Multi-nucleon transfer reactions in Coulomb barrier reactions of the halo nuclei ^{6,8}He

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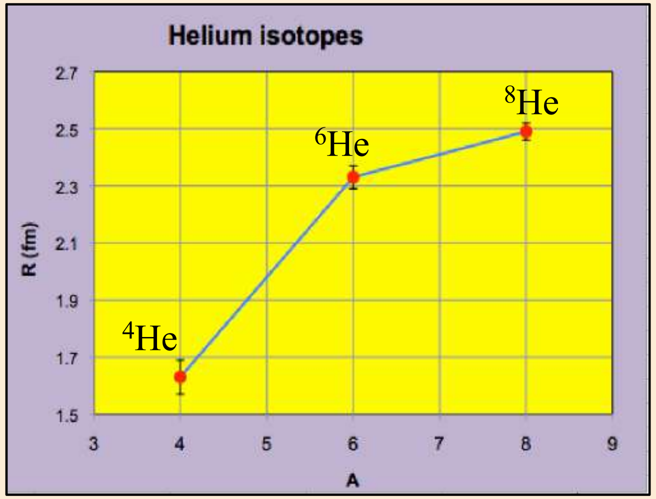
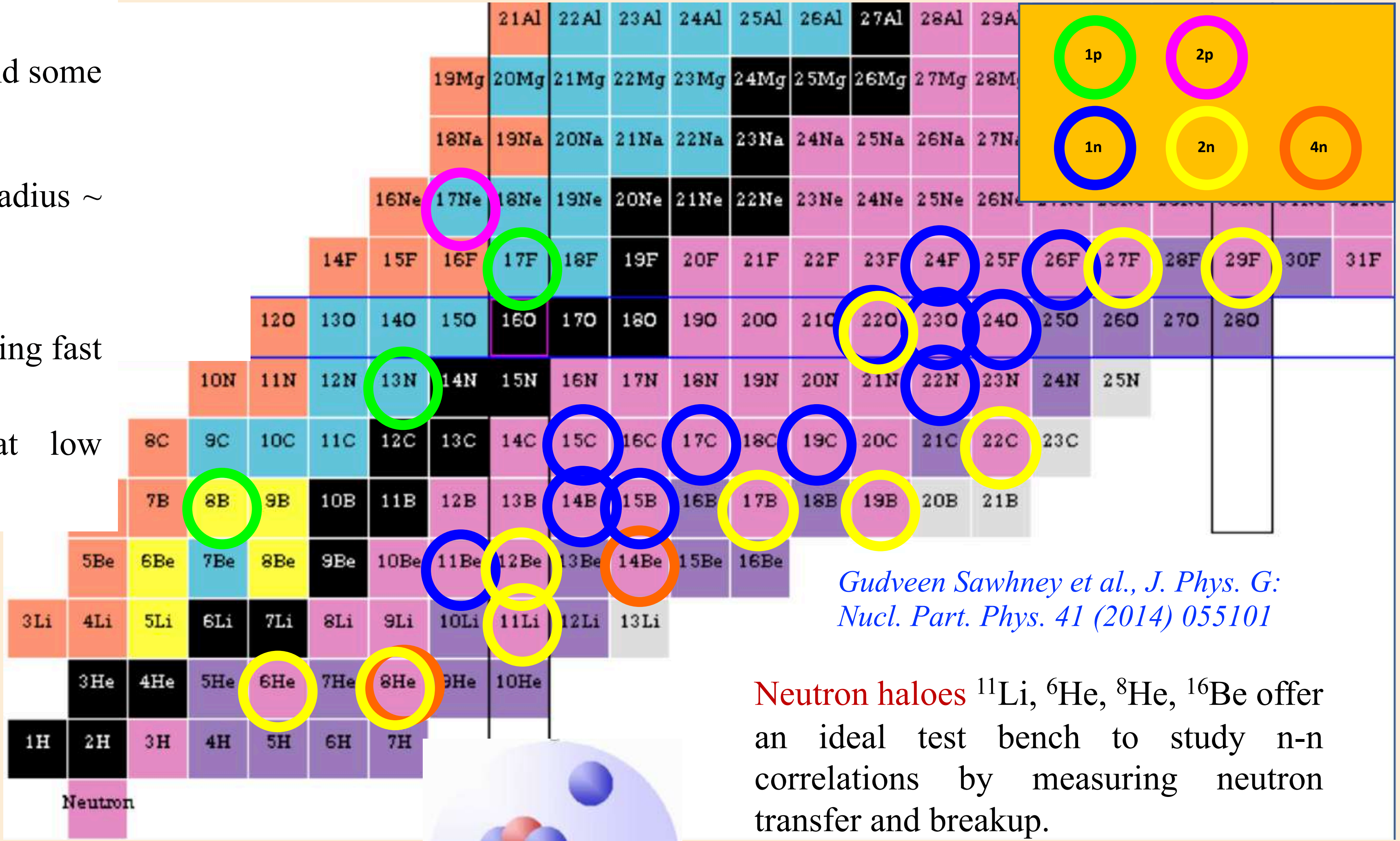
Halo nuclei

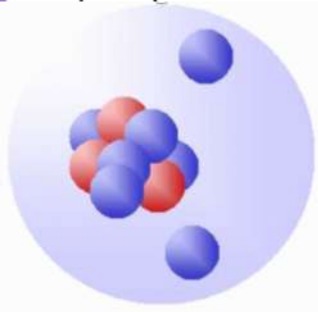
Exotic nuclear systems formed by a core and some weakly bound valence nucleons:

- Extended mass distribution and large radius ~ "halo"
- Large reaction cross sections
- Narrow momentum distributions following fast fragmentation reactions
- Concentration of dipole strength at low energies close to BU threshold



I. Tanihata, et al. Phys. Lett., B289:261, 1992.





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

Neutron haloes ^{11}Li, ^{6}He, ^{8}He, ^{16}Be offer an ideal test bench to study n-n correlations by measuring neutron transfer and breakup.

Searching for di-neutrons and tetra-neutrons

Scattering of ^{8}He +^{208}Pb at Coulomb barrier energies

- ^{8}He is the most neutron-rich bound nucleus, with a ratio of N/Z = 3 → excellent test bench for multi-neutron transfer.
- Spherical, well known double-magic target nucleus ^{208}Pb
- Coulomb barrier → large probability of neutron transfer
- Existing ^{6}He + ^{208}Pb elastic scattering data at similar incident energies ~ 22 MeV (Coulomb barrier).
- Comparing ^{6}He and ^{8}He scattering is interesting:

  → Rms. matter radii of ^{6}He and ^{8}He are very similar (2.33 fm, 2.49 fm), but they are halo and skin nuclei, respectively

  → Remove "geometrical" effects due to differences in size → better understanding of structure/dynamics of the reaction process

	S1n (MeV)	S2n (MeV)	Q1n (MeV)	Q2n (MeV)	SF(1n)	SF(2n)
^{6}He	1.771	0.973	+2.07	+8.15	1.6	1.0
^{8}He	2.140	2.574	+1.35	+6.98	2.9	1.0

N. Keeley et al., PLB 646, 222 (2007).
F. Skaza et al., PRC 73, 044301 (2006).
L.V. Chulkov et al., NPA 759, 43 (2005).

- S_{1n} and S_{2n}: higher in ^{8}He → smaller coupling to the continuum in ^{8}He ~ smaller breakup yield.
- S_{2n}: smaller in ^{6}He → larger 2n transfer and 2n-breakup
- Q_{1n} and Q_{2n}: 1n and 2n better Q-matched in ^{8}He ~ larger 1n and 2n transfer yield.
- SF(1n): higher in ^{8}He ~ larger 1n-transfer yield.
- SF(2n): Similar values ~ similar yields for 2n transfer.
- 4-neutron transfer. Unique mechanism for ^{8}He.

❖ Relative strength of the neutron transfer modes?
❖ Sequential or direct?
❖ Di-neutrons and tetra-neutrons?

Scattering of ^{8}He +^{208}Pb at 16 and 22 MeV

laboratoire commun CEA/DRF CNRS/IN2P3

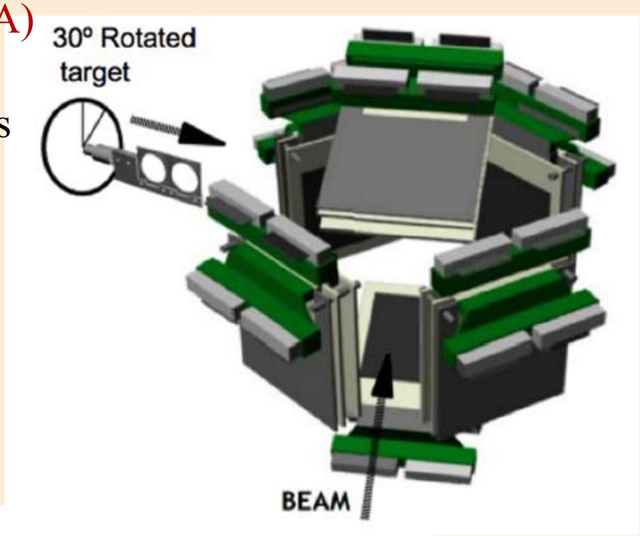
Caen, France

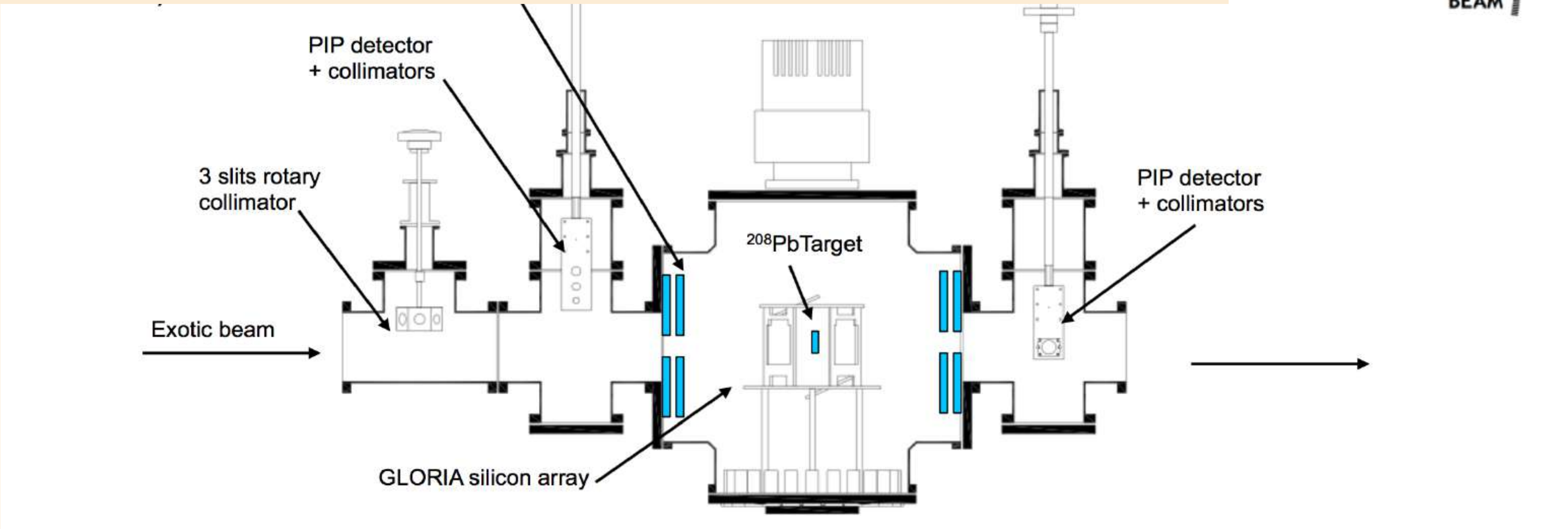
- Proposal E587S (2010)
- Measure the angular distribution of the elastic channel and the yields of ^{6}He and ^{4}He from 15° to 165° Lab.

GLObal ReactIon Array (GLORIA)

6 x DSSSD Si particle telescopes

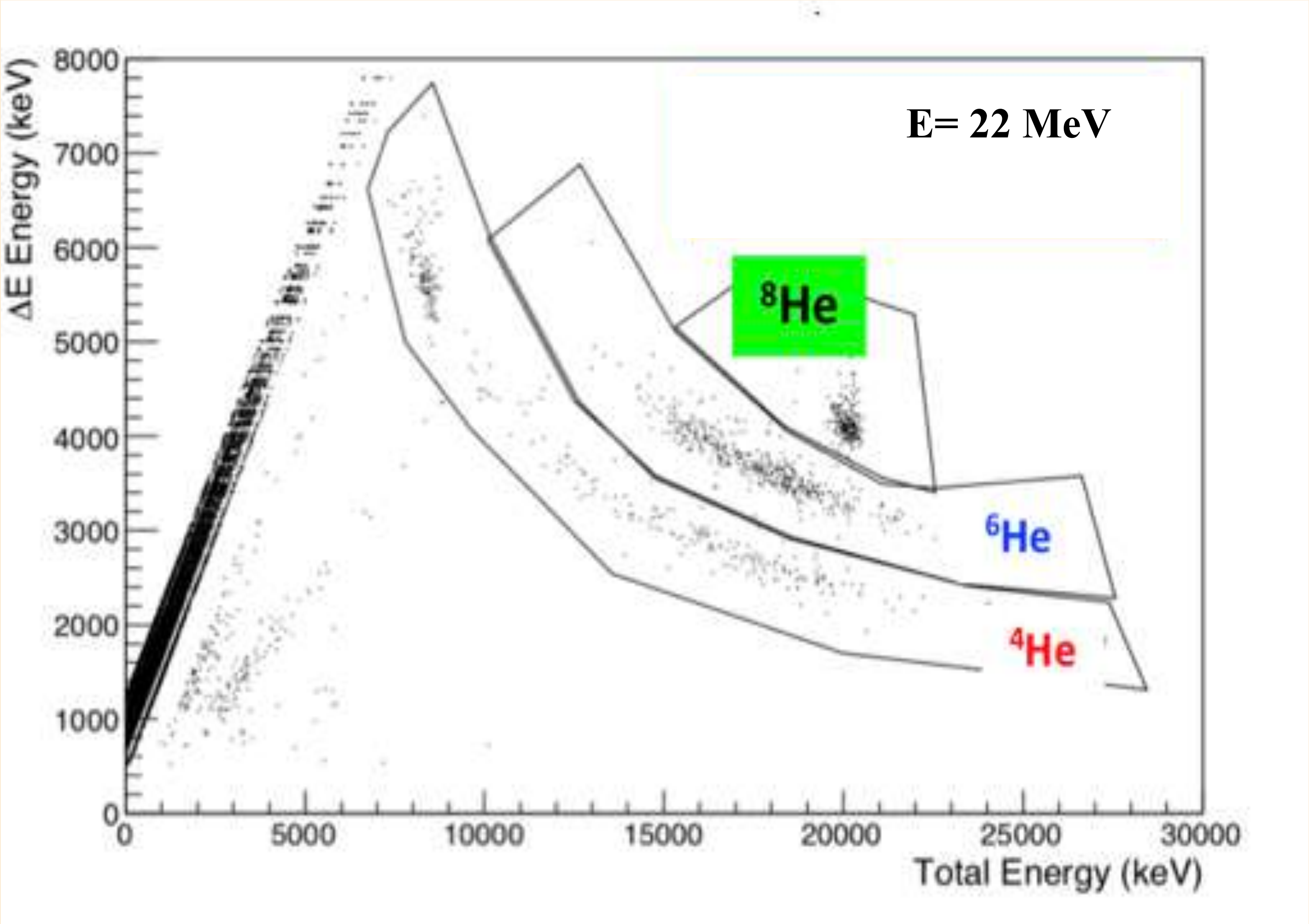
- 40 um DE & E, 1 mm
- Total solid angle: 26 %
- Angular range: 15 -165 deg.
- Angular res. ~ 3 deg.



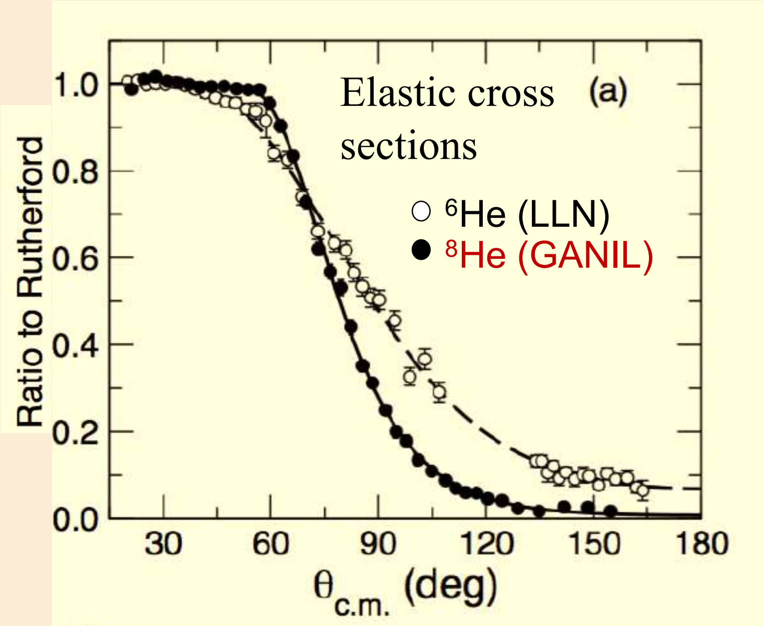


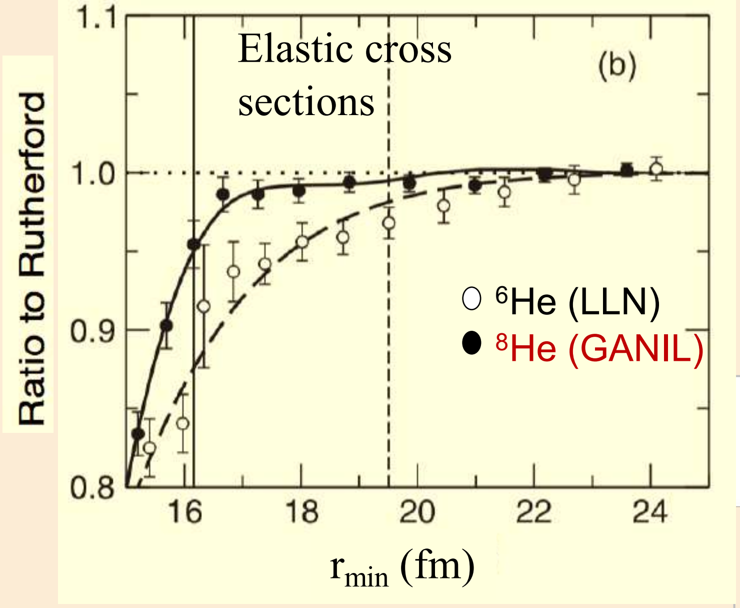
G. Marquínez-Durán et al. Nucl. Inst. Meth. A 755, 69 (2014).

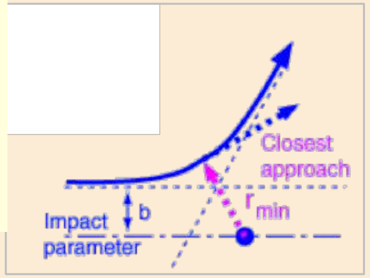
Particle identification



Elastic cross sections







OM calculations: Vr, Wi Woods-Saxon

Projectile	V	r_V	a_V	W	r_W	a_W	σ_R (mb)
^{8}He	143.7	1.631	0.587	37.1	1.481	1.148	1529
^{6}He	147.4	1.237	0.618	19.8	1.090	1.766	1425

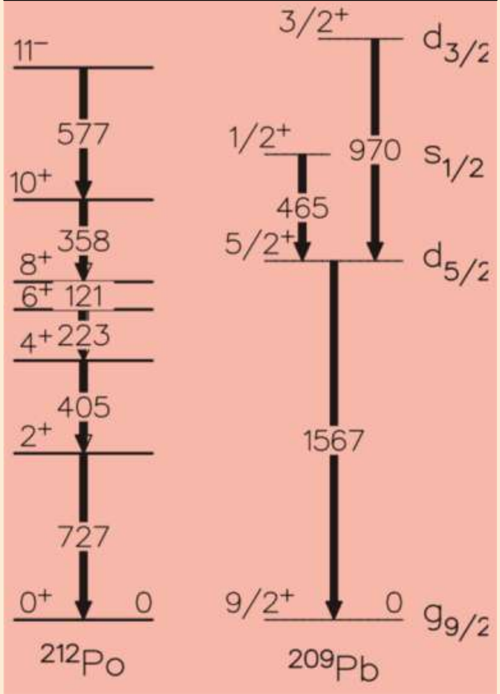
- Larger total reaction cross section for ^{8}He than for ^{6}He → **larger neutron transfer** as compared to ^{6}He.
- Consistent results of Z. Podolyák, et al., in ^{8}He + ^{208}Pb @ 26 MeV

  → γ decay of low-spin states in ^{209}Pb → suggests strong one-neutron stripping process,

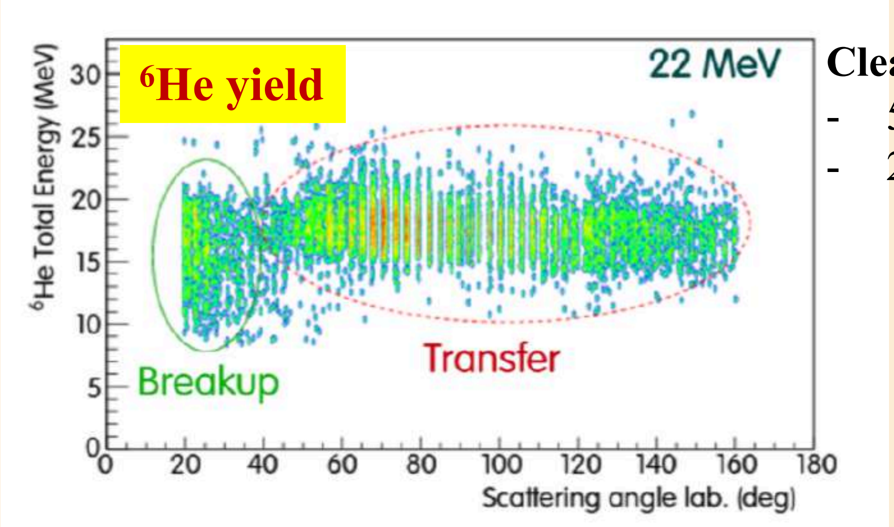
  → Strength comparable to fusion-evaporation channel ^{208}Pb(^{8}He,4n)^{212}Po

Z. Podolyák, et al., Nucl. Instr. Meth. A 511, 354 (2003).

EXOGAM Ge-array



^{4}He and ^{6}He yields



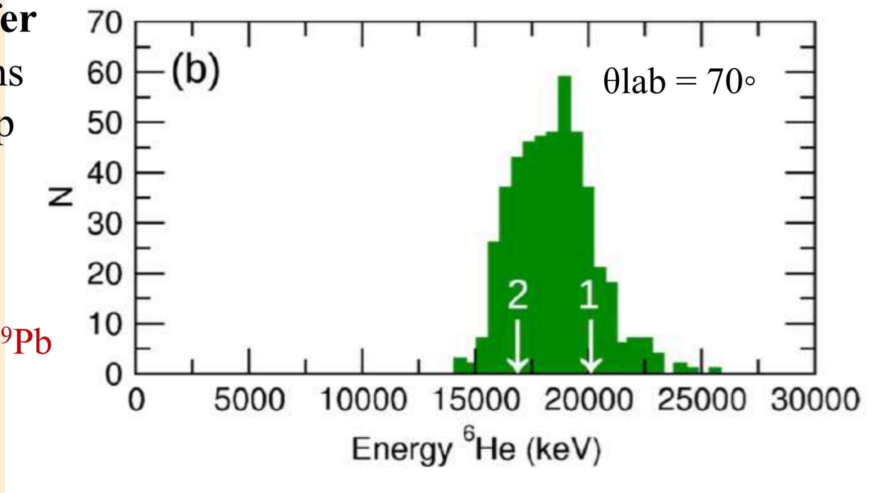
Clear separation between breakup/transfer

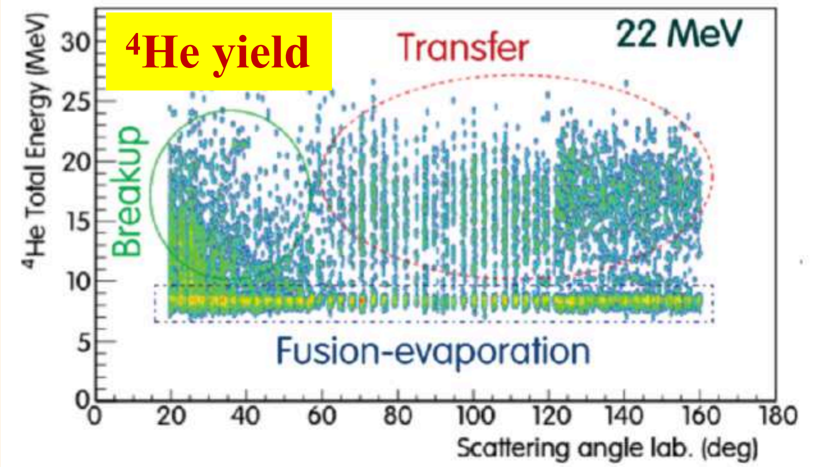
- 50◦ - 160◦ from neutron transfer reactions
- 20◦ - 40◦ , from ^{6}He → ^{4}He + 2n breakup

(1) 2n transfer: ^{208}Pb(^{8}He, ^{6}He)^{210}Pb

(2) 1n transfer: ^{208}Pb(^{8}He, ^{7}He → ^{6}He + n)^{209}Pb

"TRANSFER"





Moderate separation between breakup/transfer and fusion-evaporation

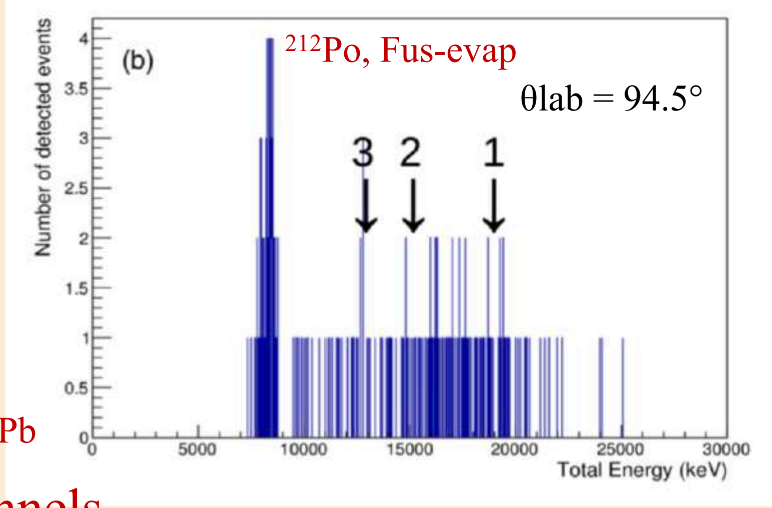
- α from fusion-evaporation events ^{212}Po
- 60◦ - 160◦ from neutron transfer reactions
- 20◦ - 40◦ , from ^{8}He → ^{4}He + 4n breakup

(1) 4n transfer: ^{208}Pb(^{8}He, ^{4}He)^{212}Pb

(2) 3n transfer: ^{208}Pb(^{8}He, ^{5}He → ^{4}He + n)^{211}Pb

(3) 2n transfer: ^{208}Pb(^{8}He, ^{6}He*1.8 → ^{4}He + 2n)^{210}Pb

"TRANSFER"

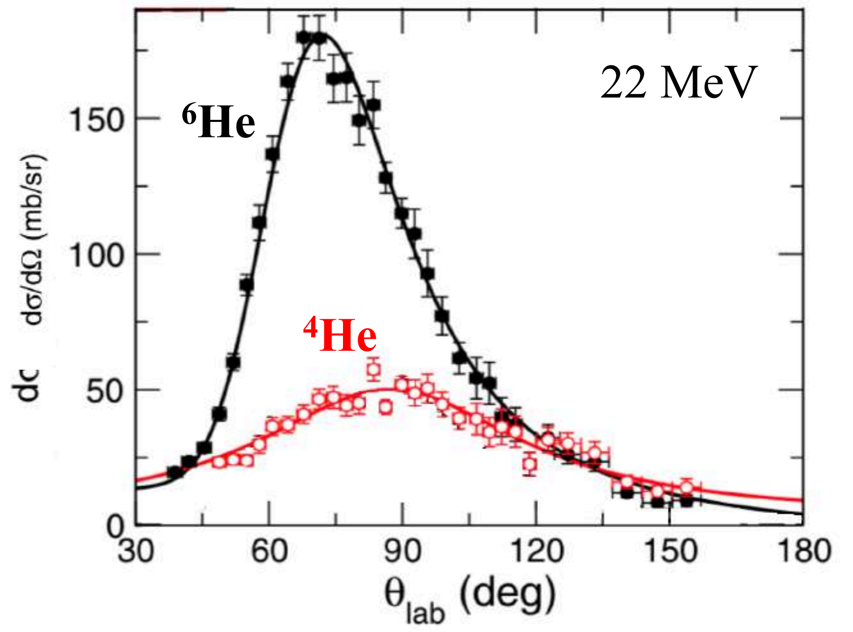


Kinematics consistent with neutron transfer channels

G. Marquínez-Durán et al., Phys. Rev. C ***98, 034615 (2018).***

Cross sections

^{6,4}He cross sections



^{6,4}He: The shape of the angular distributions consistent with a transfer reaction mechanism.

^{6}He:

- Competition of 1n and 2n transfer

^{4}He:

- Small spectroscopic factor for the ⟨^{8}He| ^{6}He$^{*}_{1.8}$ + 2n⟩ overlap → expected 3n or 4n transfer to ^{211}Pb and ^{212}Pb, respectively.

Reaction mechanisms

^{6}He

	Reaction	Q (MeV)	Q_{opt} (MeV)
2n transfer →	^{208}Pb(^{8}He, ^{6}He)^{210}Pb	+7.00	−0.8
1n transfer →	^{208}Pb(^{8}He, ^{7}He → ^{6}He + n)^{209}Pb	+1.40	−0.4
2n breakup →	^{208}Pb(^{8}He, ^{8}He* → ^{6}He + 2n)^{208}Pb	−2.14	

^{4}He

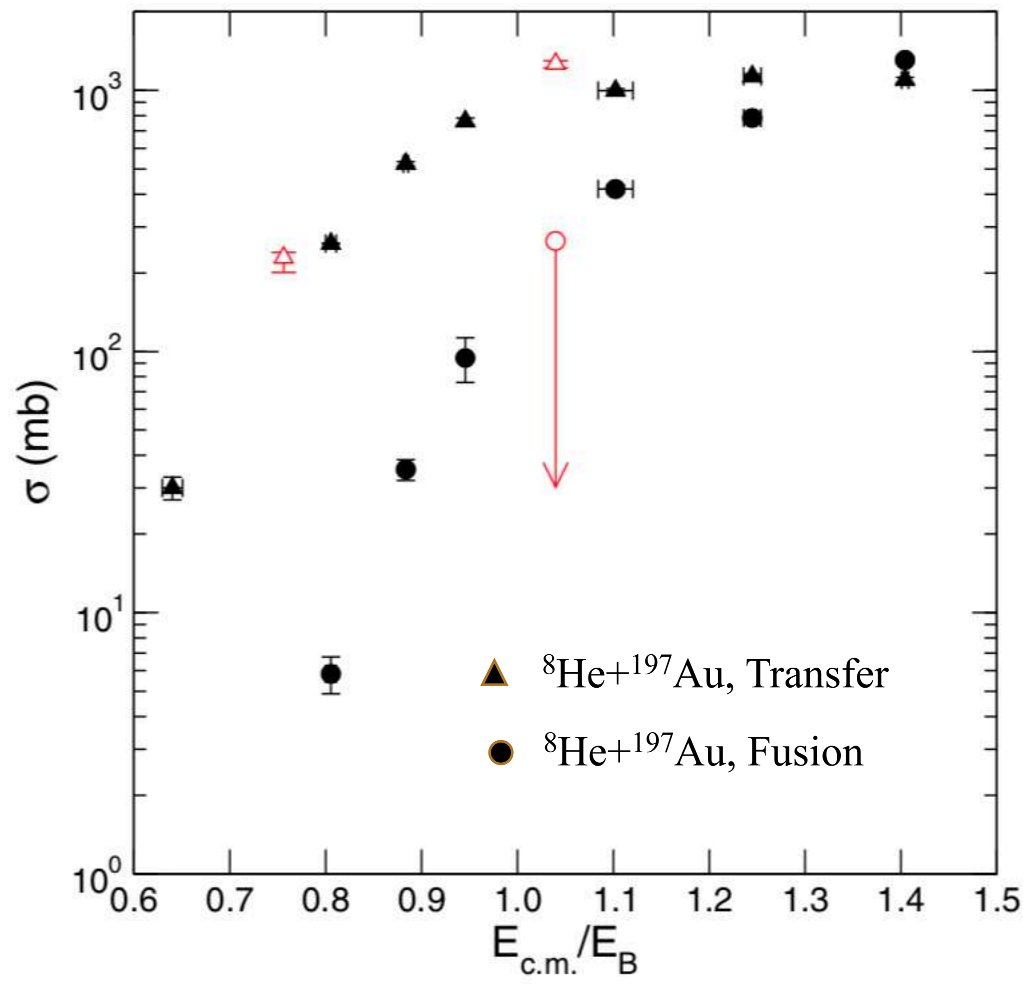
	Reaction	Q (MeV)	Q_{opt} (MeV)
4n transfer →	^{208}Pb(^{8}He, ^{4}He)^{212}Pb	+14.99	−1.7
3n transfer →	^{208}Pb(^{8}He, ^{5}He → ^{4}He + n)^{211}Pb	+9.12	−1.2
2n transfer →	^{208}Pb(^{8}He, ^{6}He$^{*}_{1.8}$ → ^{4}He + 2n)^{210}Pb	+5.20	−0.8
4n breakup →	^{208}Pb(^{8}He, ^{8}He* → ^{4}He + 4n)^{208}Pb	−3.11	
4n breakup →	^{208}Pb(^{8}He, ^{8}He* → (^{6}He$^{*}_{1.8}$ → ^{4}He + 2n) + 2n)^{208}Pb	−3.94	

Total cross sections

E_{lab} (MeV)	$\sigma_{^6He}$ (mb)	$\sigma_{^4He}$ (mb)	σ_R (mb)
16	203^{+10}_{-28}	26 ± 5	254 ± 60
22	871 ± 31	393^{+10}_{-33}	1529 ± 40

Assume:

$\sigma_{Trans} = \sigma_{6He} + \sigma_{4He}$ $\sigma_{Fus} = \sigma_R - \sigma_{Trans}$



Good overall agreement between ^{8}He + ^{208}Pb and ^{8}He + ^{197}Au.

A. Lemasson, *et al.*, Phys. Lett. B **697**, 454 (2011).

A. Lemasson, *et al.*, Phys. Rev. Lett. **103**, 232701 (2009)

G. Marquínez-Durán *et al., Phys. Rev. C* ***98*, *034615 (2018).***

→ Scattering of ^{8}He + ^{208}Pb dominated by transfer channels

Probing transfer of neutron clusters with Coulomb barrier reactions induced by ^{8}He

Objective. Measurement of the angular distributions of transfer cross sections for ^{6}He and ^{4}He yields in coincidence with neutrons and gammas, in the scattering of ^{8}He+^{208}Pb at the energy of 22 MeV.

I. Martel[1,2], N. Keeley[3], K. Kemper[4], K. Rusek[5], L. Acosta[6], L. Aguado[2], L. Barrón[6], J. Carpio[2], E. Chávez[6], A. Chbihi[7], C. García-Ramos[2], G. de Angelis[8], G. de France[7], N. Erduran[9], A. Gadea[10], A. Goasduff[8], J.A. Gómez-Galán[2], A. Gottardo[8], A. Illana[8], G. Jaworski[4], T. Kurtukian-Nieto[11], K. Mahata[12], F. Manchado de Sola[2], D. Marín-Lambarri[6], F.M. Marqués[13], M. Mazzocco[14], D. Mengoni[8], J. Nyberg[15], A.K. Orduz[7], M. Palacz[4], S. Pandit[12], V. Parkar[12], M. Pedro-Carrasco[2], Z. Poldoyak[16], R. Raabe[17], M. Renaud[17], A.M. Rodríguez-Pérez[2], F. Salguero[2], A.M. Sánchez-Benítez[19], M. Sánchez-Raya[2], J. Sánchez-Segovia[2], A. Shrivastava[12], N. Soic[20], D. Testov[8], J. Smallcombe[1], J.J. Valiente-Dobón[8], R. Wolski[18].

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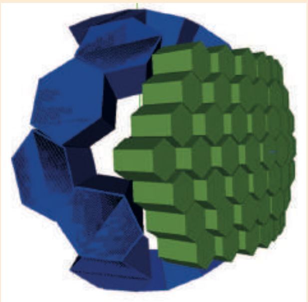
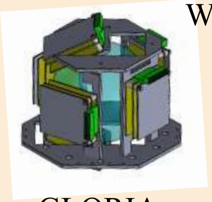
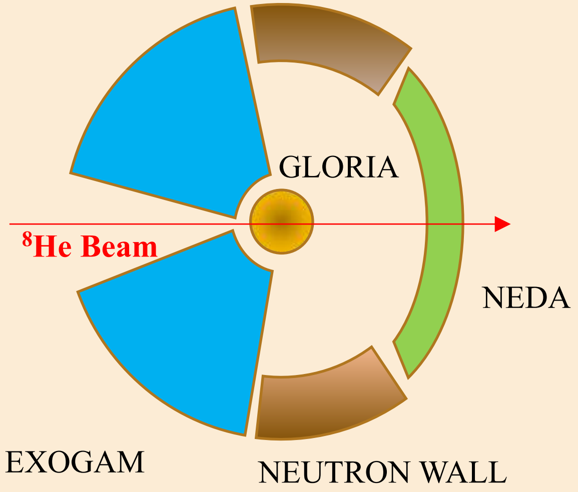
EXOGAM



NEDA +NEUTRON WALL



GLORIA



Summary and conclusions

- Sequential 1n-transfer to low-energy levels in ^{209}Pb seems to dominate the ^{6}He angular dsitribution.
- The data on ^{4}He is well reproduced by including a direct tetraneutron transfer component to highly excited states in ^{212}Pb.
- However, model uncertainties are too large to withdraw conclusive results.
- New proposal at SPIRAL1/GANIL to measure $^{6,4}He$ exclusive data in coincidence with gammas an neutrons.
- Everybody welcome to join the new proposal, just send me an email to imartel@uhu.es

Thanks!!

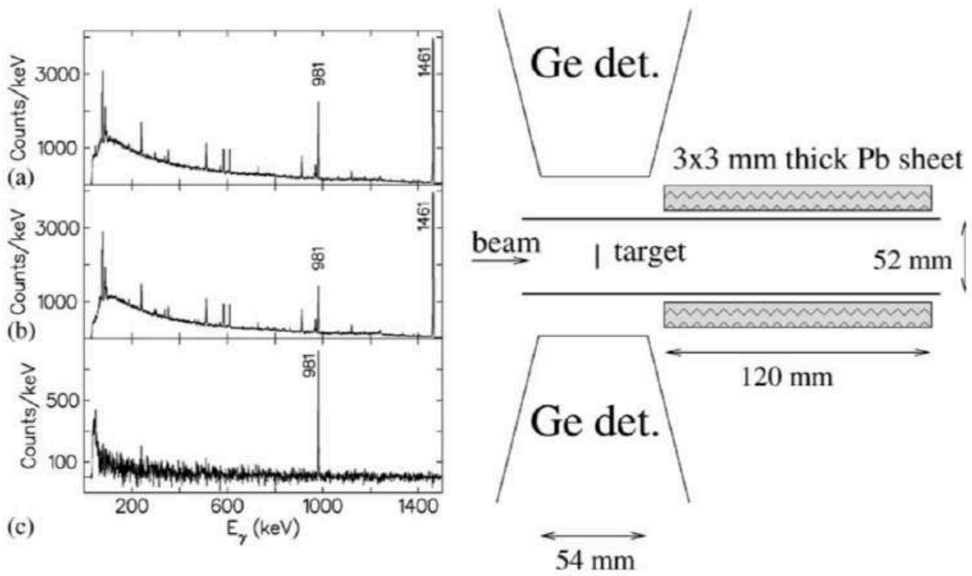


Fig. 2. The effect of using lead shielding on the beam tube. (a) γ-ray spectrum without Pb shielding, (b) with Pb shielding, (c) the difference spectrum of spectra (a) and (b). The (a) and (b) spectra are normalised to the 1461 keV intensity. The beam intensity was $\approx 4 \times 10^4$ ions/s. The setup with the position and thickness of the Pb shielding is also shown.

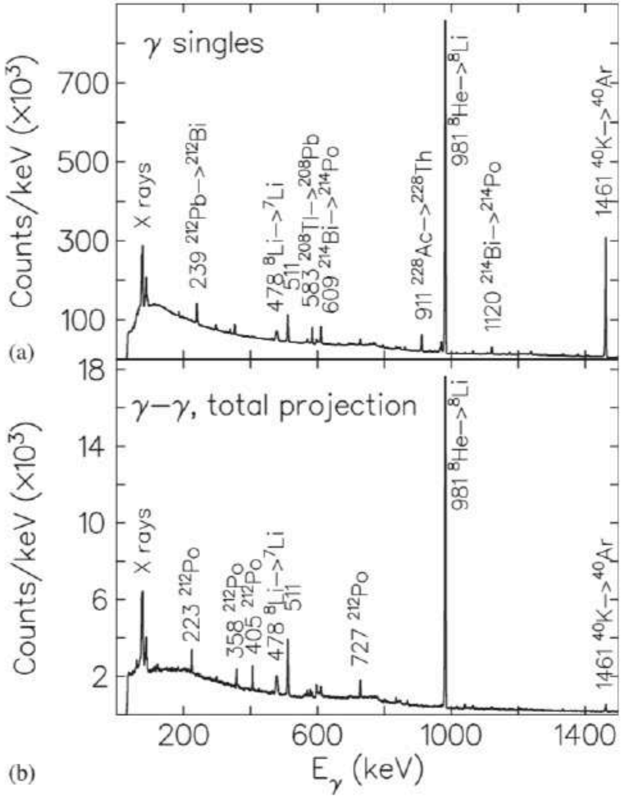


Fig. 1. Singles γ-ray (a) and γ–γ coincidence matrix projection, (b) spectra from the $^{8}He + ^{208}Pb$ reaction (see text for details).