Exotic clustering investigation in ^{13}B and ^{14}C nuclei using RIBs

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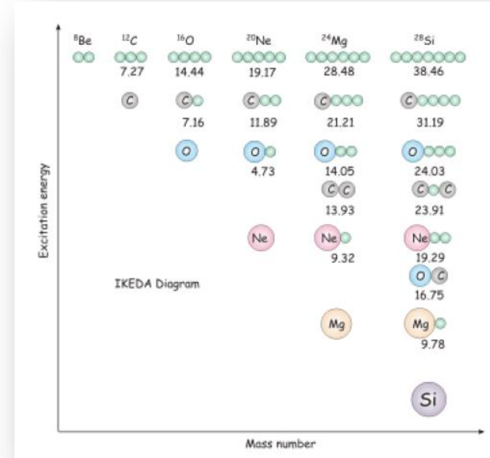
Conventional cluster structure

Cluster structure is a well established feature of many light N≈Z nuclei

Weak coupling picture:

1. Clusters are formed by tightly bound nucleons (cluster is stiff, i.e. not easy to excite);
2. Weakly coupled inter-cluster motion is considered.

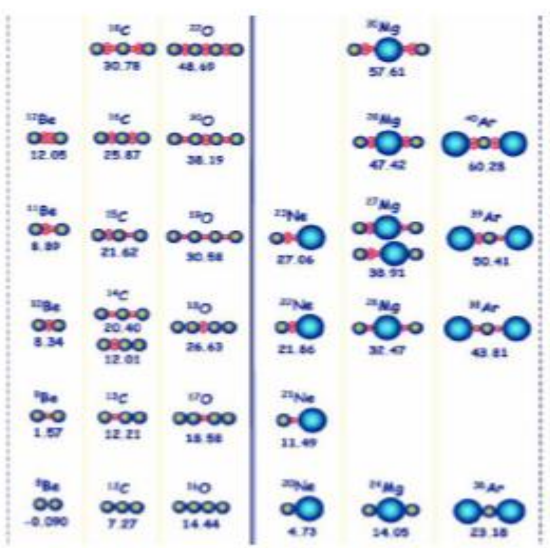
Threshold rule: i.e. these states appear close to the threshold for breaking-up into the cluster constituents.



K. Ikeda et al. Supp.Progr.Theo.Phys. 68(1980)1

Clusters in n-rich nuclei

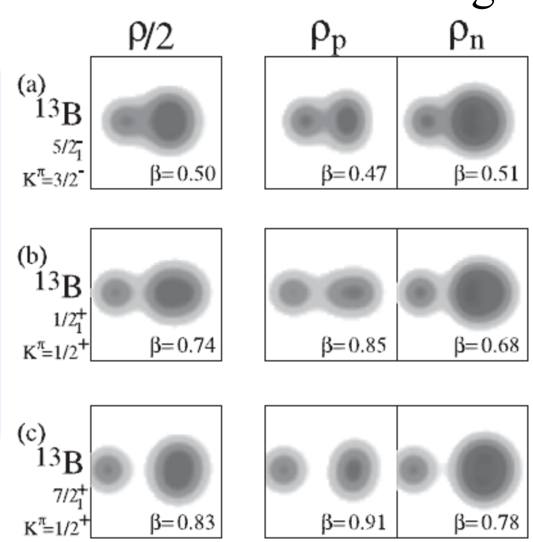
Molecules



➤"**molecules**" made of α bound together by *n* and/or *p*.

➤**clusters** where at least one component is a soft "**exotic**" nucleus.

"Exotic" clustering



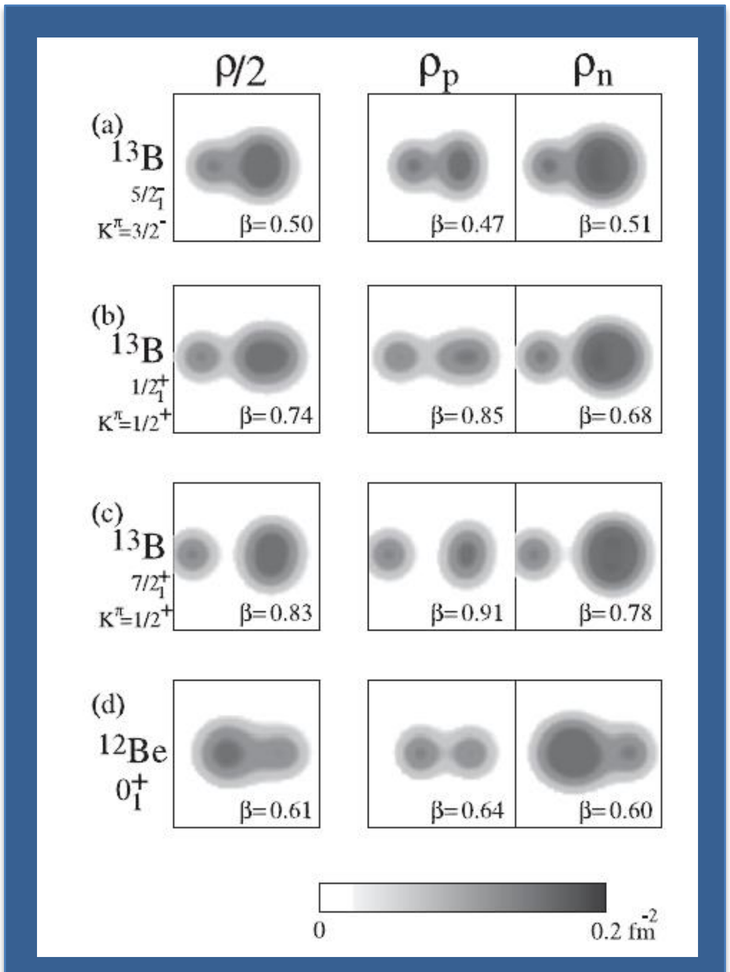
Y. Kanada En'yo et al. Prog.Theor.Phys.120(2008)917

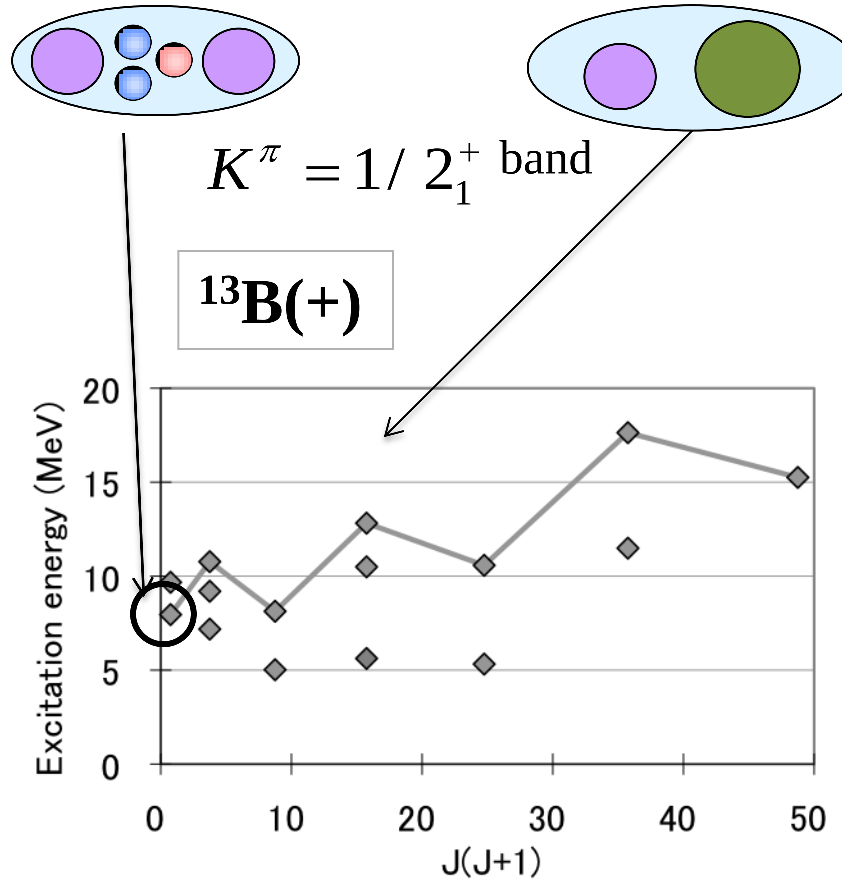
Excited states of ^{13}B studied with AMD

AMD calculations

Y. Kanada En'yo et al. Prog.Theor.Phys.120(2008)917

No known states ^{13}B E_x>11 MeV





Inverse Kinematic Resonant Elastic Scattering Method

K.P.Artemov et al. Sov.J.Nucl.Phys. 52(1990)408

Elastic scattering of heavy projectiles **B** on a light targets **b** (protons or αs) in order to study properties of the compound nucleus C resulting from

$$B+b \rightarrow C^* \rightarrow B+b$$

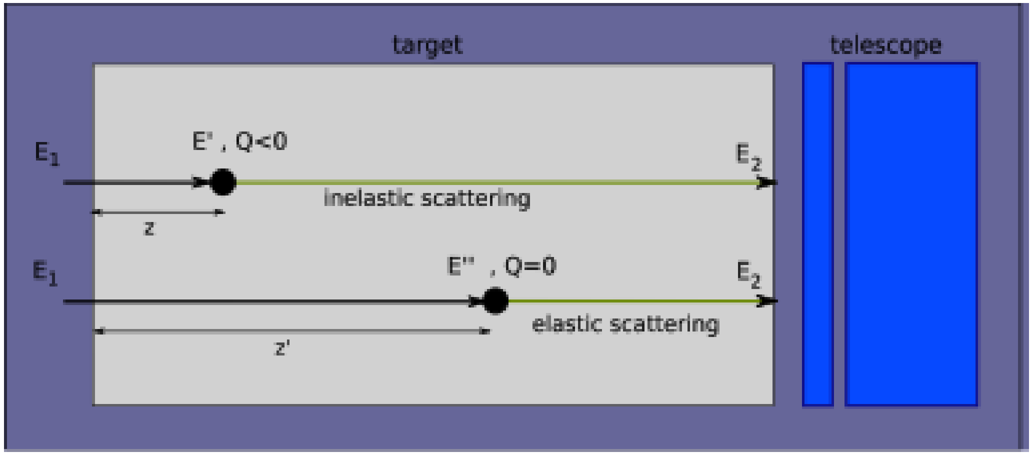
Excitation function measured at $\theta_{cm} \approx 180^o \Rightarrow$ enhanced visibility of resonances with respect to potential and Coulomb scattering.

- thick solid
- gaseous target (H, He)
  - ✓ easy to change target thickness (changing gas pressure)
  - ✓ more homogeneous target
  - ✓ possibility to have very extended targets

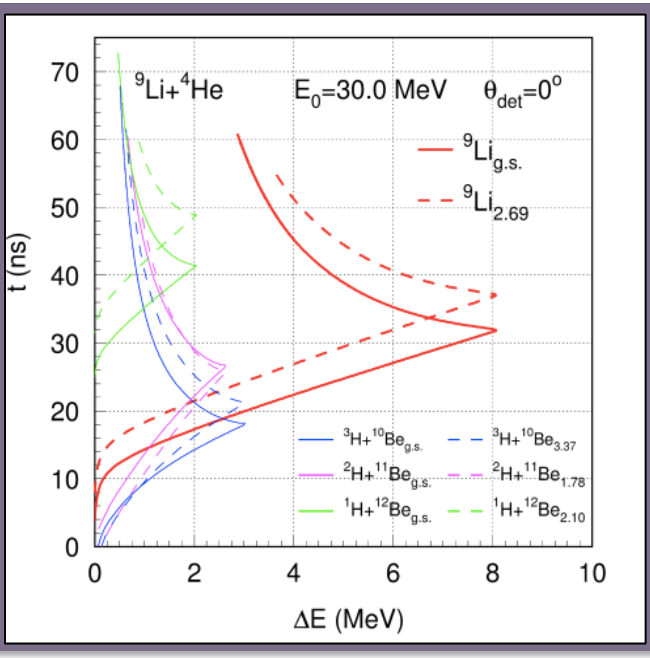
Importance of Time measurement

➢ Background ⇒ radioactive decay of the beam, inelastic scattering and reaction events. From α or Hydrogen spectra no possibilities to discriminate different reaction processes.

Time measurement



Calculations of
Time *vs* ΔE for a ΔE thickness=50μm
Elastic, inelastic and some reaction process are considered



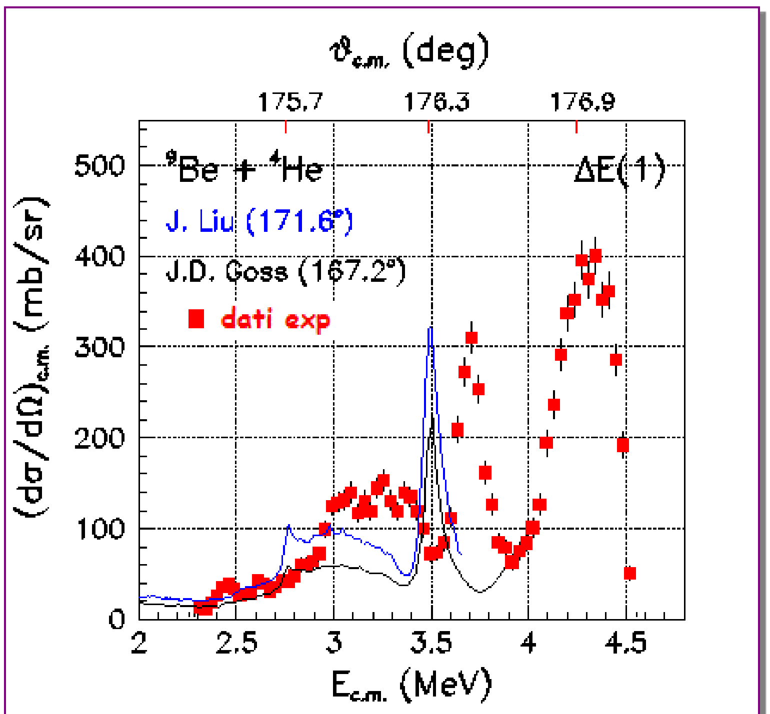
Problems with stopping power calculations.

Excitation function $^{9}Be+^{4}He$ at $E_{c.m.}$<4.5MeV

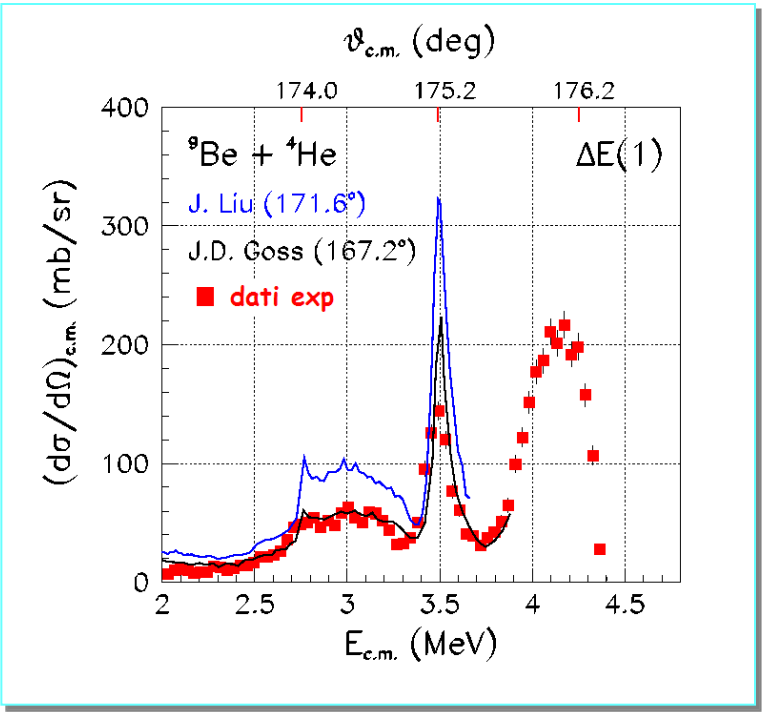
■ Excitation function $^{9}Be + \alpha$ with resonance scattering method. M. Zadro et al, NIM B259 (2007).

— Excitation function $\alpha+^{9}Be$ measured with thin target method varying beam energy at small steps J. Liu [NIM B 108,(1996) 247] , J.D. Goss [PRC 7,(1973) 247]

dE/dx from SRIM



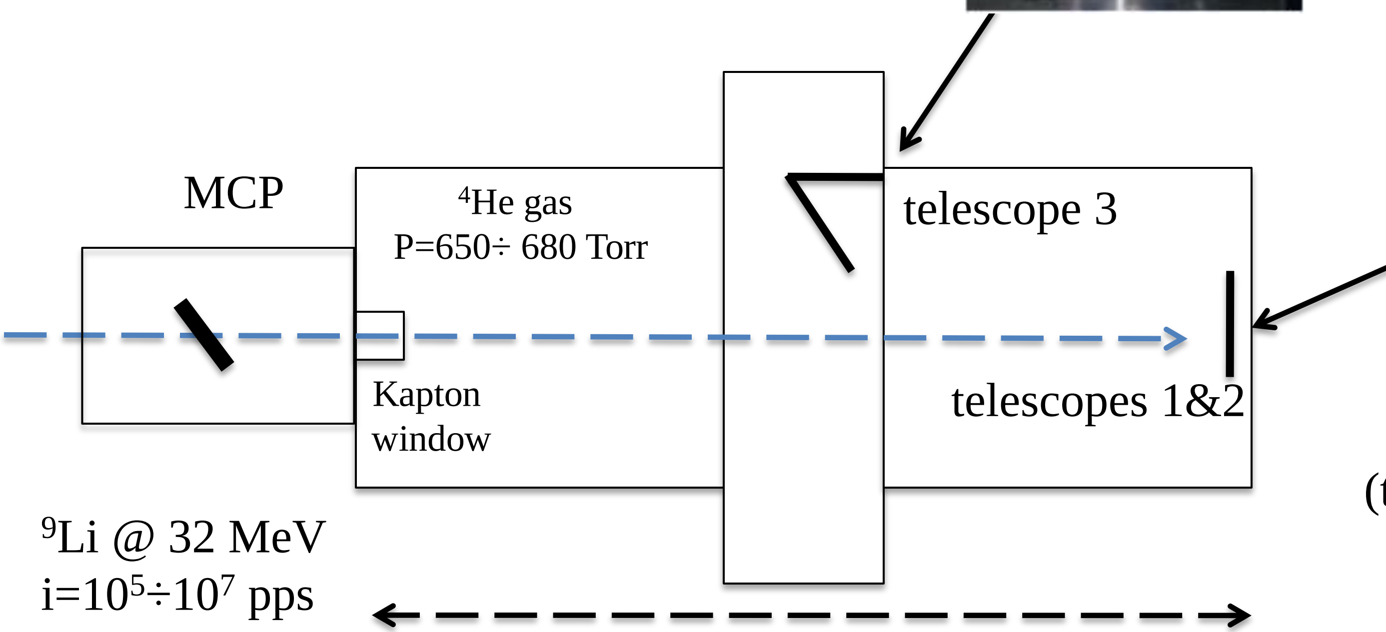
dE/dx measured



Cluster states in ^{13}B: ^{9}Li+α at TRIUMF

Detectors:

MCP : ToF measurement
and beam-particle counting
3 Si-telescopes :
4 quadrant ΔE detectors: 50 μm
E- single pad: 1000 μm

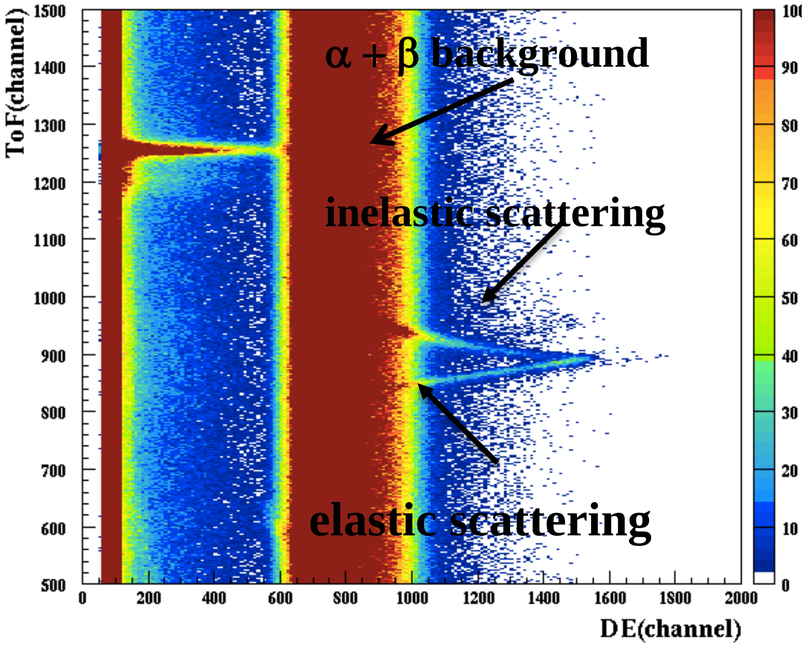


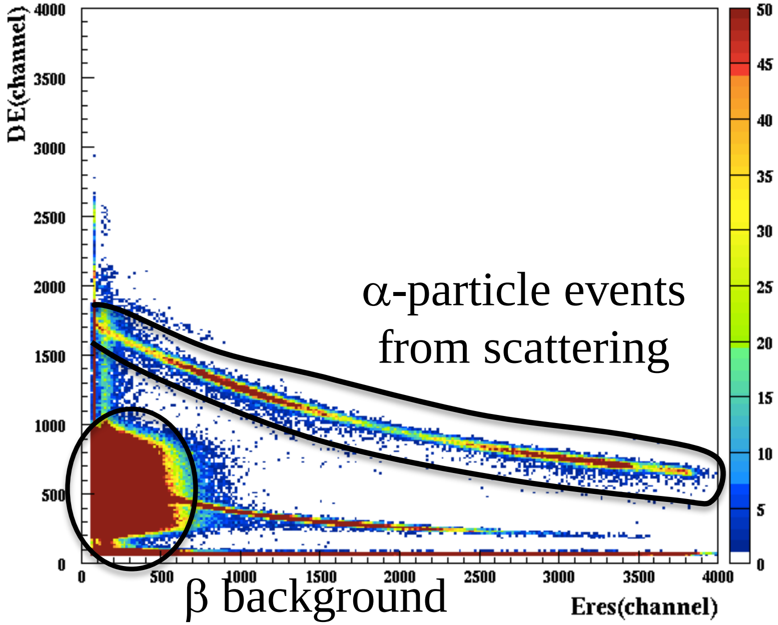
0^{0} detectors
(telescopes 1 & 2)

^{9}Li @ 32 MeV
i=10^{5}÷10^{7} pps

1.5 m
TUDA chamber

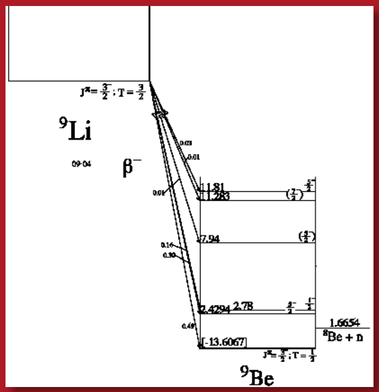
$^9Li + ^4He$ @ TRIUMF



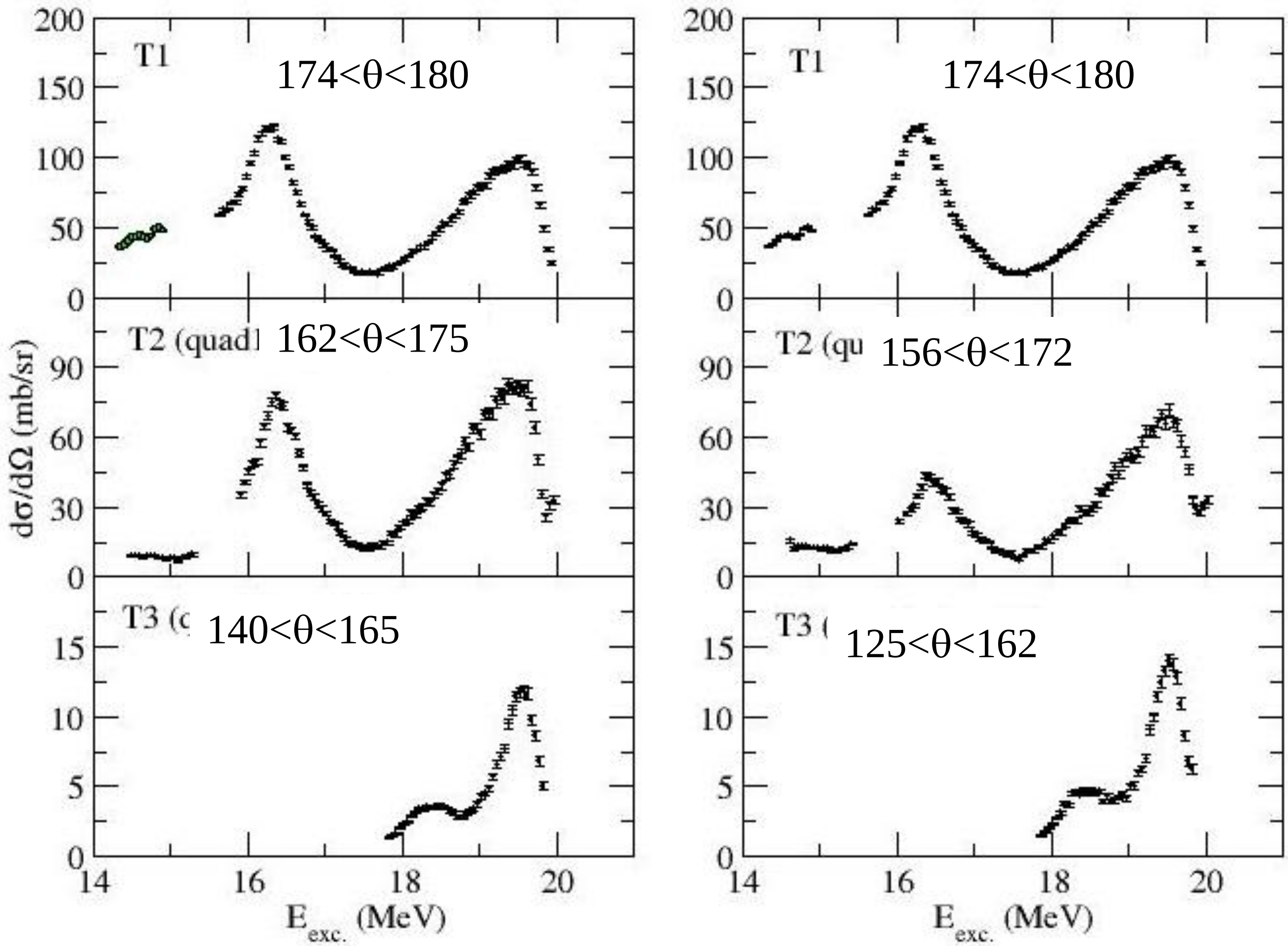


Uncorrelated α and β particles coming from ^9Li radioactive decay. Due to the large size of the detectors β particles release large energy in both ΔE and E detectors. α–energy not sufficient to punch-through the ΔE

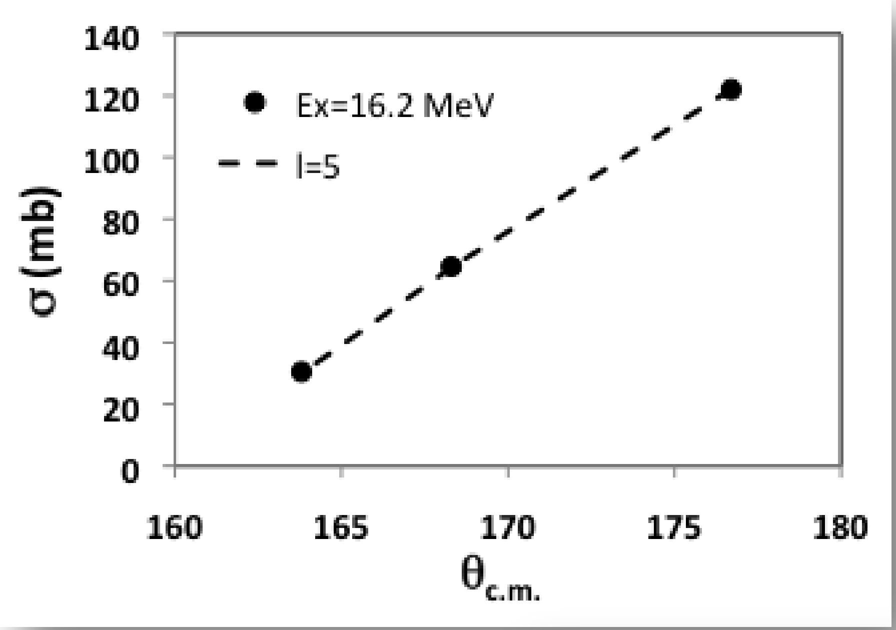
^9Li decay scheme

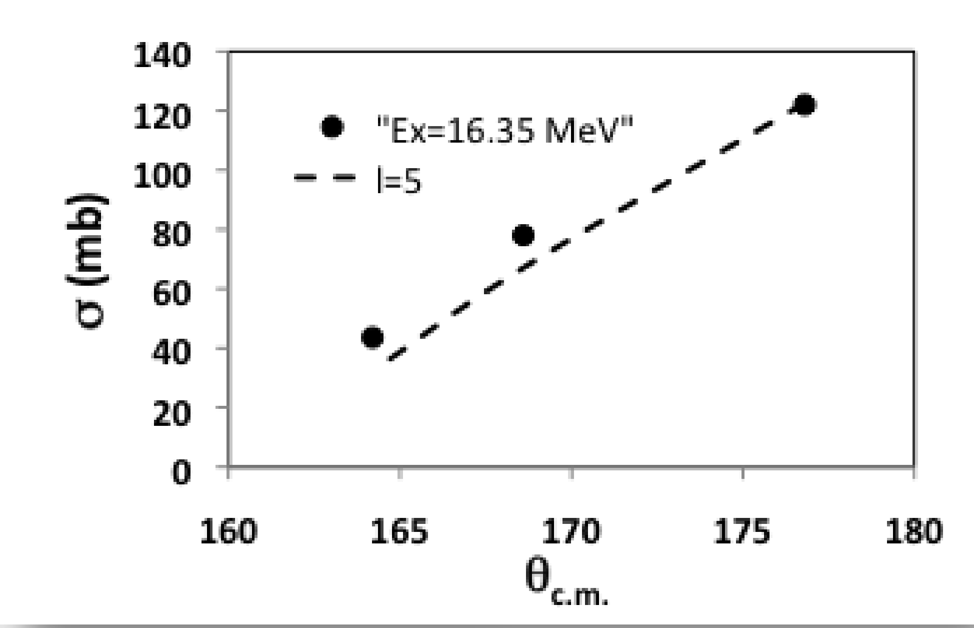


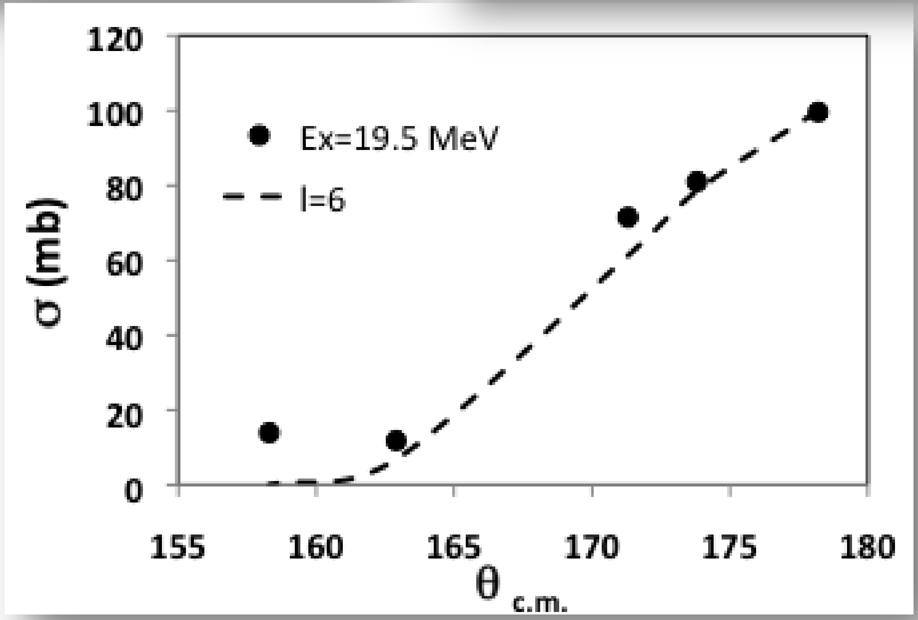
^{13}B excitation function



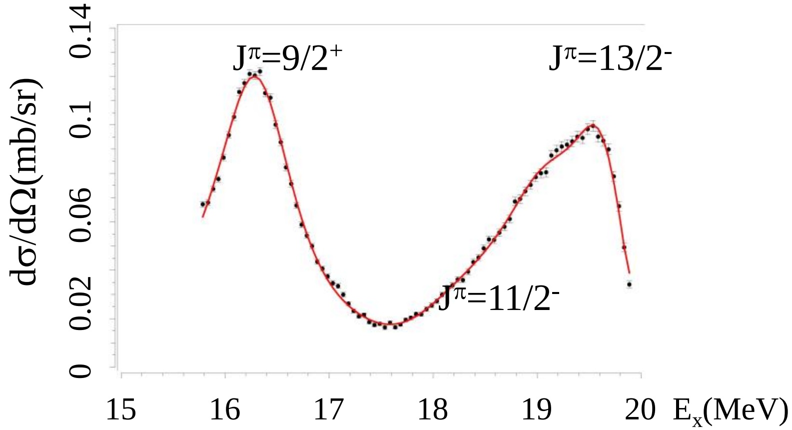
Estimation of angular momentum involved



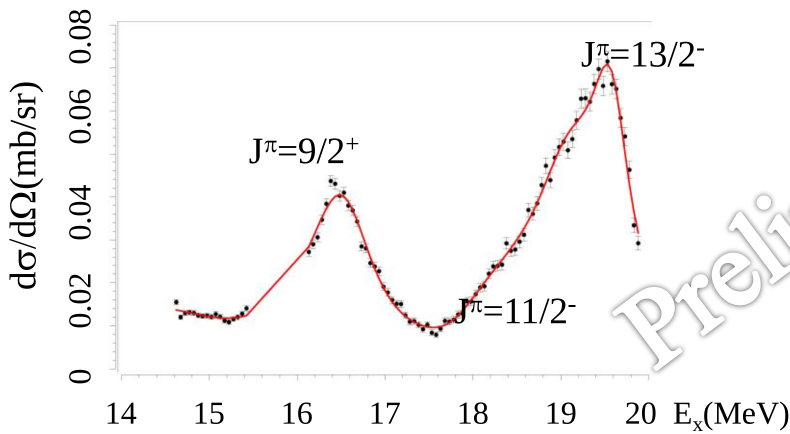




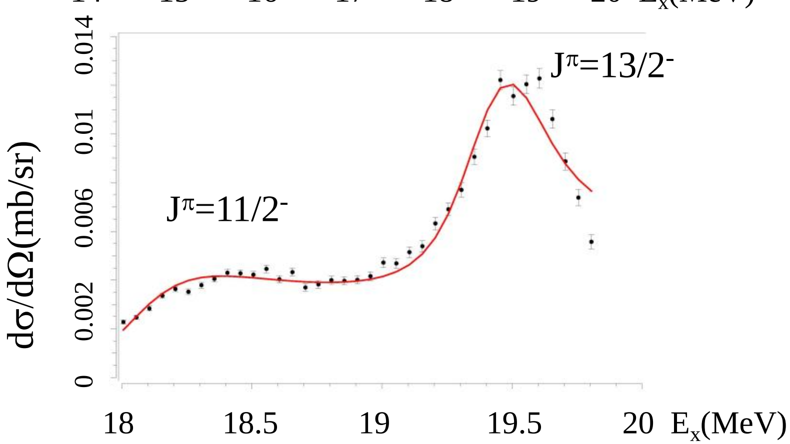
R-matrix f



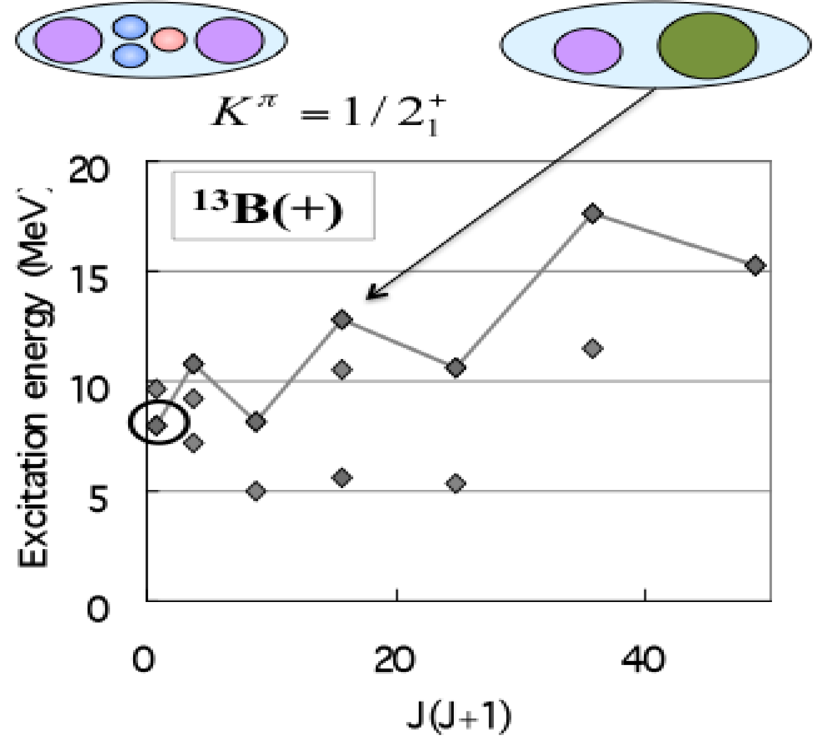
Jπ=9/2+
Jπ=13/2-
Jπ=11/2-
dσ/dΩ(mb/sr)
0 0.02 0.06 0.1 0.14
15 16 17 18 19 20 Ex(MeV)



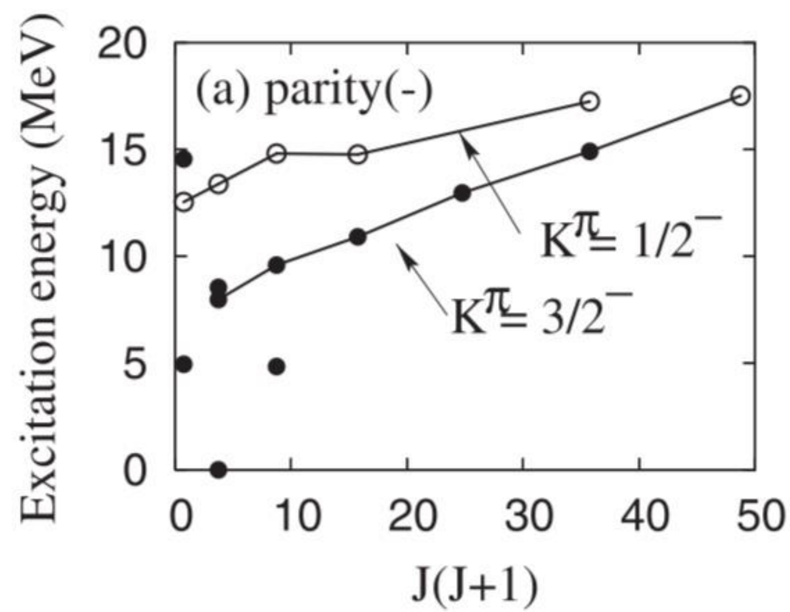
Jπ=13/2-
Jπ=9/2+
Jπ=11/2-
Preliminary
dσ/dΩ(mb/sr)
0 0.02 0.04 0.06 0.08
14 15 16 17 18 19 20 Ex(MeV)



Jπ=13/2-
Jπ=11/2-
dσ/dΩ(mb/sr)
0 0.002 0.006 0.01 0.014
18 18.5 19 19.5 20 Ex(MeV)

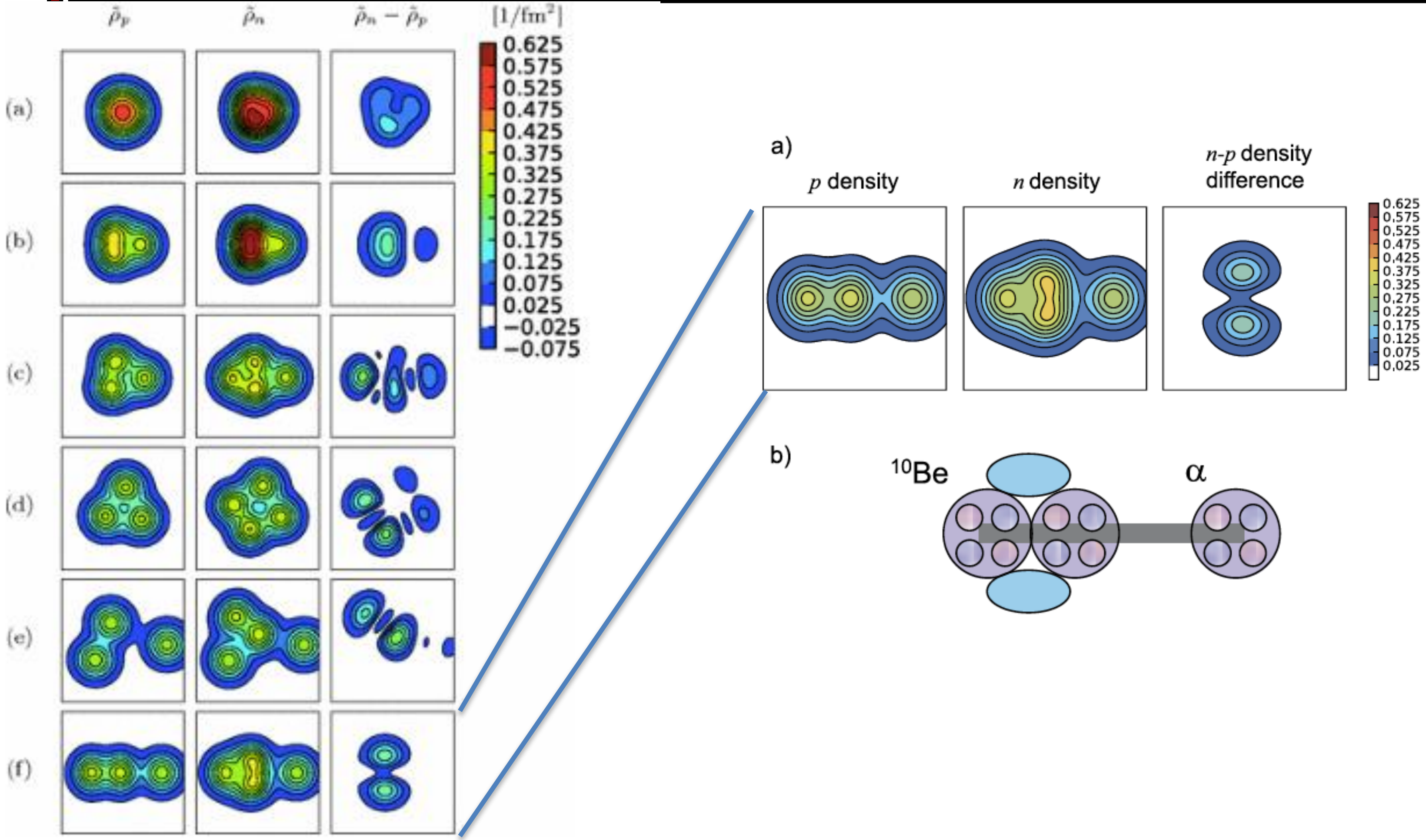


$K^{\pi} = 1/2_1^+$
13B(+)
Excitation energy (MeV)
0 5 10 15 20
0 20 40
J(J+1)



(a) parity(-)
Kπ= 1/2−
Kπ= 3/2−
Excitation energy (MeV)
0 5 10 15 20
0 10 20 30 40 50
J(J+1)

Linear chain state in ^{14}C

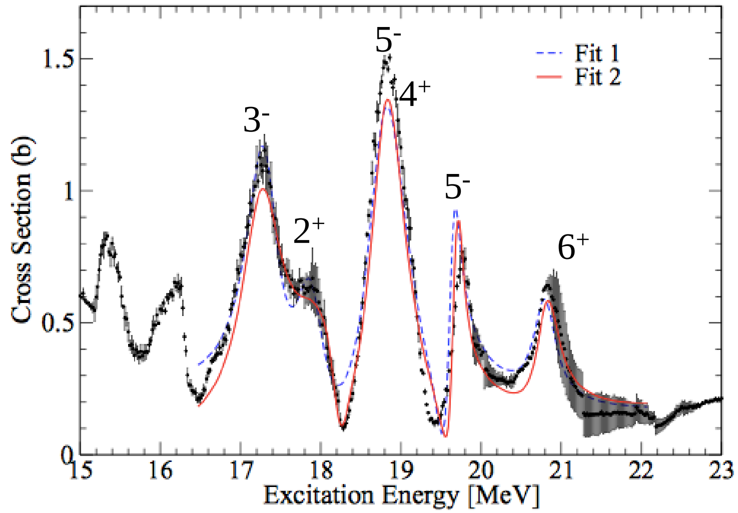


No linear chain α-structure nor linear chain band was found in ^{12}C.
They may exist in ^{14}C being stabilised by excess of neutrons.
This is predicted to occur in ^{14}C by AMD calculations.

Suhara, Y. Kanada-En'yo, Phys. Rev. C 84 (2011) 024328
T. Suhara, Y. Kanada-En'yo, Phys. Rev. C 82 (2010) 04430

^{14}C excitation function: previous results

elastic + inelastic scattering

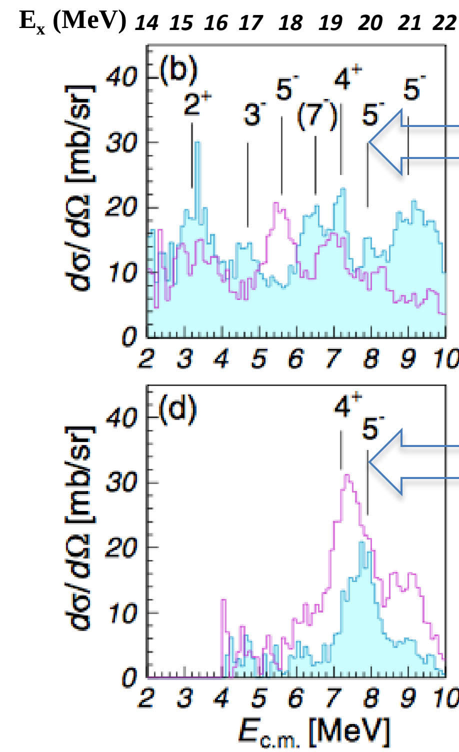


M. Freer et al. PRC 90, 054324 (2014)

^{10}Be+^{4}He @ Notre Dame.

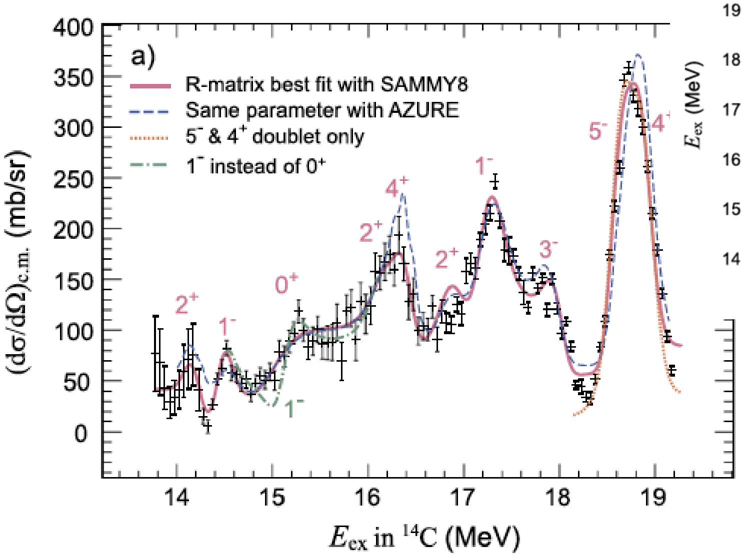
A. Fritsch et al. PRC 93, 014321 (2016)

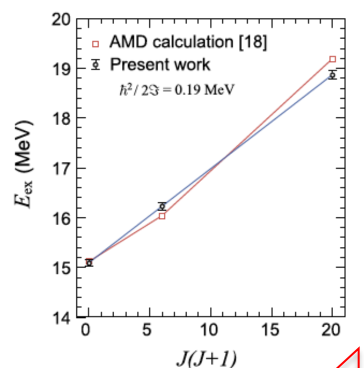
Active target ($i_{beam} \cong 10^3$ pps)



Elastic scattering

Inelastic scattering





Authors claim that inelastic excitation is negligible and that “genuine” elastic events are selected. But excitation function similar to the one of Freer et al.

H. Yamaguchi et al. / Physics Letters B 766 (2017) 11

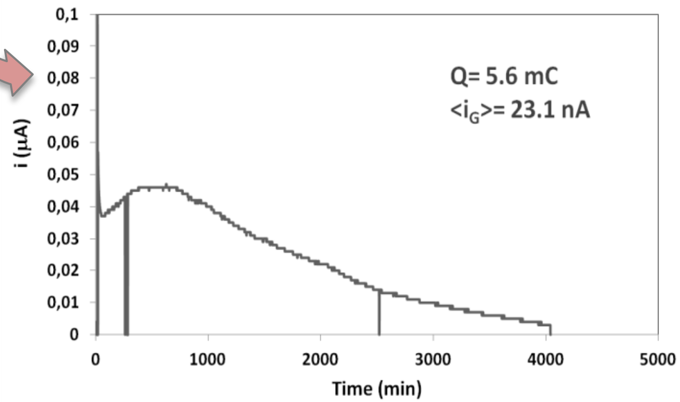
Production of a ^{10}Be radioactive beam in batch-mode at LNS

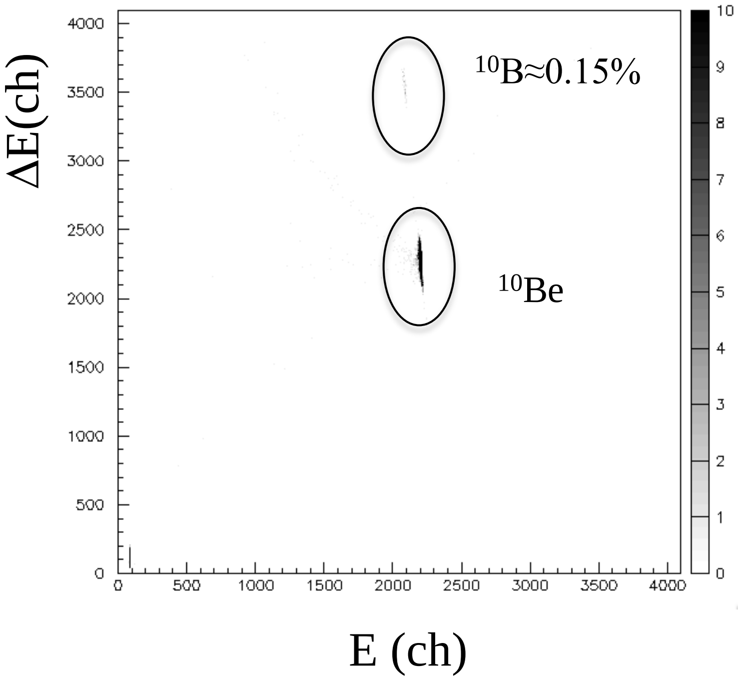
^{10}BeO (^{10}Be $T_{1/2}=1.39\times10^{6}$ y) mixed with Ag was prepared at PSI (Zurich) and used in the source cathode of the Tandem accelerator. Several tests were done to choose the best preparation and cathode condition. Collaboration also with CIRCE laboratory.

Cathode preparation tested

Cathode	Dimensions (mm x mm)	BeO:Ag	Ag ADDING	Q(mC)	<i> nA
A	2X2	1:10	1/3 added bef. 2/3 after glowing	1,21	17,20
B	2X1	1:10	1/3 added bef. 2/3 after glowing	1,36	15,30
C	2X1	1:10	Ag added before glowing	2,41	27,50
D	2X2	1:10	1/3 added bef. 2/3 after glowing		
E	2X2	1:35	1/3 added bef. 2/3 after glowing	2,92	15,90
F	2X1	1:35	1/3 added bef. 2/3 after glowing		
G	2X2	1:35	Ag added before glowing	5,59	23,20
H	2X1	1:35	Ag added before glowing	3,61	43,60

Beam current as a function of time in the tandem source

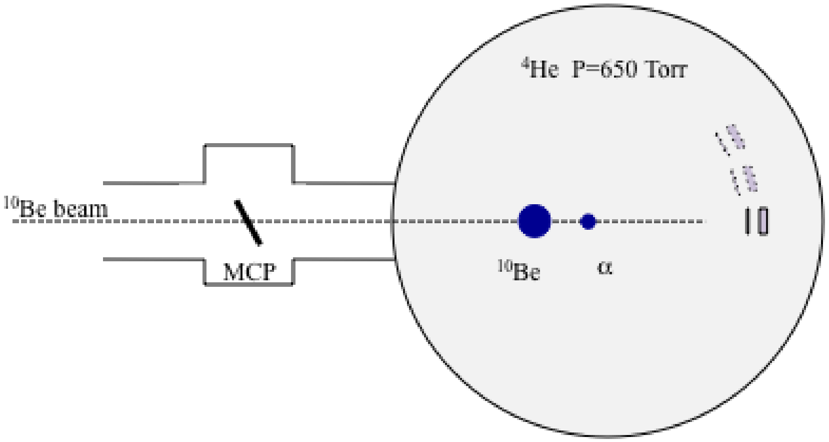




^{10}Be^{4+} @ 47 MeV
i≅10 nA*e* for a few days
on target, after collimation, i≅1 nA*e*
^{10}B contamination < 0.2%

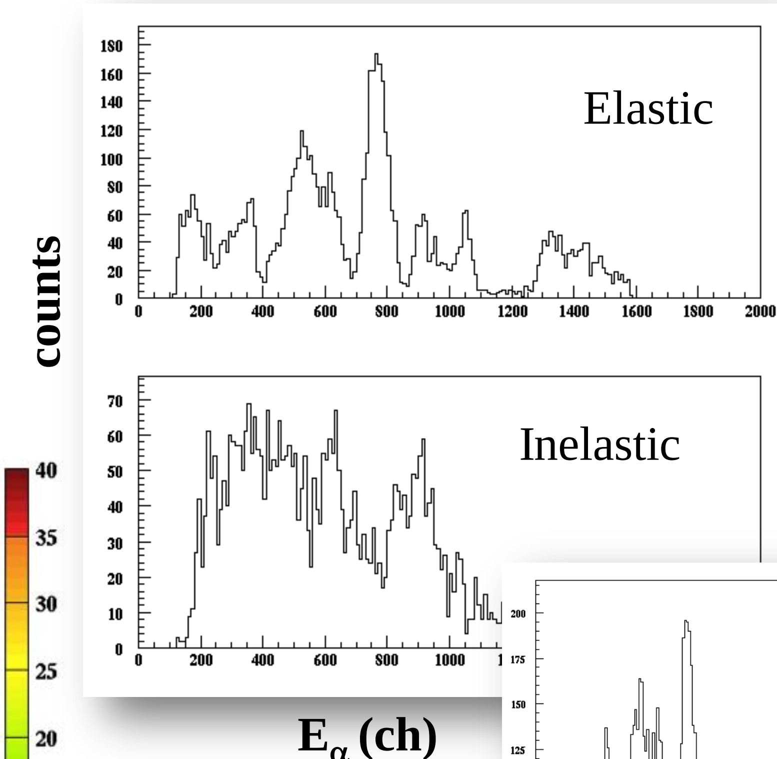
^{10}Be+α resonant elastic scattering at LNS TANDEM

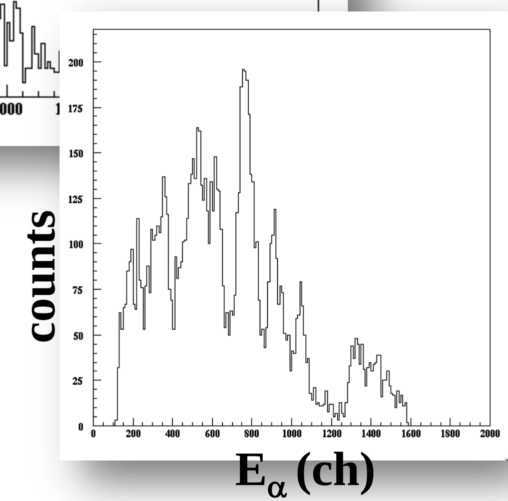
^{10}Be+^{4}He resonant elastic scattering on thick target to investigate α-chain-states in ^{14}C.
RIB intensity on target from 10^3 to 10^5 times larger than in previous experiments



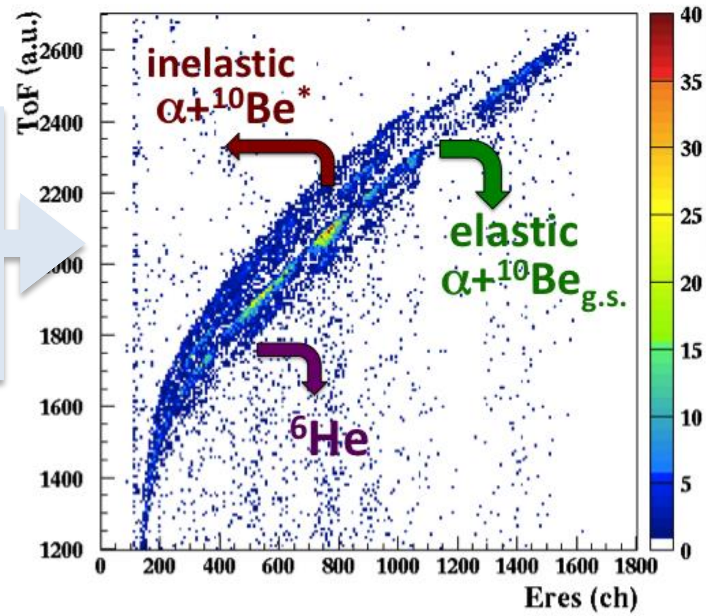
Experimental set-up

^{14}C excitation function





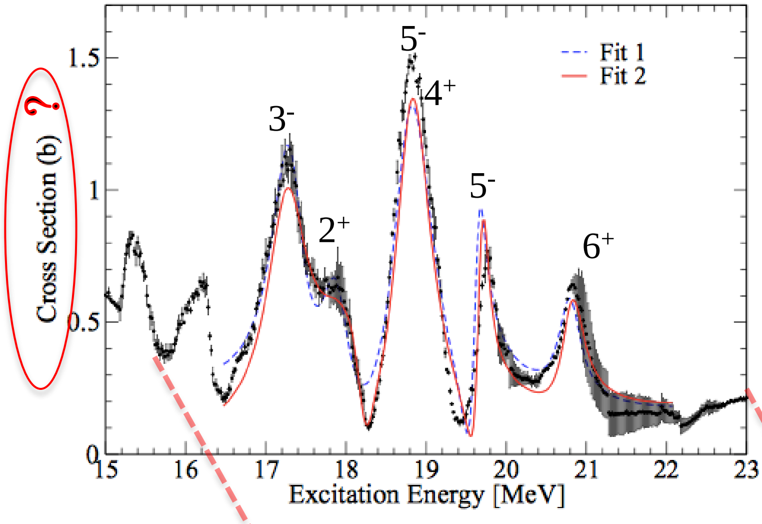
For the first time clear separation between elastic and inelastic events

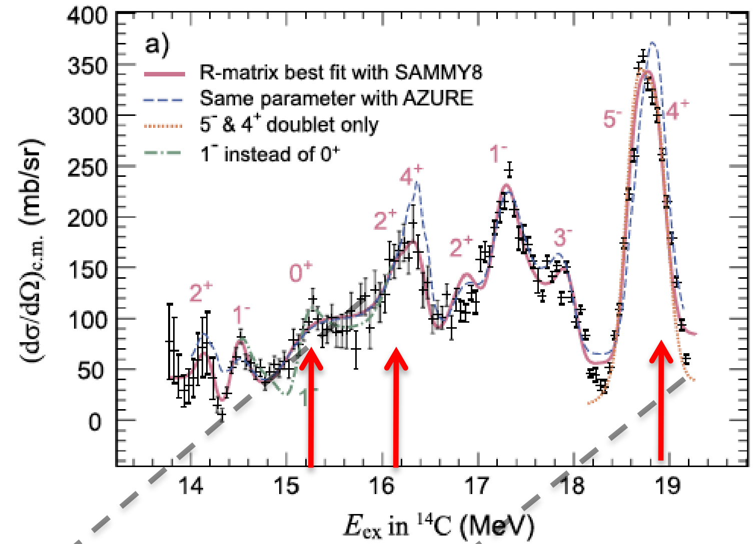


^{10}Be beam LNS - results of test experiment

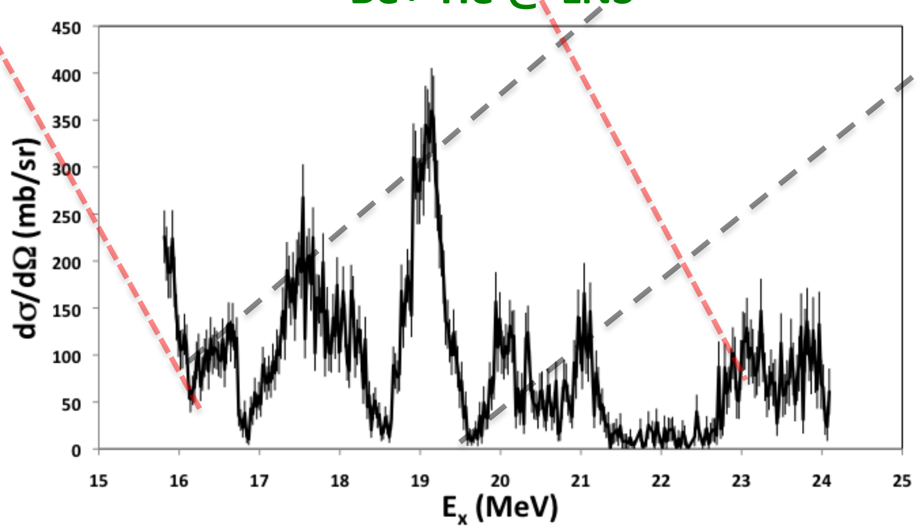
M. Freer et al. PRC 90, 054324 (2014)

H. Yamaguchi et al. / Physics Letters B 766 (2017) 11





^{10}Be+^{4}He @ LNS



Existence of molecular α-chain configuration to be confirmed.
The hunting continues!

Summary

- Existence of linear chain configuration and exotic cluster configurations are predicted by AMD calculations in n-rich C and B isotopes respectively.

- Resonant scattering of light nuclei powerful tool to investigate cluster structures.

- Use of extended targets + ToF allows discrimination of reaction processes.

- Important precise knowledge of stopping power. Measured stopping power used in the present analysis.

- ^{9}Li+^{4}He excitation function shows presence of structures at high excitation energy. Possible ^{13}B α-cluster states? R-Matrix analysis is being performed.

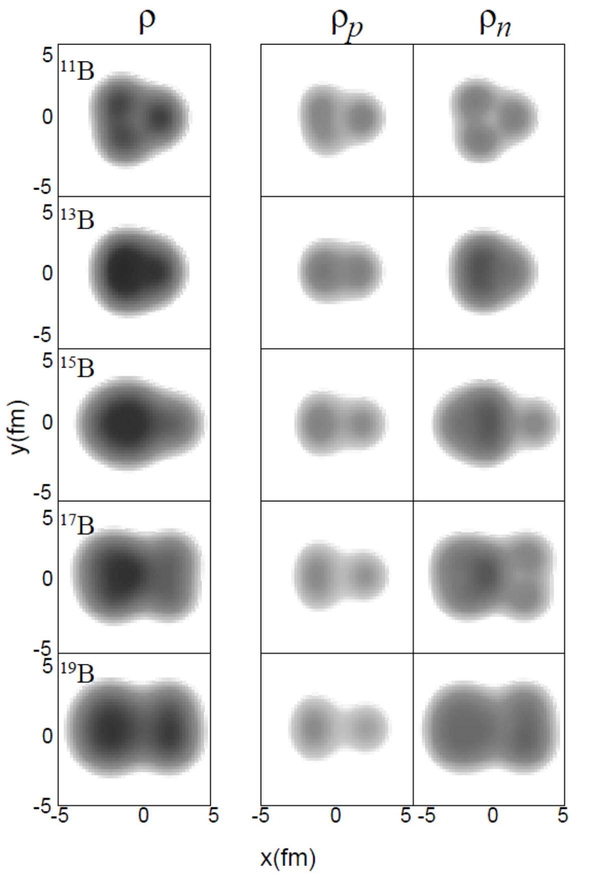
- ^{10}Be radioactive beam developed at LNS with intensity typical of stable beams.

- Previous measurement of ^{10}Be+^{4}He excitation function disagree on the role of inelastic excitation of ^{10}Be. Inelastic contribution as large as elastic at 0^0. Spectroscopic information need to be re-derived.

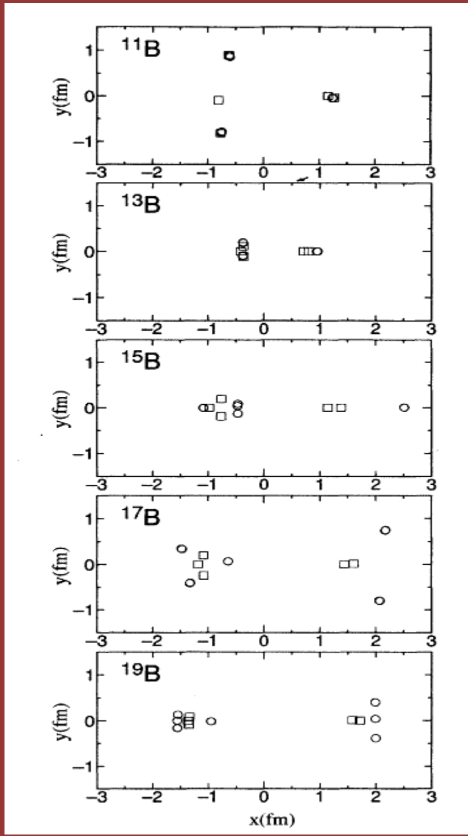
Exotic clustering: B isotopes

In n-rich nuclei the condition that the cluster must be a stiff particle (e.g α particle) is dropped .
Antisymmetrized Molecular Dynamics calculations (AMD) predicts the existence of cluster configuration of Li-He type in B isotope.

B isotopes density distribution



Center wave function spatial distribution



→ ^{7}Li – α structure

H. Yamaguchi et al.PRC 83, 034306 (2011)

→ N=8 shell closure

Well developed di-nuclear structure

^{11}Li-^{8}He

Y. Kanada-En'yo and H. Horiuchi Prog. Theor. Phys. Supp.142(2001)205 and Kanada En'yo et al PRC 52 (1995) 647