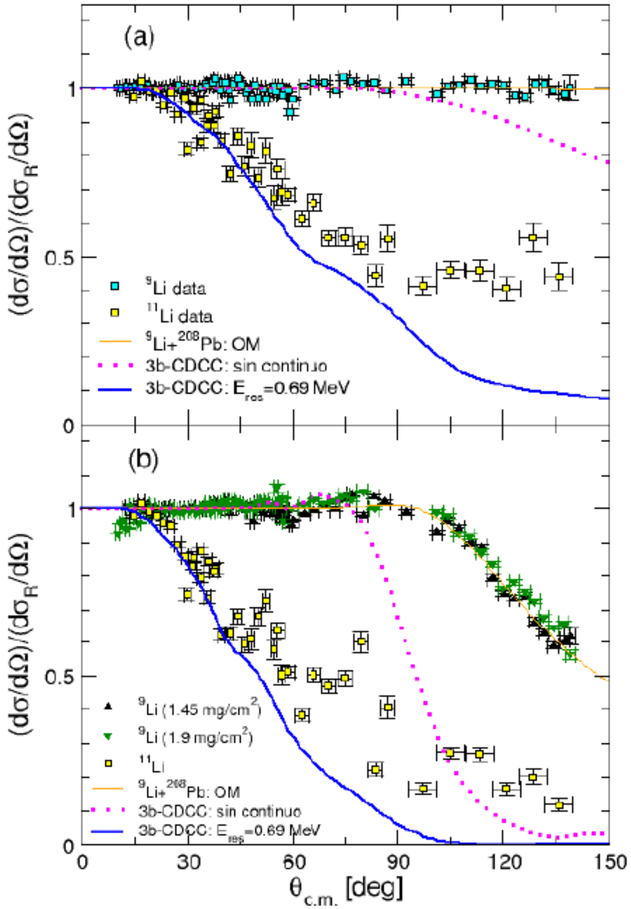
Study of ^{11}Li + ^{208}Pb scattering at energies around the Coulomb barrier.

M. Cubero, et al. PRL 109, 262701 (2012)

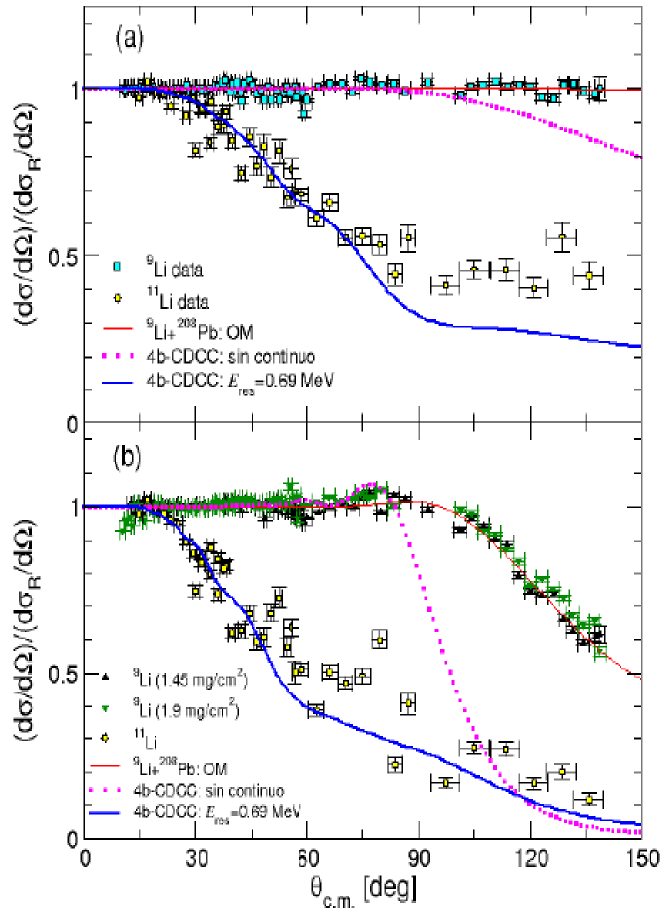
TRIUMF- E1104

E=24 MeV

E=29 MeV



3 Body CDCC (9Li+dineutron)

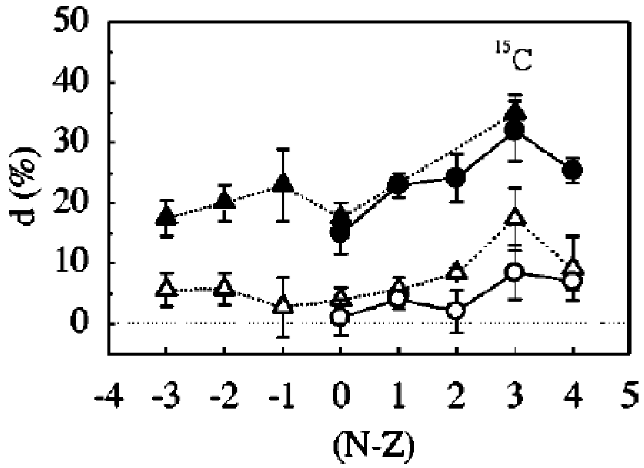


4 Body CDCC (9Li+n+n)

ε_b fit to elastic (11Li) and 9Li yield data → 0.69 MeV (and consistent with Nakamura B(E1))

- Elastic 11Li data and 9Li yields can be described above and below the barrier using 4 –body CDCC
- Major contribution to the absorption of elastic channel comes from dipole coulomb coupling.

D.Q. Fang et al., Phys. Rev. C 61 (2000) 064311



Isospin dependences of the “difference factor” *d* for C isotopes at intermediate energy (~25 A MeV). The curves are to guide the eye.

▲ ● Glauber calculations

△ ○ BUU models

$$d = \frac{\sigma_R(\exp) - \sigma_R(G)}{\sigma_R(G)},$$

σ_R(exp): exp. cross sect. at int. energies

σ_R(G): extrapolated cross sect. from a fit of high-energy data using Glauber model.

Boltzmann-Uehling-Uhlenbeck

“d” ~ 10 – 20 % for stable nuclei & around stability// ~ 30 – 40 % for exotic structures

“For 15 C, the abnormal increase of the difference factor ***d*** as compared to its neighbours and the narrow width of momentum distribution support the assumption of its possible anomalous nuclear structure. Further experiments are needed to confirm above conclusions.”

→ Is 15C a Halo nucleus?

CDCC calculations (simplified)

1. Inert 14C core → probably reasonable, given that the first excited state of 14C is high-lying
2. Included couplings:
   - Bound first excited state of 15C
   - L=0,1,2,3 and 4 n+14C continuum

3. Ground state is assumed to be a pure 14C(0+) plus a neutron in the 2s_1/2 level.
4. No resonances included → important for BU but not for Elastic
5. The n+14C binding potential → standard Woods-Saxon with r0=1.25xA^1/3 and a0=0.65 fm.
6. The 14C + 208Pb potential is a 12C + 208Pb one (no suitable 14C OM potentials being available) and the neutron + 208Pb OM potential is an empirical one. For the actual analysis 7. No tuning of binding potential to reproduce known electromagnetic properties like B(E2) for excitation of the bound 1st excited state.

CRC calculations

The 1n-stripping can be quite accurately calculated with CRC:

→ Dominant 1n-stripping will be to bound states in 208Pb (the Q value is around +2.7 MeV).
→ Deal with the breakup and transfer contributions separately