Clustering in ^{10,12}Be and ^{13}B examined by reactions of ^{9}Li beam on LiF target

Neven Soić, Ruđer Bošković Institute Zagreb, Croatia

ISAC-II experiment S1620 TRIUMF Vancouver

"Examining the helium cluster decays of the ^{12}Be excited states by triton transfer to the ^{9}Li beam", spokespersons: N. Soić, M. Freer

Neven Soić, *Nikola Vukman*, Petra Čolović, Milivoj Uroić

Ruđer Bošković Institute, Zagreb, Croatia

Martin Freer

School of Physics and Astronomy, University of Birmingham, United Kingdom

Martin Alcorta, Devin Connolly, Annika Lennarz, Chris Ruiz, Matthew Williams

TRIUMF, Vancouver, Canada

Alessia Di Pietro

INFN – Laboratori Nazionali del Sud, Catania, Italy

Thomas Davinson, Alan Shotter

School of Physics and Astronomy, University of Edinburgh, United Kingdom

Athanasios Psaltis

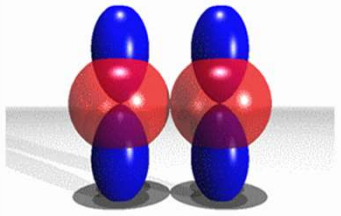
McMaster University, Hamilton, Canada

Structure of neutron-rich light nuclei

- **nuclear molecules:**

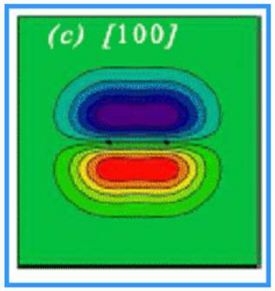
covalent exchange of neutrons between α's → increased stability of the system

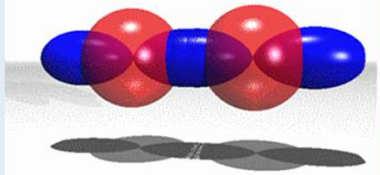
^{10}Be



^{4}He+n:^{4}He+n

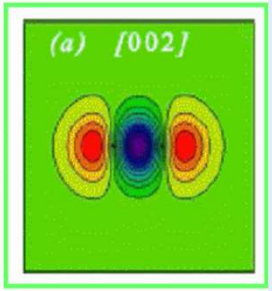
Bonding π





^{4}He+n:^{4}He+n

Bonding σ

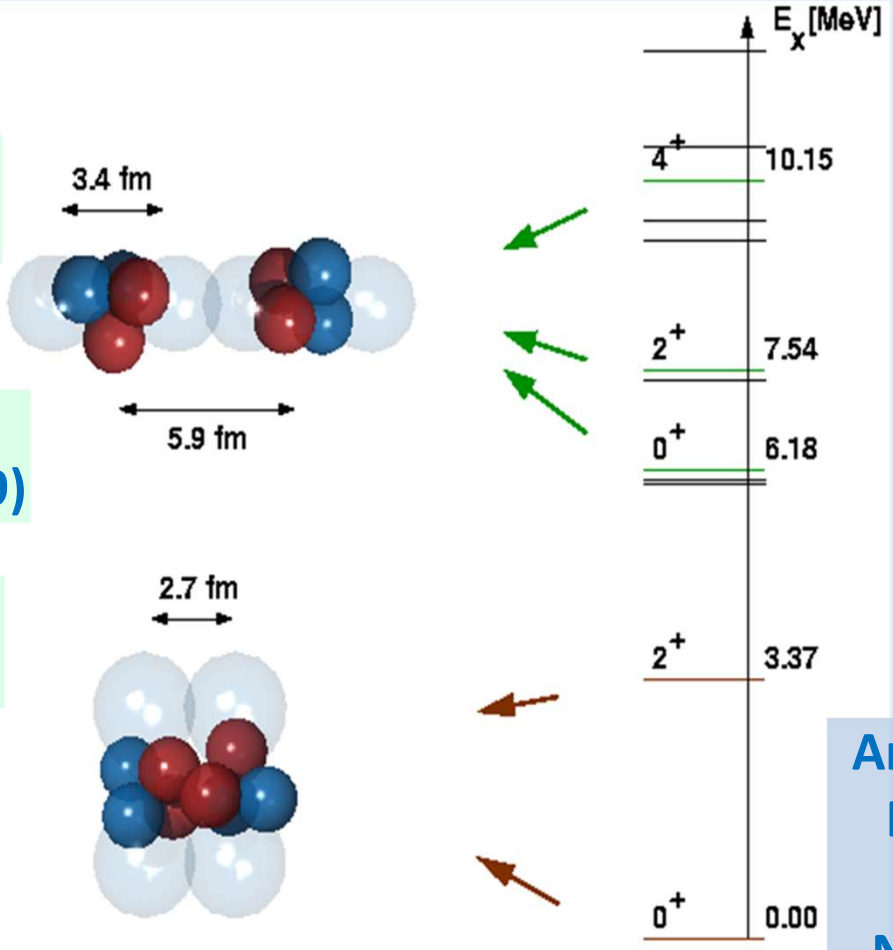


N.Soić *et al*, Europhys.Lett. (1995)

M.Milin *et al*, Europhys.Lett. (1999)

Đ.Miljanić *et al*, Fizika (2001)

M.Milin *et al*, Nucl.Phys. (2005)

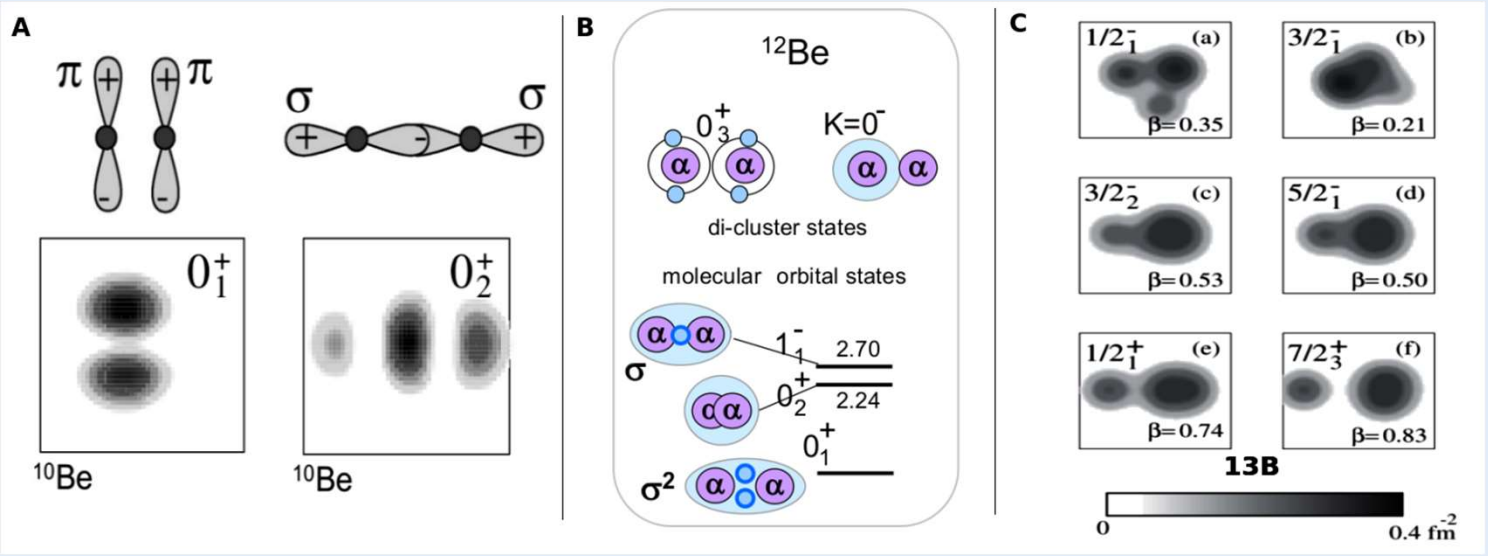


M.Freer *et al*, Phys.Rev.Lett. (2006)

American Institute of Physics Physics News Update 762, "Nuclear Molecule: Nature's smallest dumbbell"

Neutron-rich isotopes of Be & B

- evolution of clustering with addition of neutrons & proton on the α-α cluster structure
- unbound ^{8}Be → α-Xn-α molecular structures in ^{10,12}Be
  → α-Xn-p-α molecular structures in boron isotopes
- various theoretical aproaches with common results of well developed clustering



Molecular orbitals & 2/3-center clustering in **AMD** formalism: density distributions of the states in: A) ^{10}Be, B) ^{12}Be, C) ^{13}B.

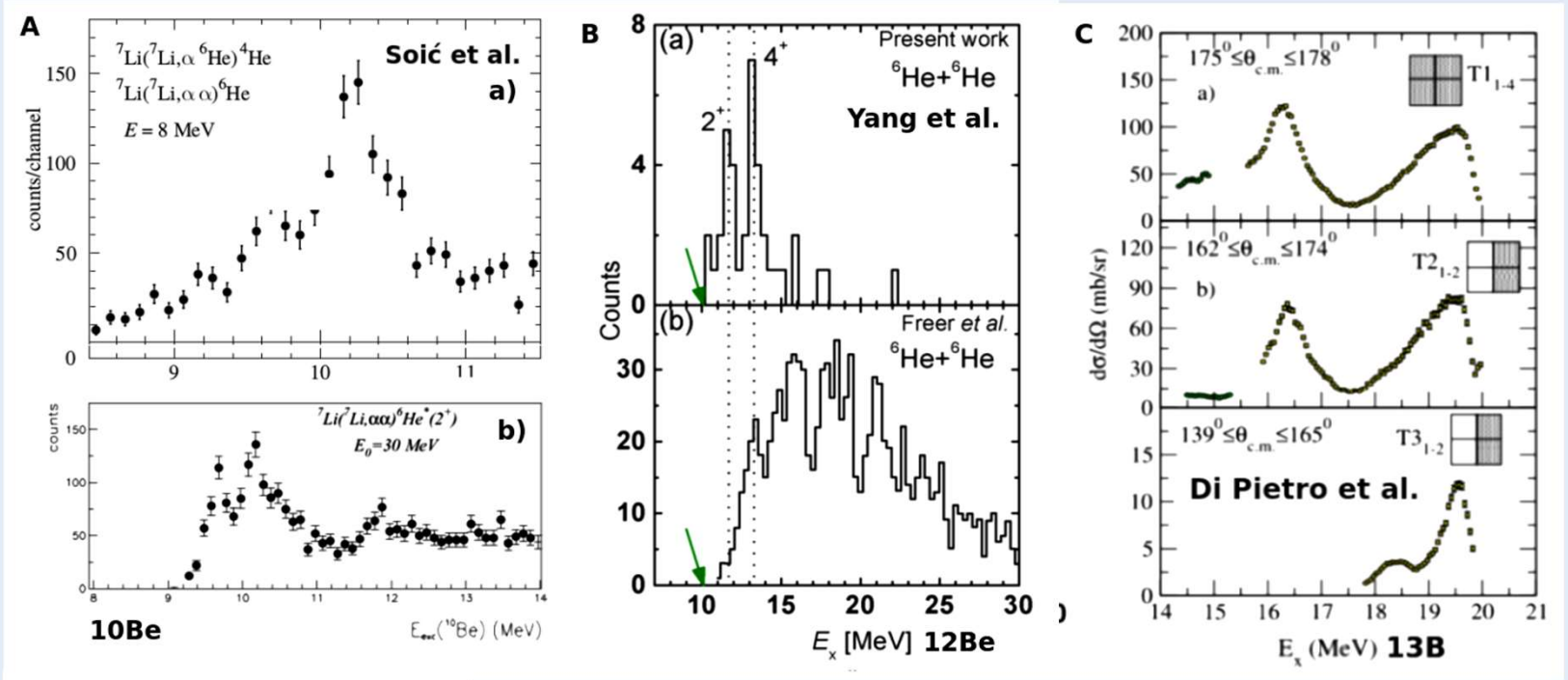
Y. Kanada-En'yo et al. PRC 60 (1999) 064304

Y. Kanada-En'yo et al, PTEP 1 (2012) 01A202

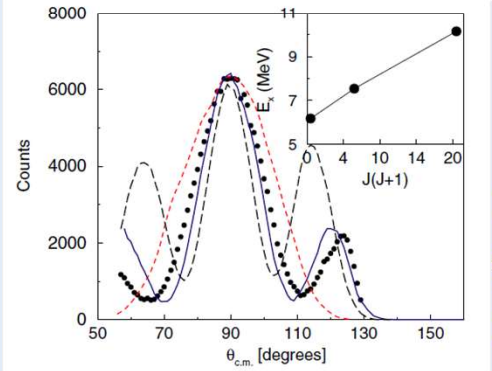
Y. Kanada-En'yo et al. PTEP 120 (5) (2008) 917

^{10,12}Be & ^{13}B experimental studies

- ^{10}Be: transfer reactions, inelastic breakup, resonant elastic scattering
- ^{12}Be: inelastic breakup
- ^{13}B: inelastic breakup, resonant elastic scattering



Experimental results on helium cluster decays of: A) ^{10}Be: ^{4}He+^{6}He, ^{4}He+^{6}He* B) ^{12}Be: ^{6}He+^{6}He, C) ^{13}B: ^{4}He+^{9}Li



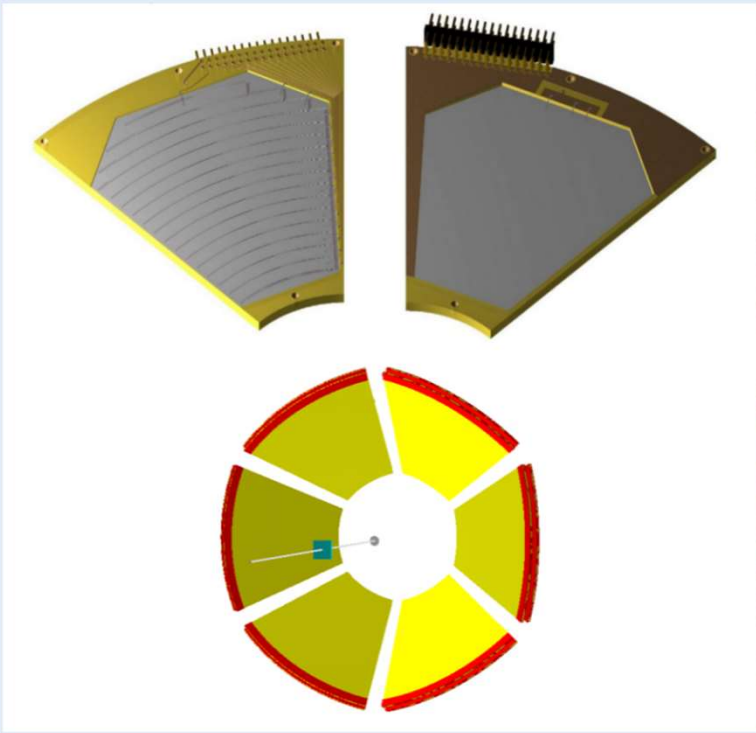
ZH. Yang et al PRL 2014
M. Freer et al, PRL 1999

A. Di Pietro et al. PLB 2022

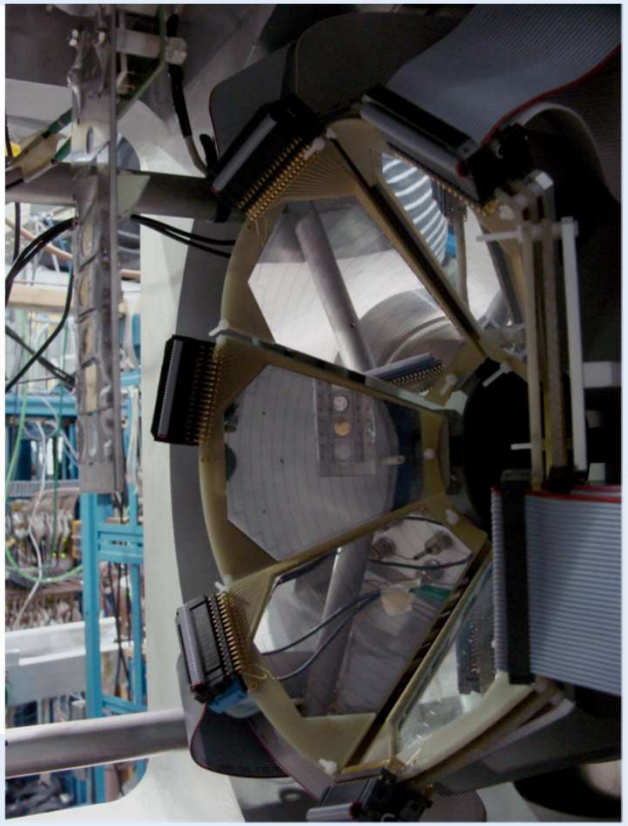
N. Soić et al, EPL 1996
Đ. Miljanić et al, Fizika 2001
M. Freer et al, PRL 2006

Experiment S1620@TRIUMF

- Experiment "Examining the helium cluster decays of the ^{12}Be excited states by triton transfer to the ^{9}Li beam", spokespersons: N.Soić, M.Freer
- ISAC-II facility ^{9}Li beam: 74.8 MeV, average intensity 4x10^{6} pps
- Natural lithium LiF target $\sim 1 \mathrm{mg/cm^2}$



Micron Semiconductor Ltd
YY1 single side strip detectors
16 strips
ΔE+E: 70 μm + 1500 μm



lampshade geometry:
360° in Φ and 16.5-48° in Θ (~2°/strip)

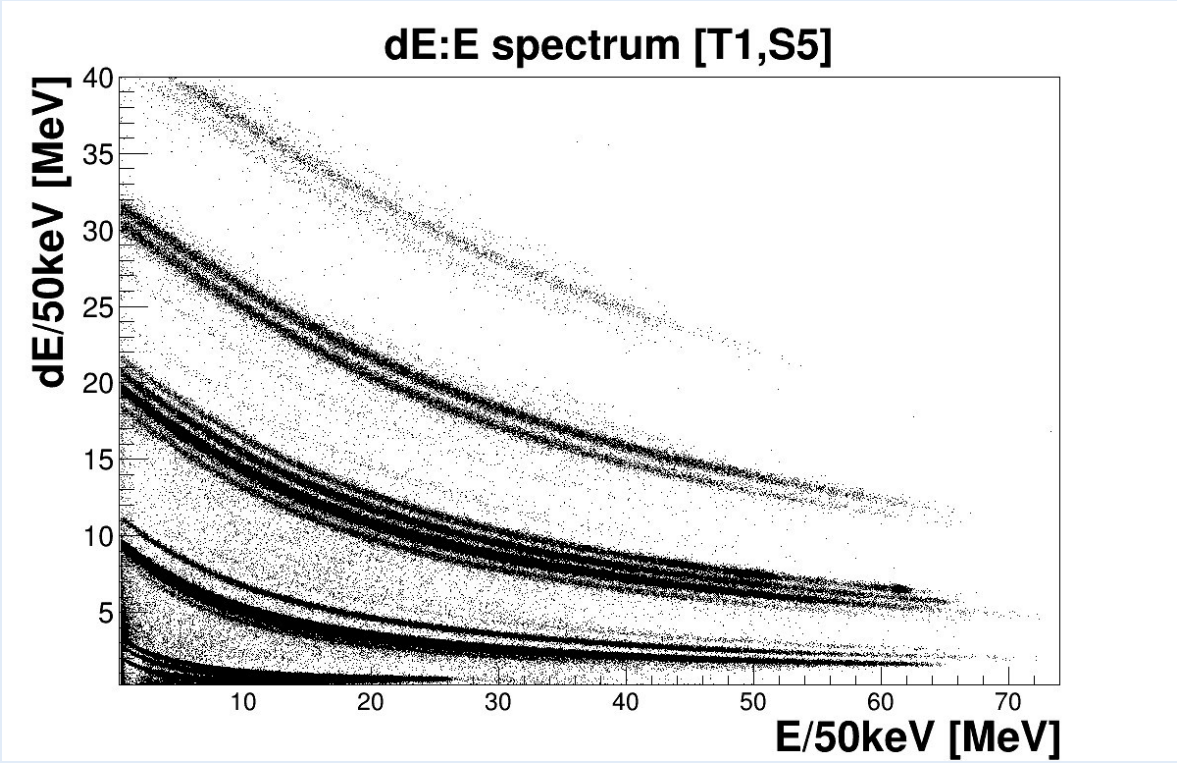
Shematic presentation of LAMP detector telescope setup. Photo of the detector array

dT	$\Delta\phi_{12}^{nom.}$	$\Delta\phi_{12}^{real}$
0	0°	[0°, 55°]
1	60°	[5°, 115°]
2	120°	[65°, 175°]
3	180°	[125°, 180°]

Data analysis

- a sequence of event reconstruction and event selection procedures
- reduction of background contributions
- in each step rigorous criteria for selection of the events applied and quality checks performed

1) hit reconstruction, multiple hits
2) reaction products identification
3) reaction exit channel identification
4) excited states identification



Typical PID ΔE-E spectrum for 1 strip in E detector

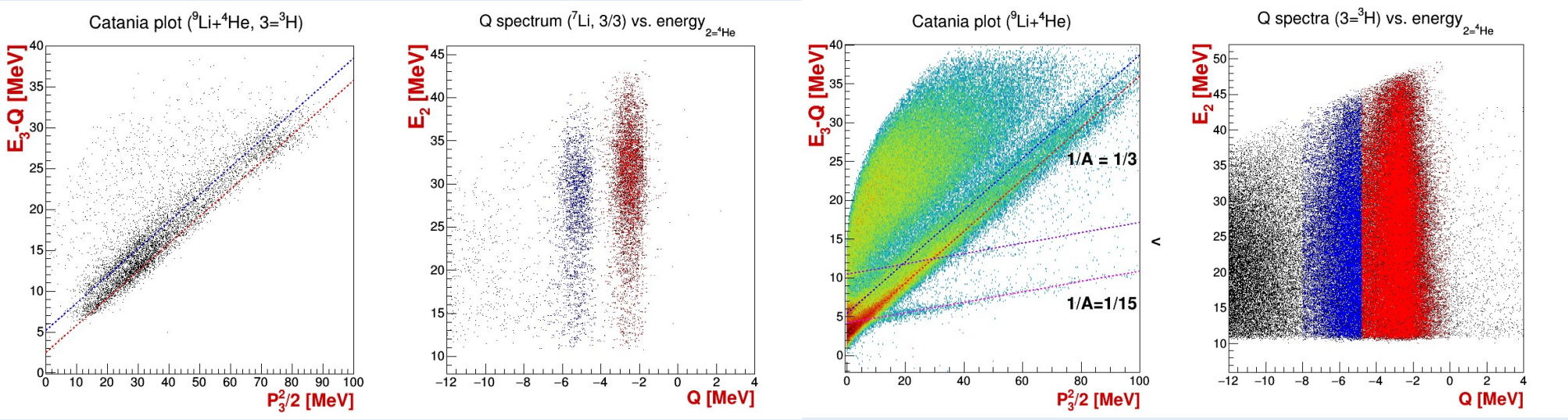
Coincident detection of 2 reaction products - kinematically complete measurements of the 3-body reactions: a full reconstruction of the event kinematics by application of momentum and energy conservation. **Detailed Monte Carlo simulations.**

Data analysis – $^{13}B^*$ decay into $^{9}Li + ^{4}He$

$^{9}Li + ^{7}Li \rightarrow ^{3}H + ^{13}B^* \rightarrow ^{3}H + \alpha + ^{9}Li$, Q = -2.46 MeV

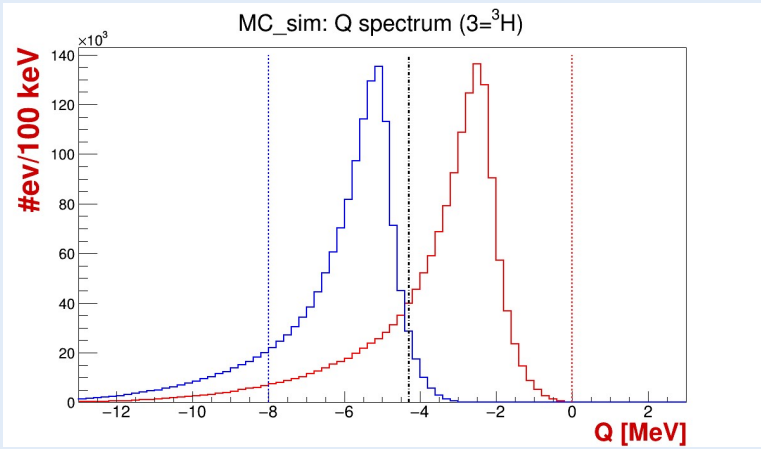
$^{9}Li + ^{19}F \rightarrow ^{15}N + ^{13}B^* \rightarrow ^{3}H + \alpha + ^{9}Li$, Q = -4.01 MeV

- reaction exit chanell identification: Q-value & Catania plot for each event



Catania plot & Q-value plot for the t+α+^{9}Li & α+^{9}Li coincidences

Results of the Monte Carlo simulations: separation of the ^{9}Li gs and 1st excited state at 2.69 MeV

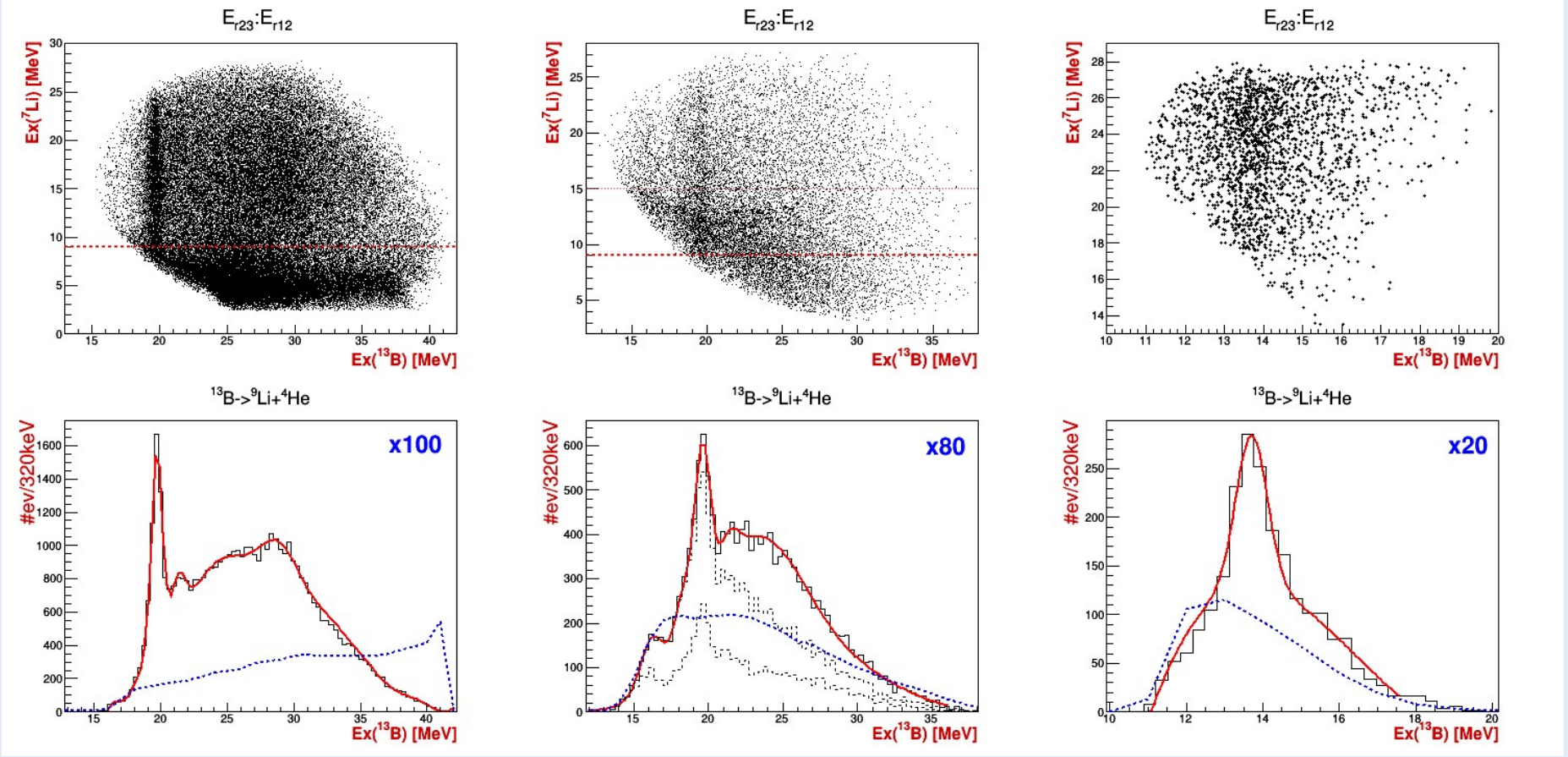


Data analysis – $^{13}B^*$ decay into $^{9}Li+^{4}He$

- excited states identification: 2D correlation plots

$$E_{r12} \propto f(E_1, E_2, \theta_1, \theta_2, \Delta\phi_{12}) \quad — \quad E_{r13} \propto Q + f(E_2^{CM}) \quad — \quad E_{r23} \propto Q + f(E_1^{CM})$$

$$\text{excitation energy: } Ex^{ij} = E^{ij}_{tr.} + E^{ij}_{rel.}$$



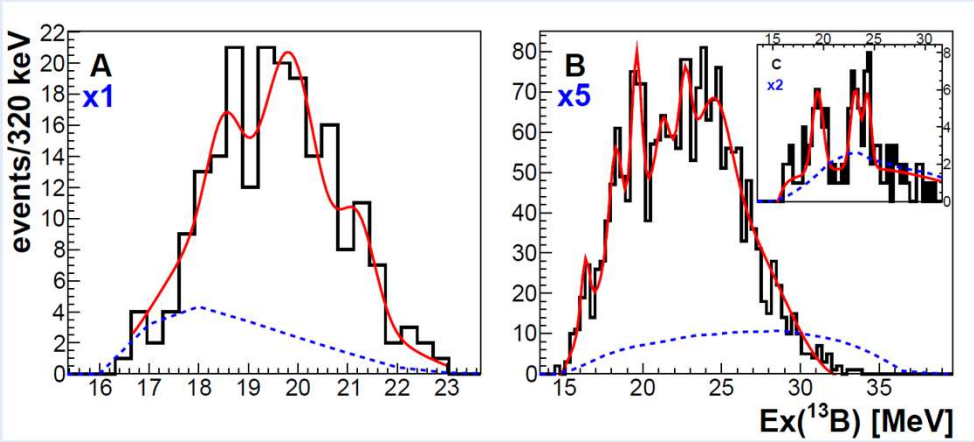
Excitation energy spectra for the ^{13}B decay to the $^{9}Li+^{4}He$ for coincident detection of ^{9}Li & ^{4}He in dT=3 (A), dT=2 (B) and dT=1 (C) telescope combinations.

^{13}B results: ^{13}B* → ^{9}Li+ ^{4}He, ^{7}Li+^{6}He, ^{10}Be+^{3}H

^{9}Li + ^{7}Li → ^{3}H + ^{6}He + ^{7}Li, Q = -7.59 MeV

^{9}Li + ^{7}Li → ^{3}H + ^{10}Be + ^{3}H, Q = -2.64 MeV

^{9}Li + ^{19}F → ^{15}N + ^{10}Be + ^{3}H, Q = -4.19 MeV



^{9}Li+^{3}H ↓ ‖ Ex [MeV] →	(12)	13.5	16.5	(18.5)	19.7	21.5
^{7}Li(^{9}Li, ^{9}Li^{4}He)$_{dT=3}$^{3}H			○	○	●	●
^{7}Li(^{9}Li, ^{9}Li^{4}He)$_{dT=2}$^{3}H			●	○	●	○
^{7}Li(^{9}Li, ^{9}Li^{4}He)$_{dT=1}$^{3}H	×	●				
^{7}Li(^{9}Li, ^{9}Li^{4}He)$_{dT=0}$^{3}H	○	●				
^{19}F(^{9}Li, ^{9}Li^{4}He)$_{dT=3}$^{15}N			○	○	●	×
^{19}F(^{9}Li, ^{9}Li^{4}He)$_{dT=3}$^{15}N*			×	○	●	○
^{19}F(^{9}Li, ^{9}Li^{4}He)$_{dT=1}$^{15}N	×	●	○	○		
^{19}F(^{9}Li, ^{9}Li^{4}He)$_{dT=1}$^{15}N*	×	●	●			
^{19}F(^{9}Li, ^{9}Li^{4}He)$_{dT=0}$^{15}N	●	●				
^{19}F(^{9}Li, ^{9}Li^{4}He)$_{dT=0}$^{15}N*	○	●				

Excitation energy spectra for the ^{13}B decays to the: ^{7}Li+^{6}He (A, dT=1) and ^{10}Be+^{3}H (B, dT=3,C, dT=3 on 19F).

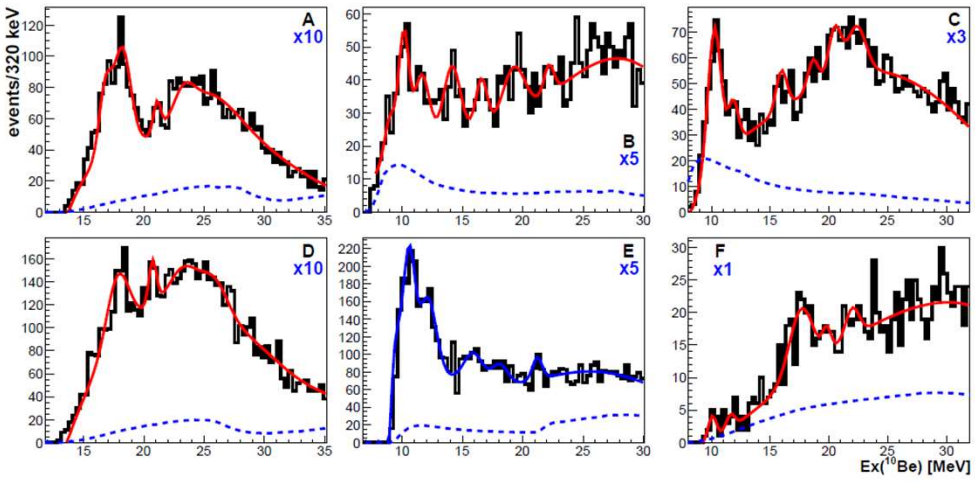
Note: ^{7}Li=g.s. + 0.48 MeV

^{7}Li+^{6}He ↓ ‖ Ex [MeV] →		18.5	19.5	21.2	22.9	
^{7}Li(^{9}Li, ^{7}Li^{6}He)$_{dT=1}$^{3}H		●	●	○		
^{10}Be+^{3}H ↓ ‖ Ex [MeV] →	16.3	18.5	19.5	21.2	22.9	24.7
^{19}F(^{9}Li, ^{10}Be^{3}H)$_{dT=3}$^{3}H	○	●	●	○	○	○
^{19}F(^{9}Li, ^{10}Be^{3}H)$_{dT=3}$^{15}N			●		○	○

^{10}Be results: ^{10}Be* → ^{4}He+^{6}He, ^{4}He+^{6}He*

^{9}Li + ^{7}Li → ^{6}He + ^{10}Be* → ^{6}He + ^{4}He + ^{6}He, Q = 2.24 MeV

^{9}Li + ^{19}F → ^{18}O + ^{10}Be* → ^{18}O + ^{4}He + ^{6}He, Q = 4.23 MeV



Excitation energy spectra for the ^{10}Be decays to the ^{4}He+^{6}He and ^{4}He+^{6}He*(1.8 MeV) (E) for coincident detection of the: ^{4}He+^{6}He (A-12-dT3, B-13-dT3, D-12-dT3*, E-13*-dT3*) and ^{6}He+^{6}He (C-13+23-dT3, F-13+23-dT3).

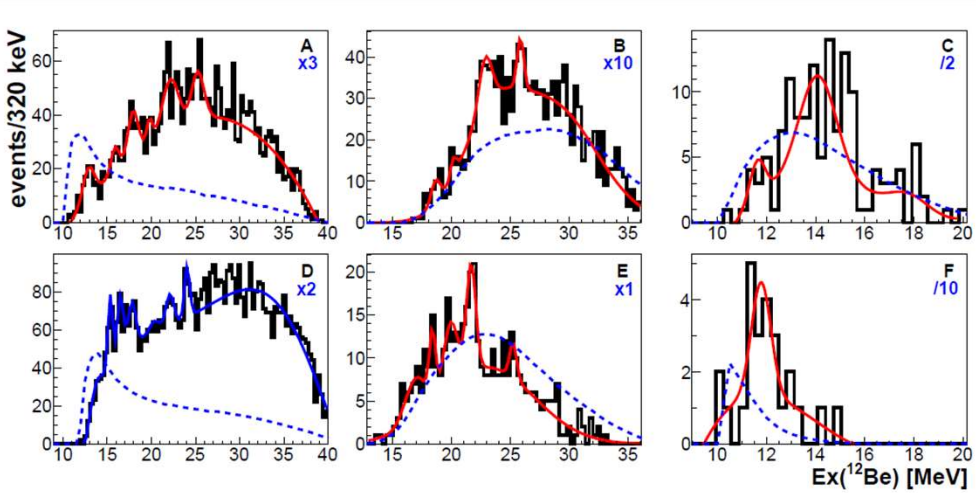
^{4}He + ^{6}He ↓ ‖ Ex (^{10}Be)[MeV] →	9.6	10.2	11.8	16.5	18.5	20.5	22.3
^{7}Li(^{9}Li, ^{4}He^{6}He^{6}He) (12+13)	●	●	●	○			
^{7}Li(^{9}Li, ^{4}He^{6}He)$_{dT=3}$^{6}He (12)				○	●	●	●
^{7}Li(^{9}Li, ^{4}He^{6}He)$_{dT=3}$^{6}He* (12)				○	●	●	○
^{7}Li(^{9}Li, ^{4}He^{6}He)$_{dT=0}$^{6}He (12)	●	○	●				
^{7}Li(^{9}Li, ^{4}He^{6}He)$_{dT=0}$^{6}He* (12)	●	○	●				
^{7}Li(^{9}Li, ^{4}He^{6}He)$_{dT=3}$^{6}He (13)	○	●	●	●	○	○	○
^{7}Li(^{9}Li, ^{6}He^{6}He)$_{dT=3}$^{4}He (13+23)	×	●	●	●	○	●	○
^{7}Li(^{9}Li, ^{6}He^{6}He)$_{dT=2}$^{4}He (13+23)	×	●	●	○	●	●	○

^{4}He + ^{6}He* ↓ ‖ Ex (^{10}Be)[MeV] →	9.6	10.2	11.8	16.0	21.2
^{7}Li(^{9}Li, ^{4}He^{6}He)$_{dT=3}$^{6}He* (13)	○	●	●	○	○

^{12}Be results: ^{12}Be* → ^{6}He+^{6}He, ^{6}He+^{6}He*

^{9}Li + ^{7}Li → ^{4}He + ^{12}Be* → ^{4}He + ^{6}He + ^{6}He, Q = 2.24 MeV

^{9}Li + ^{19}F →^{16}O + ^{12}Be* → ^{16}O + ^{6}He + ^{6}He, Q = -6.98 MeV



^{6}He+^{6}He ↓ ‖ Ex (^{12}Be) [MeV] →	(11.7)	13.5	(16.5)	18.5	(20.0)	22.5	25.4
^{7}Li(^{9}Li, ^{4}He^{6}He)$_{dT=3}$^{6}He (23)	×	•	○	•	○	•	•
^{7}Li(^{9}Li, ^{6}He^{6}He)$_{dT=3}$^{4}He (12)				•	○	•	•
^{7}Li(^{9}Li, ^{6}He^{6}He)$_{dT=2}$^{4}He (12)			○	•	•	•	○
^{7}Li(^{9}Li, ^{6}He^{6}He)$_{dT=1}$^{4}He (12)	○	•	×				
^{7}Li(^{9}Li, ^{6}He^{6}He)$_{dT=0}$^{4}He (12)	•						

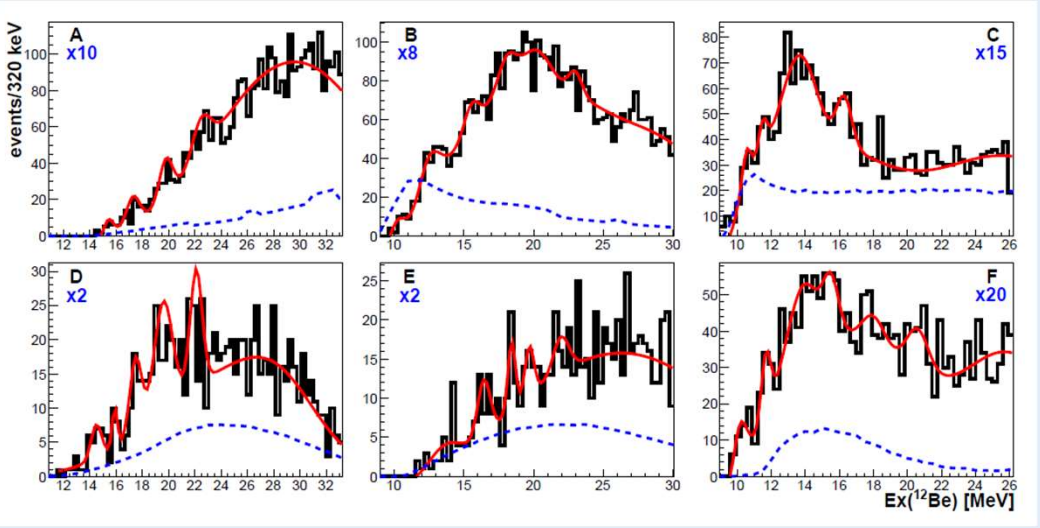
Excitation energy spectra for the ^{12}Be decays to the ^{6}He+^{6}He and ^{6}He+^{6}He*(1.8 MeV) (D) for coincident detection of the: ^{4}He+^{6}He (A-23-dT3, D-23*-dT3*) and ^{6}He+^{6}He (B-12-dT3, C-12-dT1, E-12-dT2, F-12-dT0).

^{6}He+^{6}He* ↓ ‖ Ex (^{12}Be) [MeV] →	15.4	16.5	17.8	22.1	24.0
^{7}Li(^{9}Li, ^{4}He^{6}He)$_{dT=3}$^{6}He (23)	•	•	•	•	•

^{12}Be results: ^{12}Be* → ^{4}He+^{8}He

^{9}Li + ^{7}Li → ^{4}He + ^{12}Be* → ^{4}He + ^{4}He + ^{8}He, Q = 3.402 MeV

^{9}Li + ^{19}F → ^{16}O + ^{12}Be* → ^{16}O + ^{4}He + ^{8}He, Q = -5.830 MeV



Excitation energy spectra for the ^{12}Be decays to the ^{4}He+^{8}He for coincident detection of the: ^{4}He+^{8}He (A-12-dT3, B-23-dT3, D-12-dT2, E-23-dT2) and ^{4}He+^{4}He (C-13+23-dT3, H-13+23-dT2)

^{4}He+^{8}He ↓ ‖ Ex (^{12}Be) [MeV] →	10.3	(12.1)	13.8	15.6	17.5	(19.8)	(22.3)
^{7}Li(^{9}Li, ^{4}He^{8}He)$_{dT=3}$^{4}He (23)	×	×	●	○	○	○	○
^{7}Li(^{9}Li, ^{4}He^{8}He)$_{dT=2}$^{4}He (23)			○	●	●	●	○
^{7}Li(^{9}Li, ^{4}He^{8}He)$_{dT=3}$^{4}He (12)				○	●	○	○
^{7}Li(^{9}Li, ^{4}He^{8}He)$_{dT=2}$^{4}He (12)			○	○	○	○	○
^{7}Li(^{9}Li, ^{4}He^{8}He)$_{dT=1}$^{4}He (12)	●	○	○	●	○		
^{7}Li(^{9}Li, ^{4}He^{8}He)$_{dT=0}$^{4}He (12)	●	○					
^{7}Li(^{9}Li, ^{4}He^{4}He)$_{dT=3}$^{8}He (13+23)	○	○	●	●	×	×	×
^{7}Li(^{9}Li, ^{4}He^{4}He)$_{dT=2}$^{8}He (13+23)	○	○	○	○	●	○	×

Conclusions

- the ^{9}Li + ^{7}Li experiment provided data for the number of light neutron-rich nuclei, new spectroscopic info for ^{10,12}Be & ^{13}B
- **^{13}B:** observed recently reported states decaying to the ^{9}Li+^{4}He; indications for new states in this decay channel found; indications for the ^{7}Li+^{6}He and ^{10}Be+^{3}H decay found ⇒ α+2n+p+2n+α ?
- **^{10}Be:** new states at high excitations observed in the ^{4}He+^{6}He and ^{4}He+^{6}He*(1.8 MeV) channels
- **^{12}Be:** observed states reported in previous studies of inelastic breakup to decay into ^{4}He+^{8}He and ^{6}He+^{6}He; indications for new states found; new decay channel ^{6}He+^{6}He*(1.8 MeV) observed
- could not provide info on the spin, parity and partial decay widths of the states, but provided new important spectroscopic info
- exotic cluster-decay channels at high excitations ⇒ strong support of the molecular structure of the observed states

ACKNOWLEDGMENTS

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