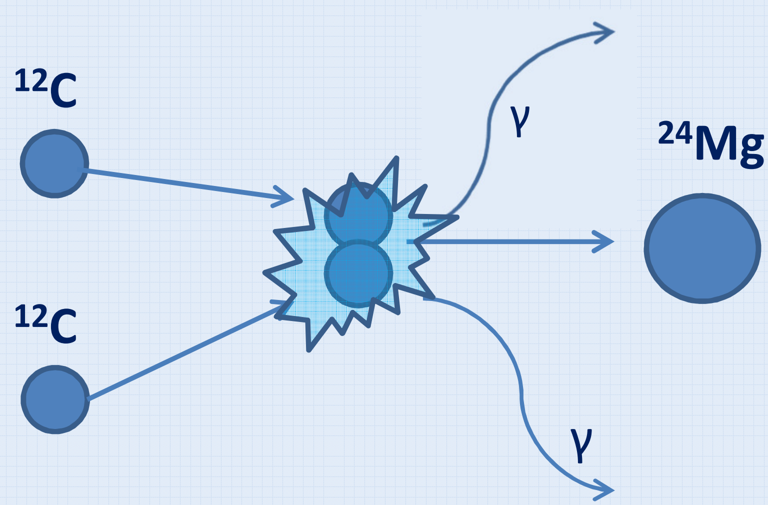
Insight into the ^{24}Mg excited states located in Gamow window for carbon - carbon burning



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Collaborators

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Motivation

- Objective: search for $^{12}C+^{12}C$ resonances at the ^{24}Mg excitations 15-20 MeV and their full characterization: excitation energy, width, spin, parity, partial decay widths
- Two-fold reason: nuclear structure & astrophysical motivation
- Work in progress, data analysis is not finished yet

Important new result is even observation of the 0^+ state at these excitations with prominent cluster structure – large probability for decay into $\alpha+^{20}Ne$

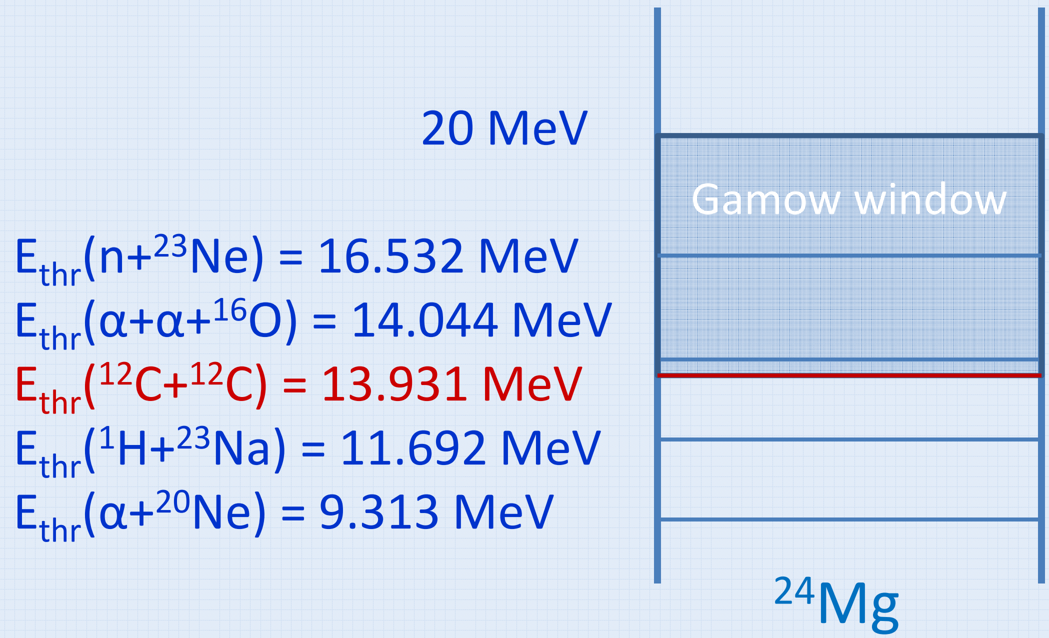
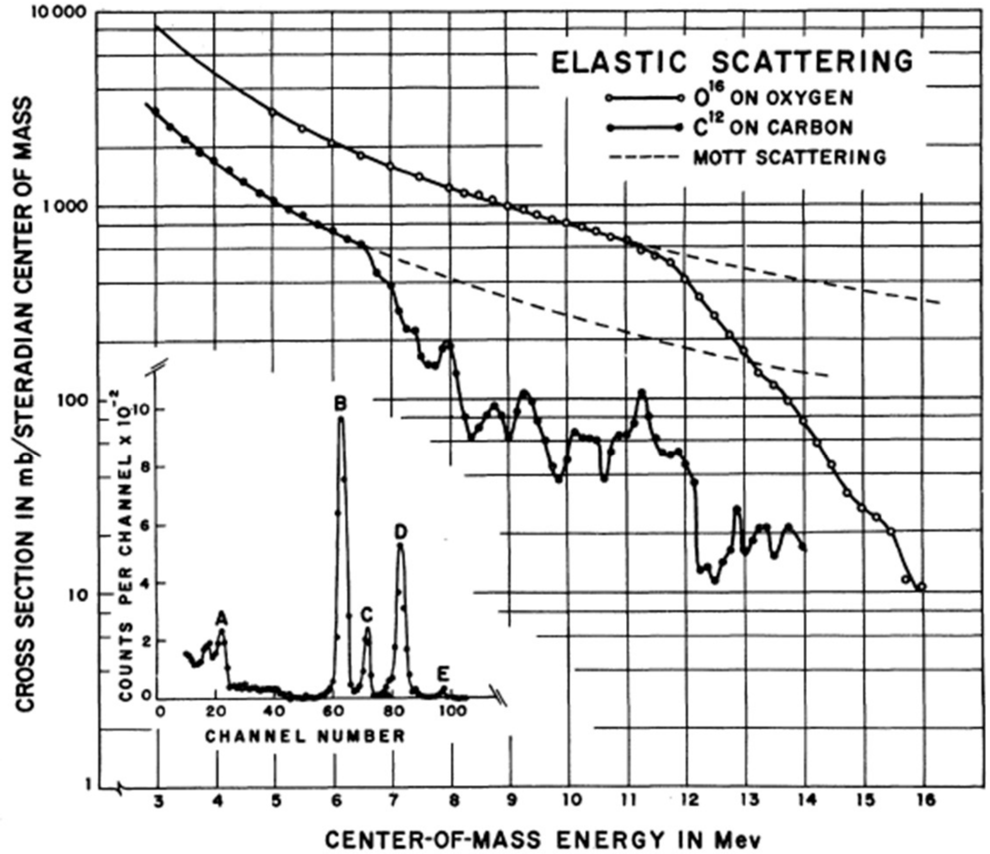


FIG. 1. Excitation curves for the elastic scattering of C^{12} by carbon and of O^{16} by oxygen. Self-supporting targets of carbon (~50μg/cm^2) and of SiO (~70μg/cm^2) and 5×5 mm Au-Si detectors, have been used in these measurements. The inset figure is a typical spectrum at $\theta_{lab} = 45°$ obtained for 21.0-Mev carbon ions on carbon. The peak legend is as follows: the double peak at *A* arises from alpha particles and protons from the reaction which completely traverse the junction and thus provide a measure of its thickness. *B* is from C^{12} elastically scattered by carbon; *C* is for C^{12} elastically scattered by oxygen; *D* is from C^{12} elastically scattered by a residual phosphorous contaminant from the stripping compound used in preparing the target, and *E* is from C^{12} elastically scattered from traces of heavier target contaminants.



365

D. A. Bromley, J. A. Kuehner, E. Almquist, Phys. Rev Lett 4 (1960) 385

Elastic scattering data
Resonant phenomena
in heavy ion reaction

E. Almquist, D. A. Bromley, J. A. Kuehner, Phys Rev Lett 4 (1960) 515

Reaction data

Formation of quasi-molecular states in ^{24}Mg

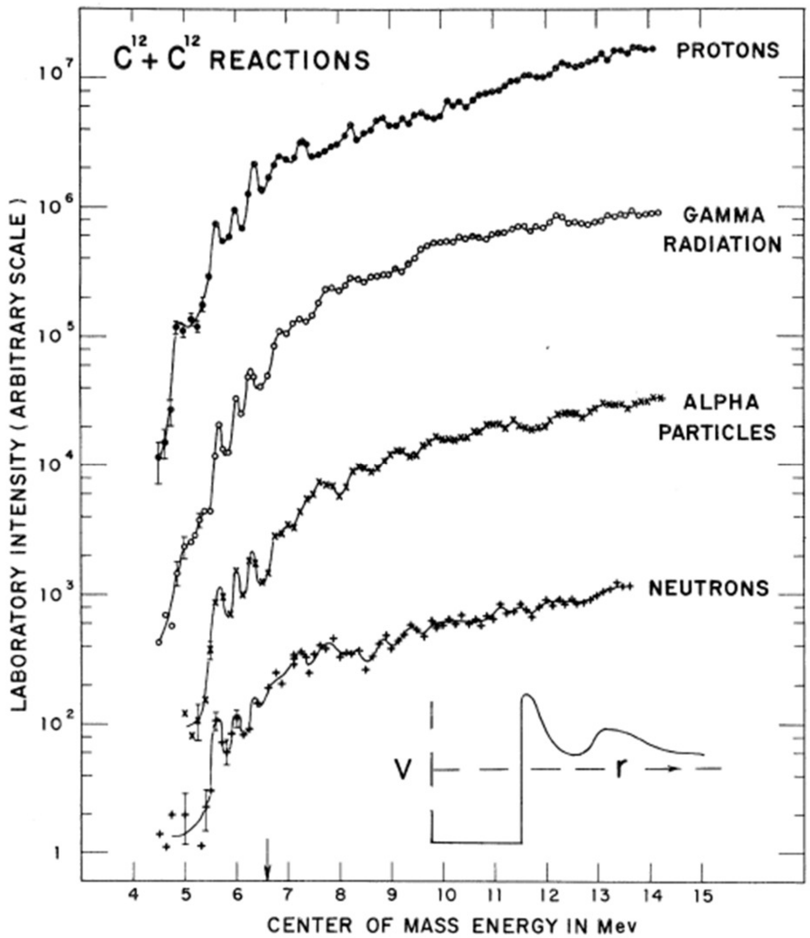


FIG. 1. Excitation curves for C^{12} on carbon reactions: protons at 27°, alpha particles at 42°, neutrons at 30°, and gamma radiation at 90°. The magnitudes of the corresponding differential cross sections (laboratory system) at 10 Mev (c.m. system) incident energy are: protons – 15 mb/sr, alpha particles – 34 mb/sr, and neutrons – 3 mb/sr. These cross sections refer to protons > 6 Mev laboratory energy, alpha particles > 7.5 Mev, and all neutrons. Detectors were, respectively: Si $p-n$ junctions (reference 2) covered by 0.007 inch of Al for protons, Au-Si surface barrier detectors (reference 2) covered by 0.001-inch Al for alpha particles, long counter of Hanson-McKibbon type for neutrons, and NaI crystal detectors biassed to detect gamma radiation > 2.8 Mev energy. Target was a self-supporting ~40-μg/cm² C foil. Statistical errors are indicated where they are significantly larger than the points. The classical Coulomb barrier is indicated at 6.6 Mev. The inset shows the quasi-molecular potential envisaged.

55 years later:

- number of resonances decaying into various channels
- kind of unique nuclear system, very complex structure
- governed by cluster structure of ^{12}C – oblate deformation in gs
- not fully understood yet

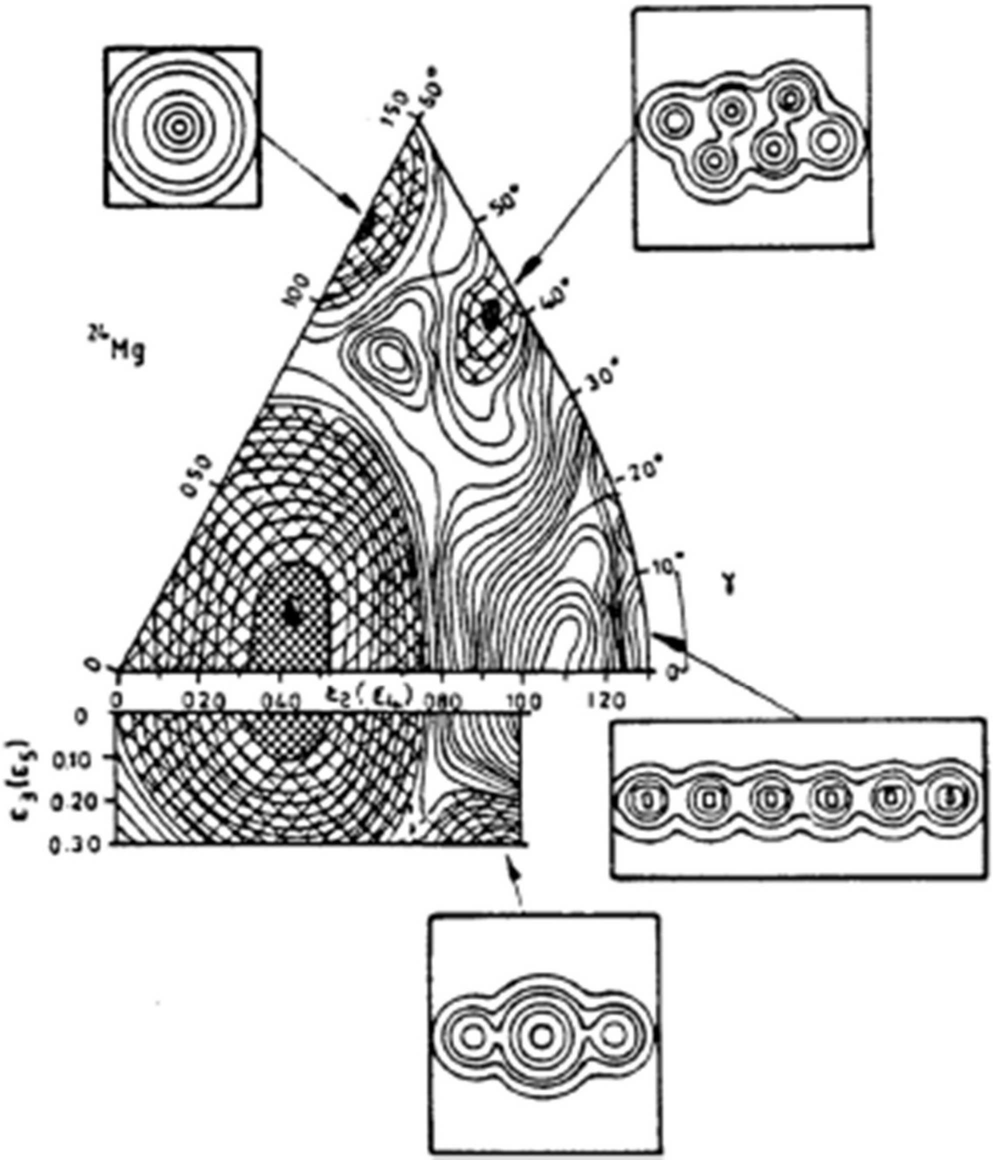
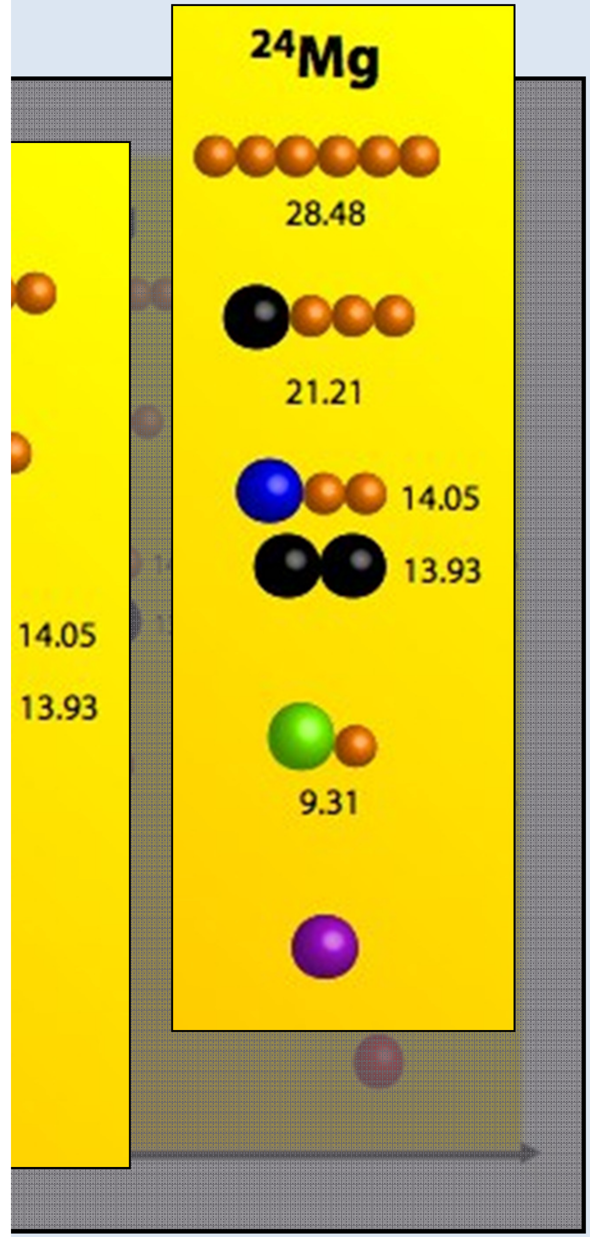
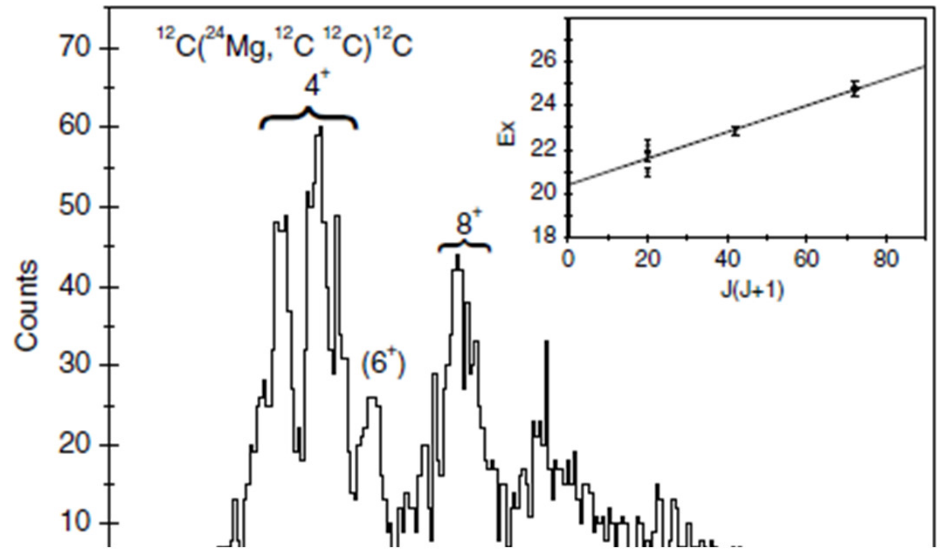


Figure 26. Nilsson–Strutinsky and α-cluster model calculations for ^{24}Mg [50, 88]. The potential energy is shown as a contour plot for the deformation parameters ϵ_2 and γ. Minima are found at particular deformations. For some of the potential minima the shapes obtained with the α-cluster model are indicated. The lower part shows the potential energy for the extension to octupole shapes with the parameter ϵ_3.



B. R. Fulton et al, Phys Lett B 267 (1991) 325

M. Freer et al, Phys Rev C 57 (1998) 1277
C. Metelko et al, Phys Rev C 68 (2003) 054321



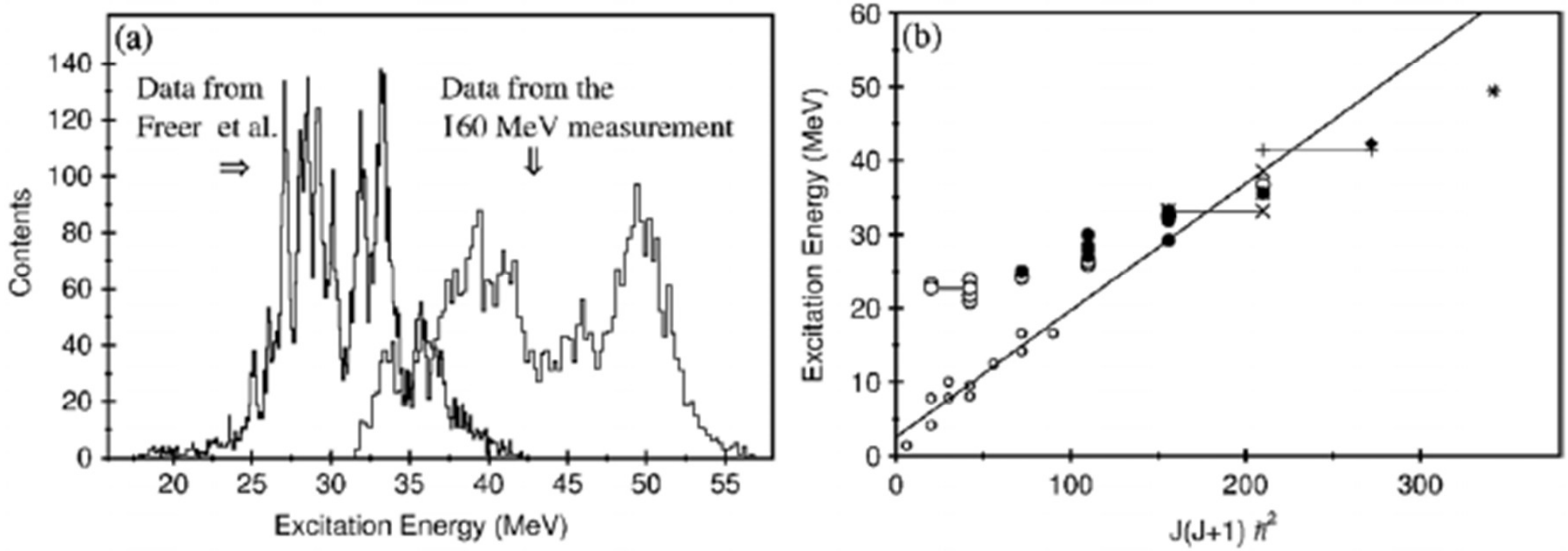


Figure 42. (*a*) Resonances observed in the $^{12}C(^{16}O,^{24}Mg^{*})$ breakup reaction [147, 148]. (*b*) The energy-spin systematics of the breakup resonances, from [148]. The smaller symbols and the solid line indicates the trend of the yrast states in ^{24}Mg.

T. Kawabata et al,

J. Phys. Conf. Ser. 436, 012009 (2013)

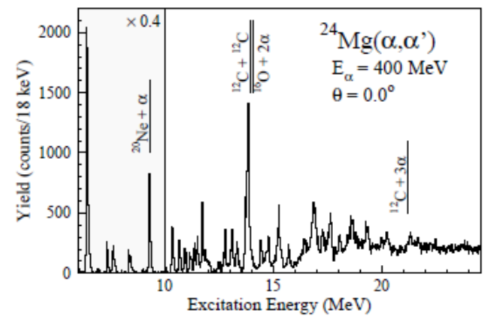


Figure 1. Typical spectrum for the $^{24}Mg(\alpha,\alpha')$ reaction measured at 0°. The excitation spectrum below $E_x = 10$ MeV is downscaled by a factor of 0.4.

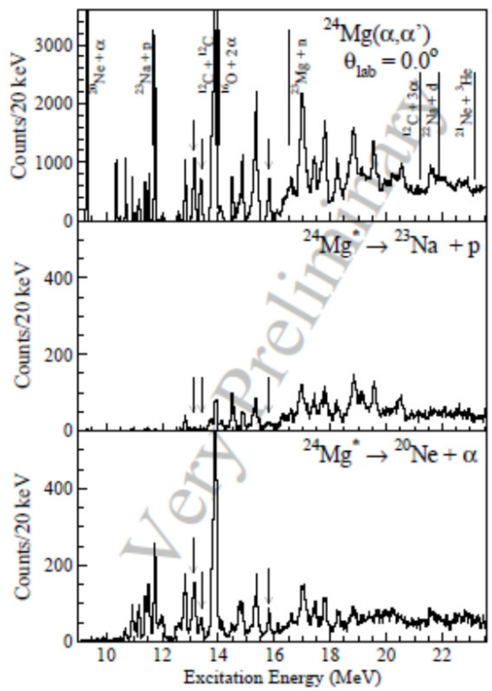


Figure 4. Excitation energy spectra in the $^{24}Mg(\alpha,\alpha')$ reaction at E_x = 9–23.6 MeV taken from the singles measurement (top) and from the coincidence measurements with decay protons (middle) and α particles (bottom). The vertical arrows show the 0^+ states at 13.1, 13.4, and 15.8 MeV.

The 13.1, 13.4 and 15.8 MeV states have prominent α-cluster structure

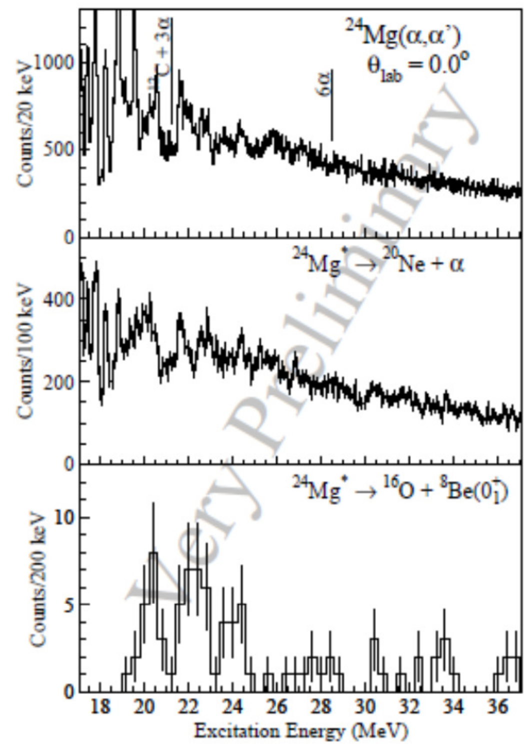


Figure 5. Excitation energy spectra in the $^{24}Mg(\alpha,\alpha')$ reaction at E_x = 17.1–37.1 MeV taken from the singles measurement (top) and from the coincidence measurements with decay α particles (middle) and ^{8}Be (bottom).

- Y. Chiba and M. Kimura, PRC 91, 061302(R) (2015)
- antisymmetrized molecular dynamics combined with the generator coordinate method

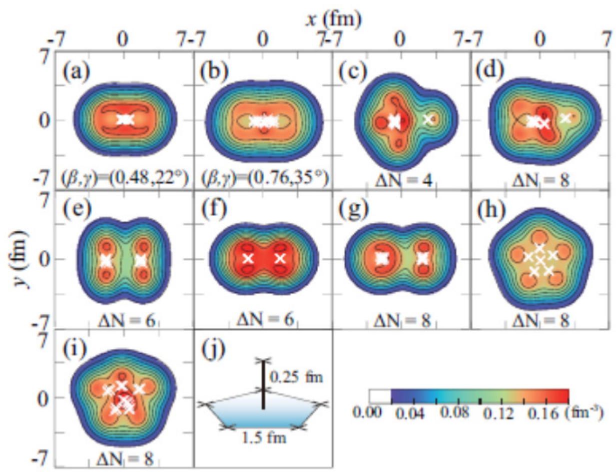


FIG. 1. (Color online) (a)–(i) Intrinsic density distributions at the $z = 0$ plane obtained by constraints on the matter quadrupole deformation parameters [(a) and (b)] and the expectation values of the harmonic oscillator quanta [(c)–(i)]. The crosses in each figure show the centroids of Gaussians describing nucleons. The contour lines are plotted in intervals of 0.02 fm^{-3}. (j) The geometry of 6α particles, in which the crosses represent the centroids of Gaussians describing α particles.

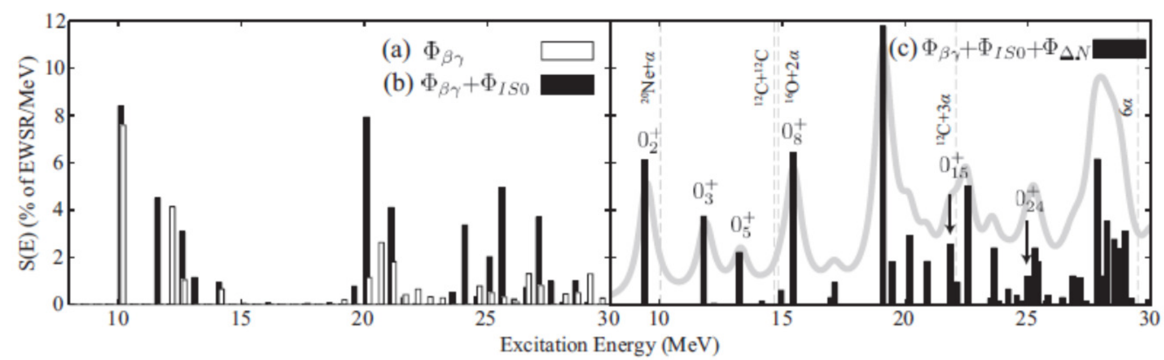


FIG. 2. The isoscalar monopole transition strength functions calculated with the basis sets (a) $\Phi_{\beta\gamma}$, (b) $\Phi_{\beta\gamma} + \Phi_{IS0}$, and (c) $\Phi_{\beta\gamma} + \Phi_{IS0} + \Phi_{\Delta N}$. The solid line in the right panel shows the strength function smeared by a Lorentzian with 0.8 MeV width. The vertical dashed lines indicate cluster decay threshold energies which are located at the observed binding energies.

The ^{24}Mg ground state has significant cluster components ^{4}He+^{20}Ne and ^{12}C+^{12}C
The ^{12}C+^{12}C configuration contributes to the O_2^+, O_3^+, O_5^+, and is the main component of the O_8^+ state at 15.3 MeV

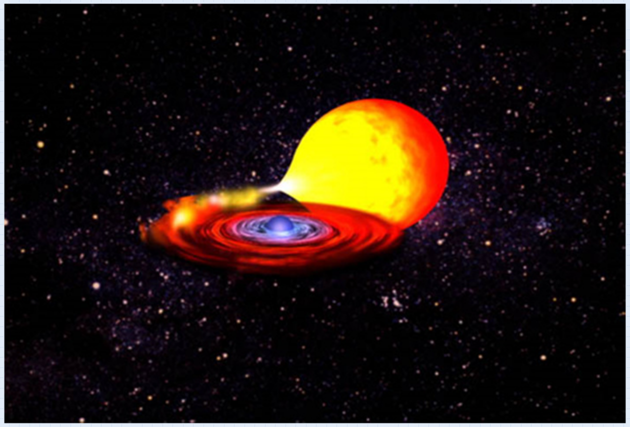
Explosive phenomena in binary systems

SNIa: initiates thermonuclear runaway on white dwarf

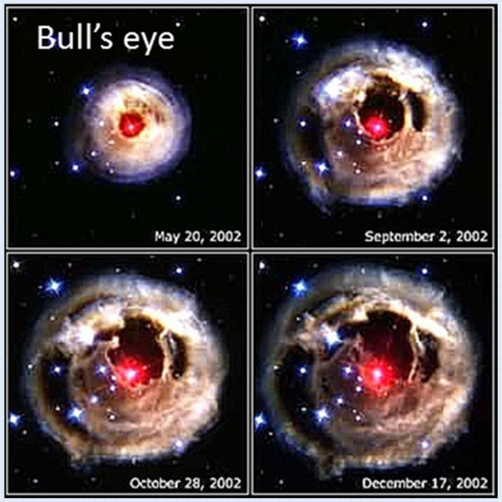
temperature 0.5 - 1.2x10^9 K → E_{cm}=1.5-3.3 MeV

Super-bursts: trigger of ^{12}C ignition

up to 2.5x10^9 K - 5.7 MeV



Stellar outbursts



Massive stars:^{12}C+^{12}C fusion is differentiating between the evolutionary paths leading to either white dwarf or heavy elements burning stages

Super-AGB stars

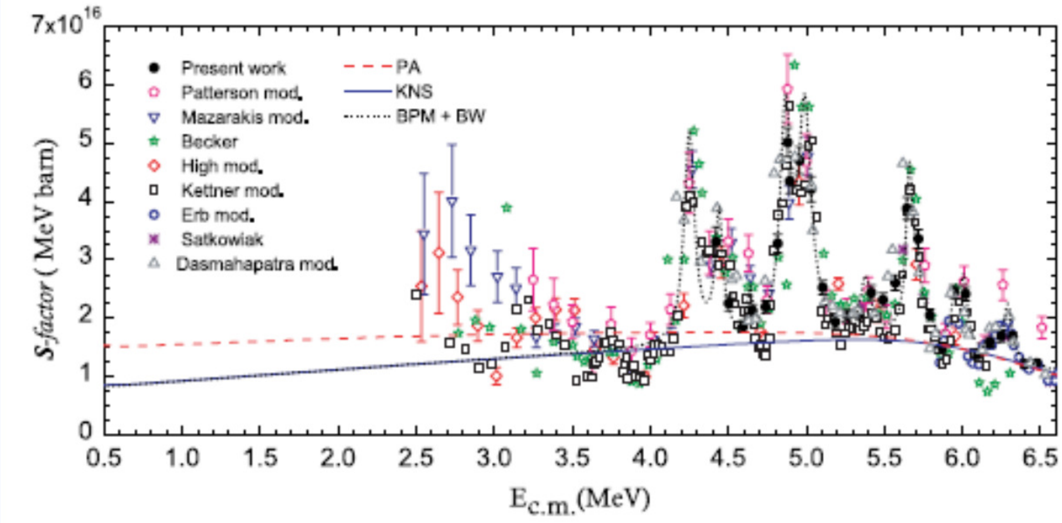
Relevant reactions:

$^{12}C + ^{12}C \rightarrow ^{24}Mg + \gamma$

$^{12}C + ^{12}C \rightarrow ^{20}Ne + \alpha$

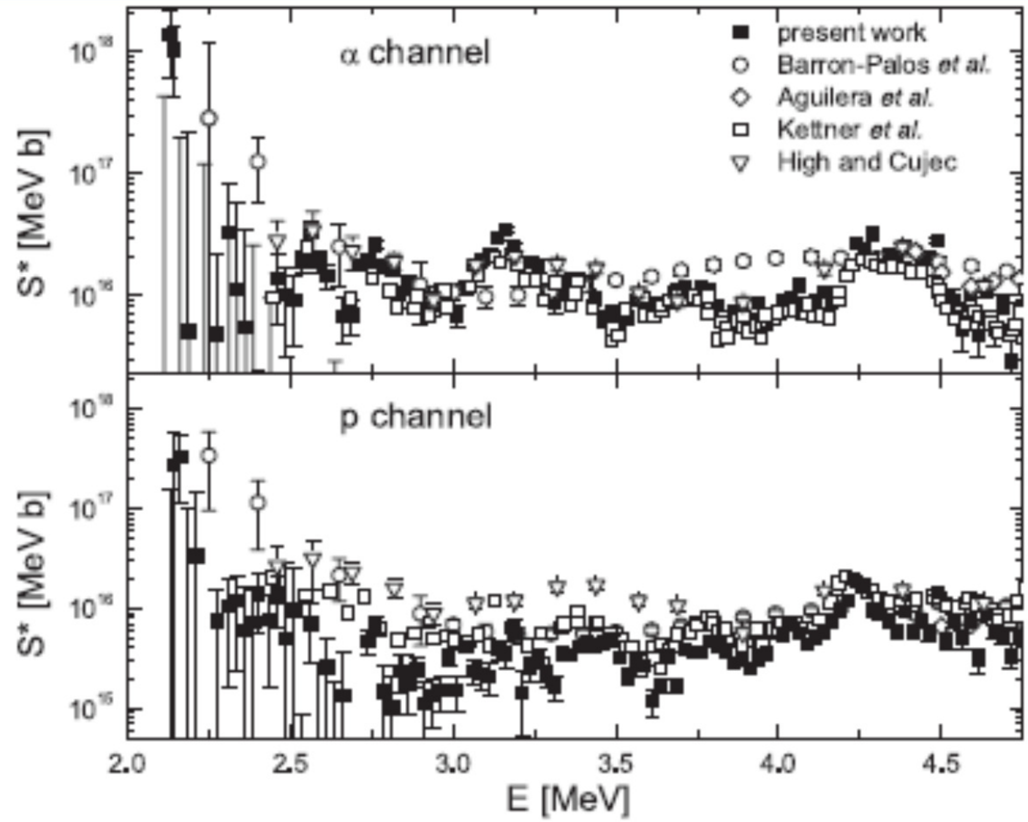
$^{12}C + ^{12}C \rightarrow ^{23}Na + p$

$^{12}C + ^{12}C \rightarrow ^{23}Mg + n$



E. F. Aguilera et al, Phys. Rev. C 73 (2006) 064601

T. Spillane et al, Phys. Rev. Lett. 98 (2007) 122501



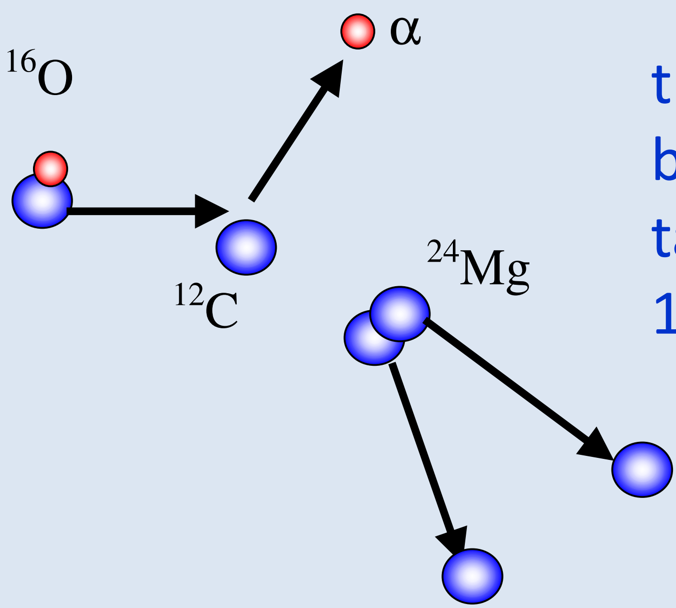
Existing data show large discrepancies

Low energy resonance ?

Experiment at INFN – LNS

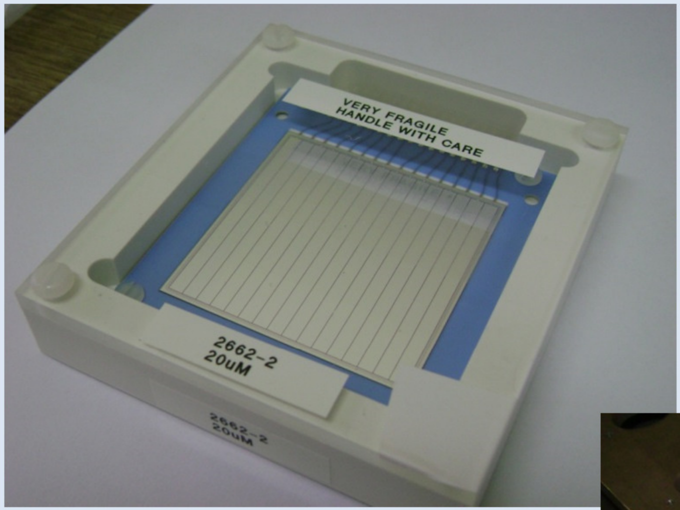
Coincident detection of 2 (or more) reaction products

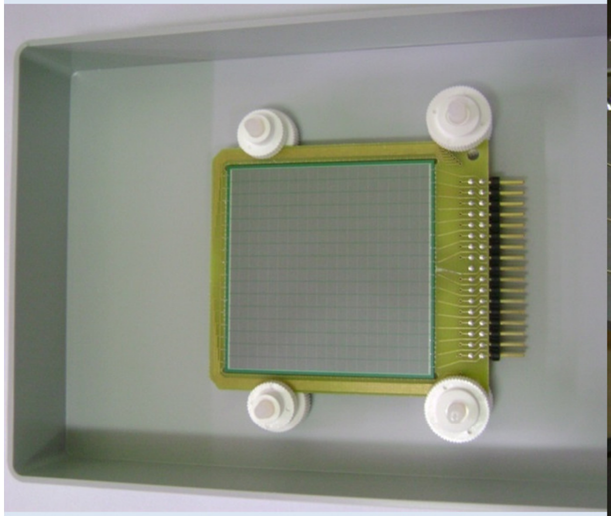
$^{12}C + ^{16}O \rightarrow ^{4}He + ^{12}C + ^{12}C$	Q=-7.16 MeV	$E_{thr}(^{24}Mg)$=13.93 MeV
$\rightarrow ^{4}He + ^{16}O + ^{8}Be$	Q=-7.37 MeV	$E_{thr}(^{24}Mg)$= 14.14 MeV
$\rightarrow ^{4}He + ^{20}Ne + ^{4}He$	Q=-2.54 MeV	$E_{thr}(^{24}Mg)$= 9.31 MeV
$\rightarrow ^{4}He + ^{23}Na + ^{1}H$	Q=-4.92 MeV	$E_{thr}(^{24}Mg)$= 11.69 MeV



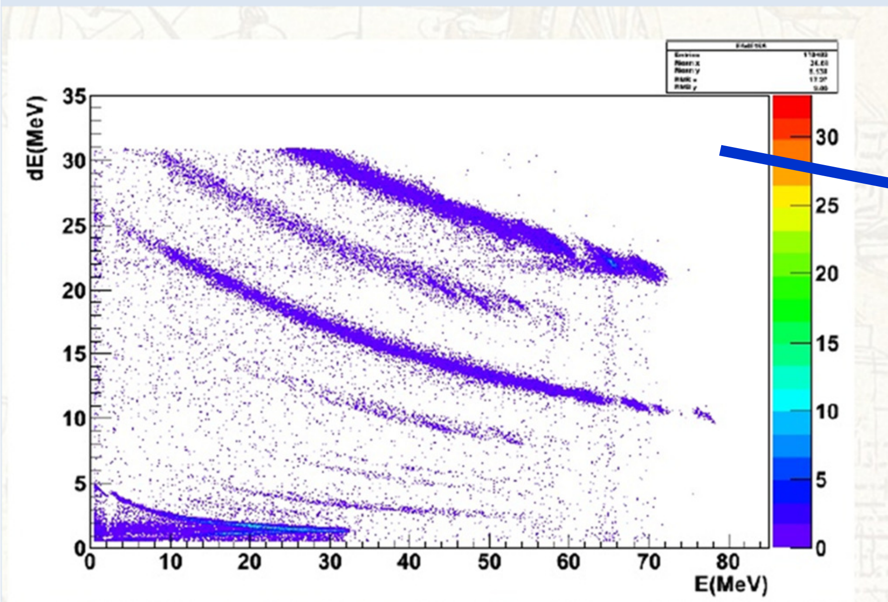
the ^{16}O beam from the tandem accelerator
beam energy 94 MeV
target ^{12}C, thickness of 45 μg/cm^2
11 days of beam-time

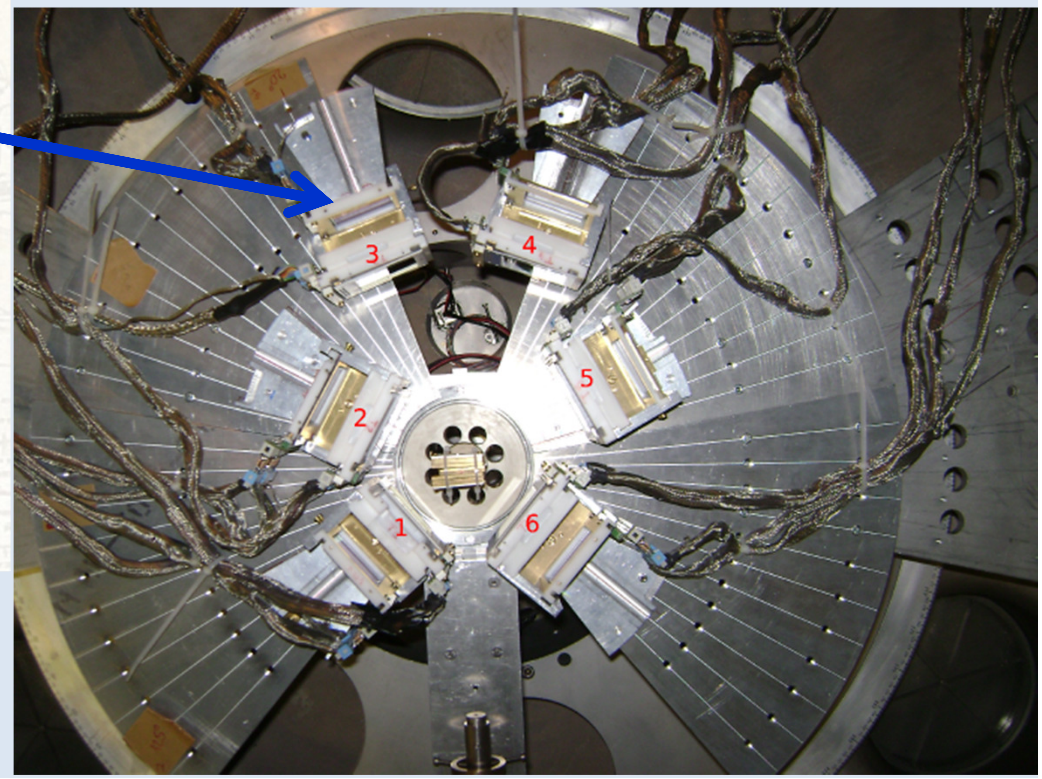
Detector telescopes: 50 x 50 mm^2
20 μm SSSD + 1000/500 μm PSD & DSSD
Particle identification from p to ^{12}C



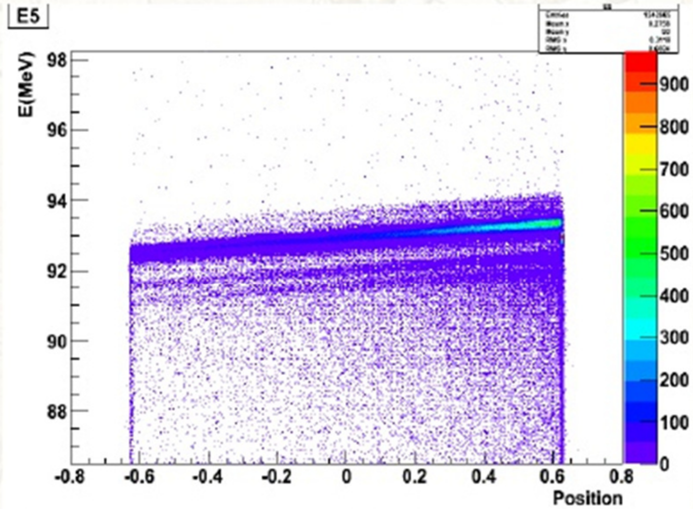


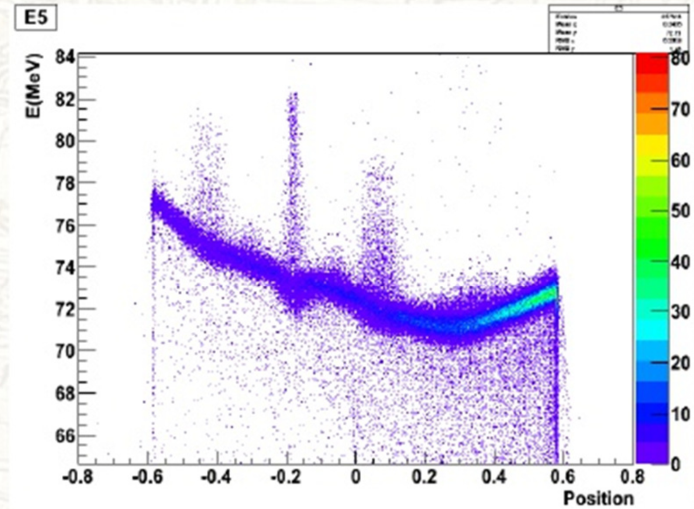
- 1 → PSSSD, d = 500 μm, *theta* = 127.5°, [113°,140°]
- 2 → PSSSD, d = 1040 μm, *theta* = 59.7°, [47°,72°]
- 3 → PSSSD, d = 500 μm, *theta* = 19.0°, [12°,26°]
- 4 → DSSSD, d = 1003 μm, *theta* = 22.2°, [16°,29°]
- 5 → DSSSD, d = 998 μm, *theta* = 63.8°, [55°,73°]
- 6 → PSSSD, d = 500 μm, *theta* = 134.0°, [120°,146°]

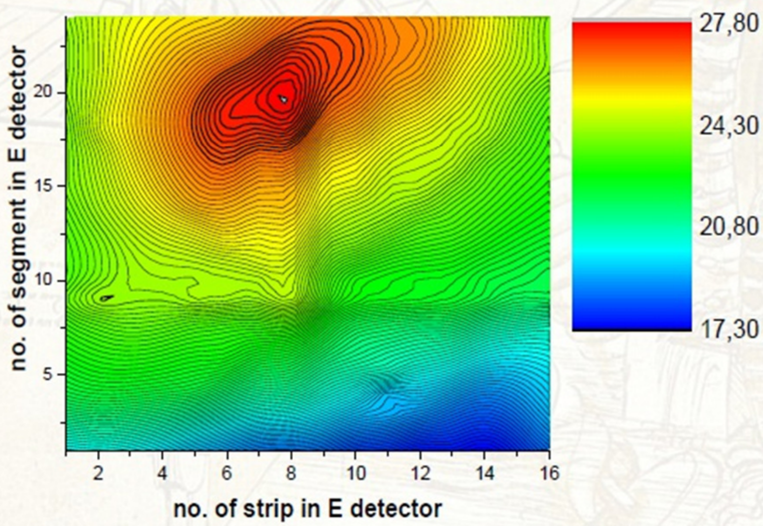


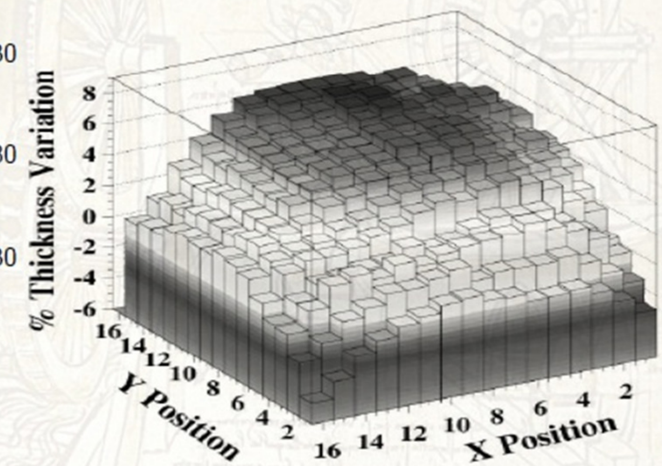


- thickness non-uniformity of thin detectors

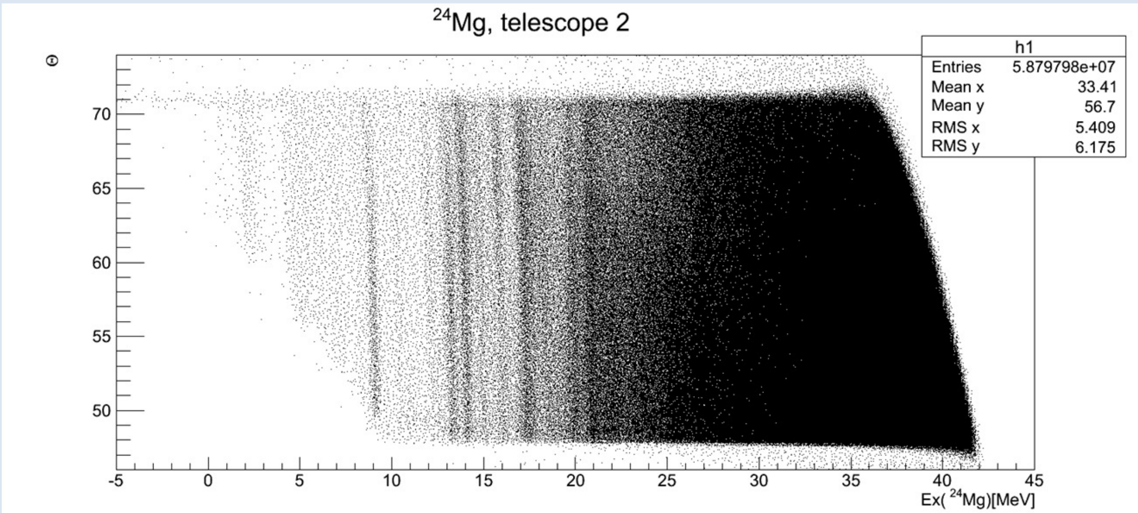


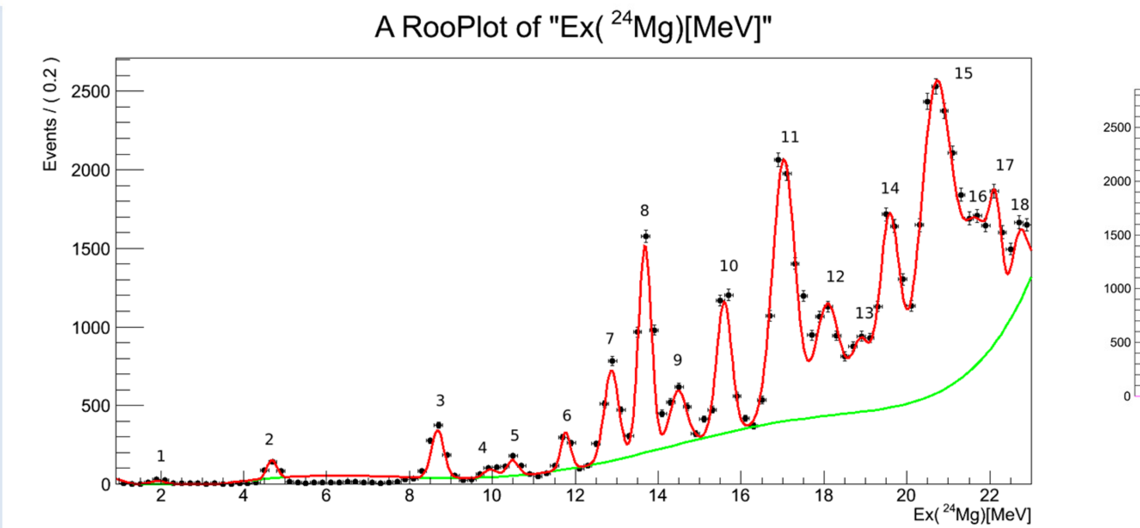




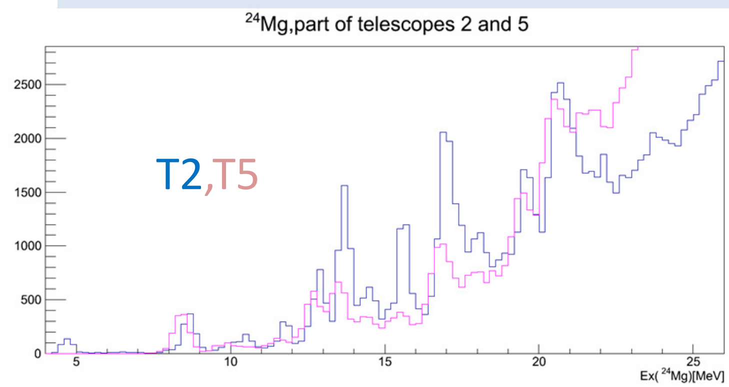


Single events ^{24}Mg spectra



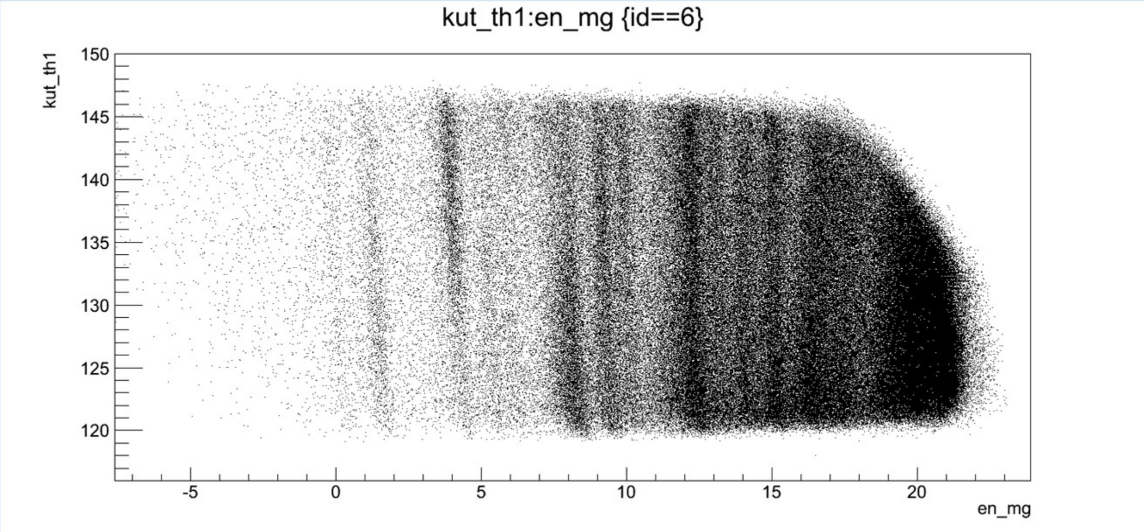


No.	Ex(MeV)	FWHM(MeV)
8.	13.1	0.4
9.	13.9	0.5
10.	15.2	0.5
11.	16.5	0.6
12.	17.4	0.7
13.	18.3	0.5
14.	19.1	0.6
15.	20.2	0.9

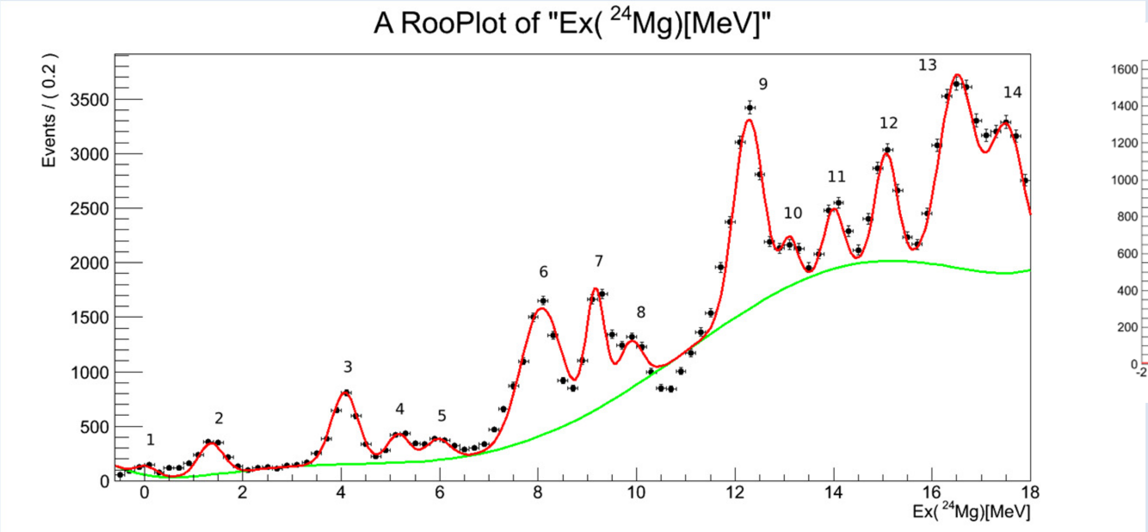


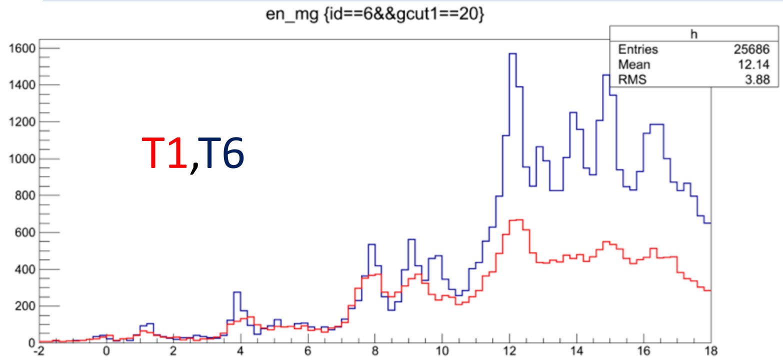
One strip data

Telescope 6



No.	Ex(MeV)	FWHM(MeV)
10.	13.1	0.4
11.	14.0	0.5
12.	15.1	0.5
13.	16.5	0.8
14.	17.5	0.8



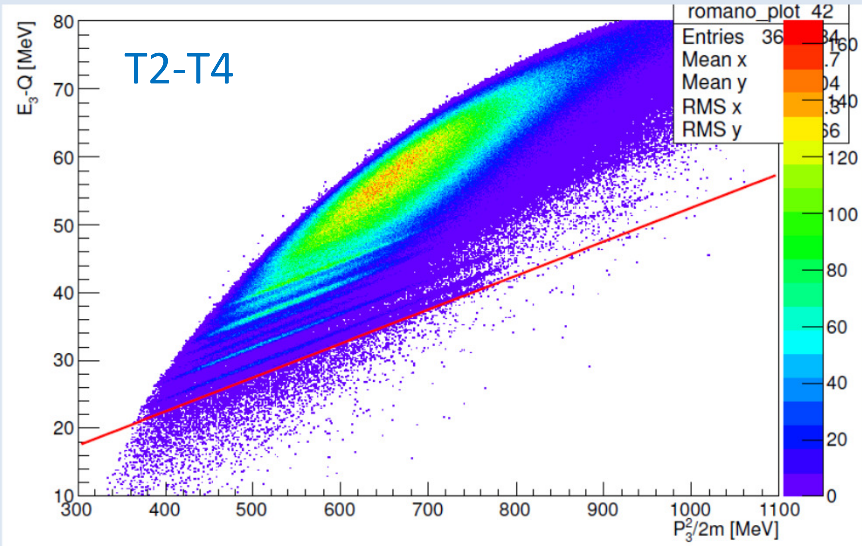


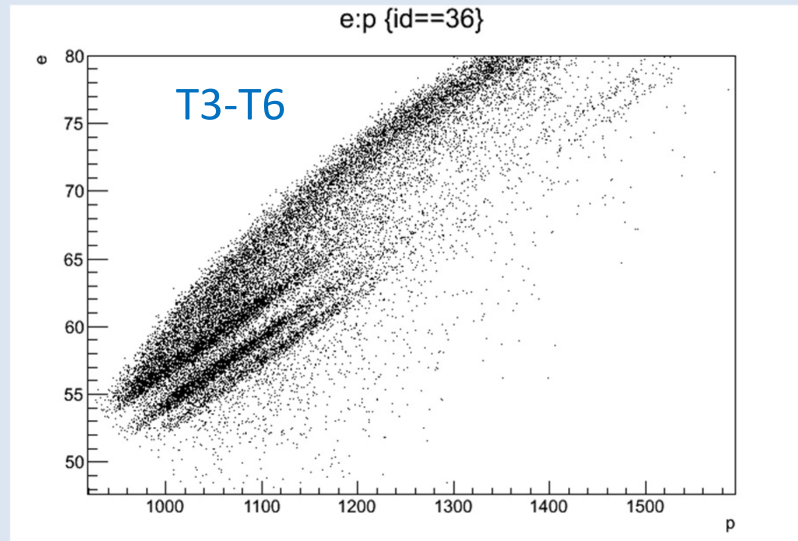
One strip data

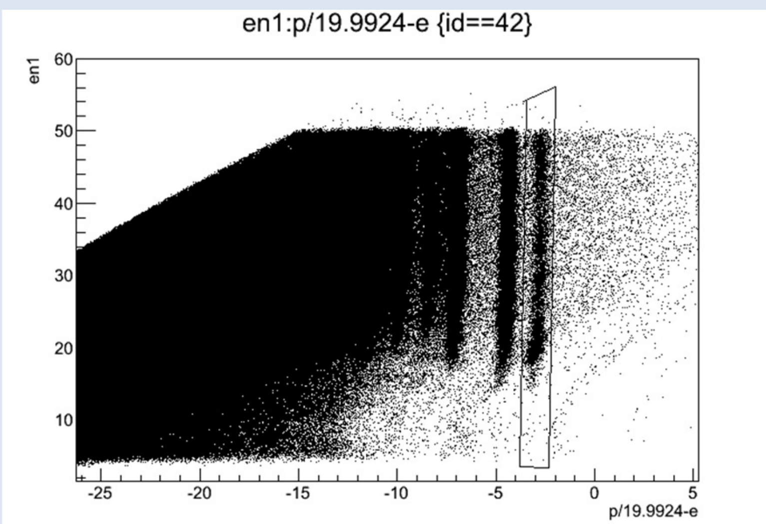
α+^{20}Ne decay

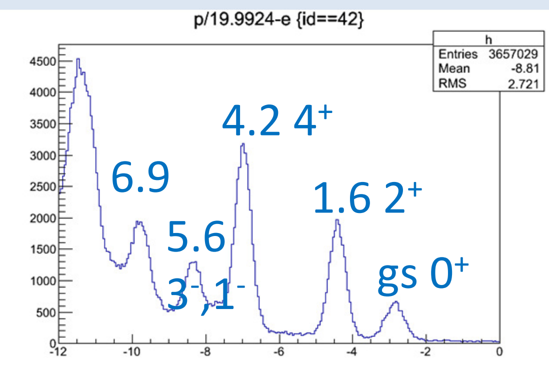
(α-α coincident events)

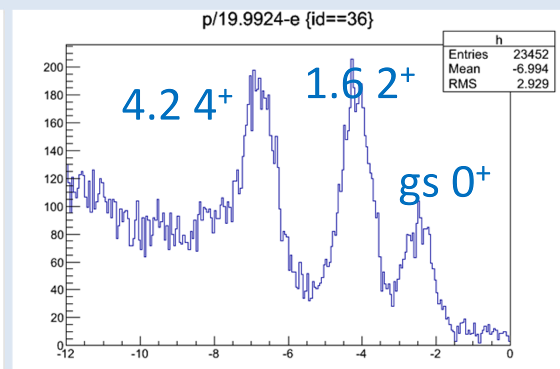
Catania plot: E_3-Q=P_3^2/(2A)



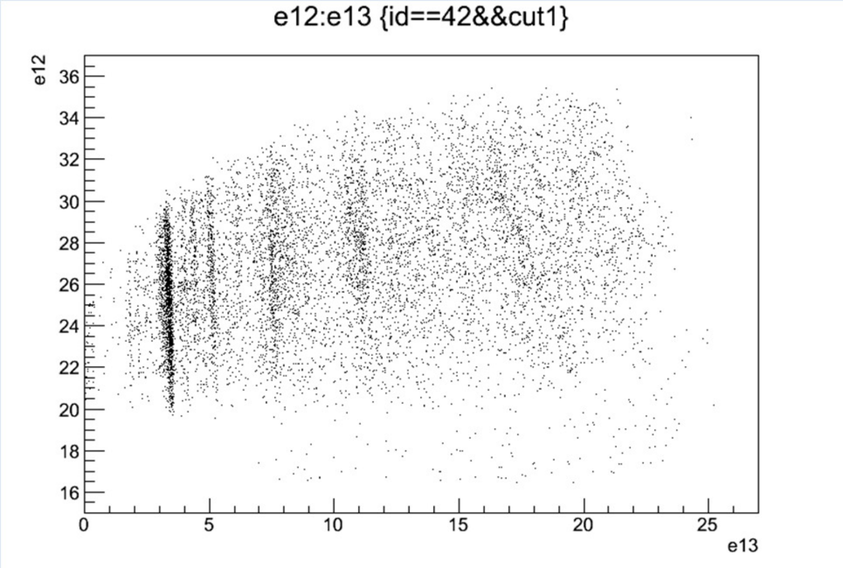


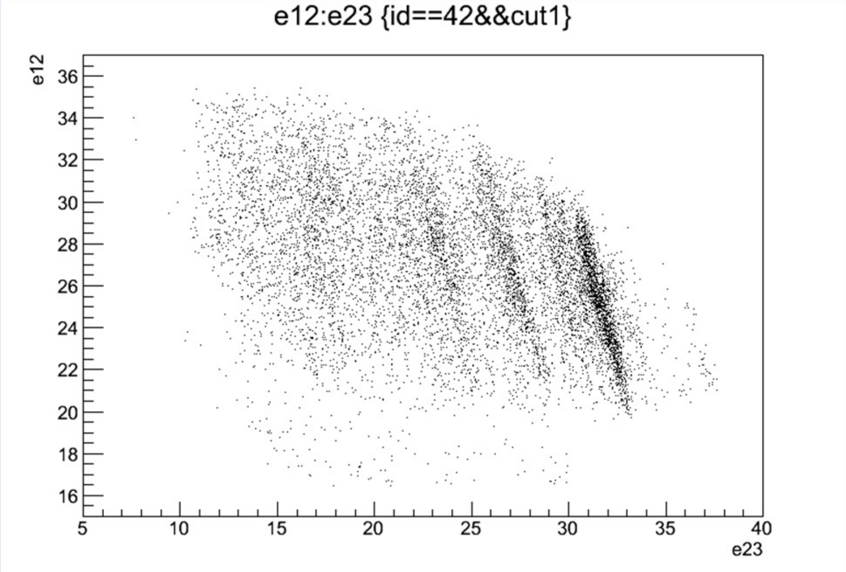


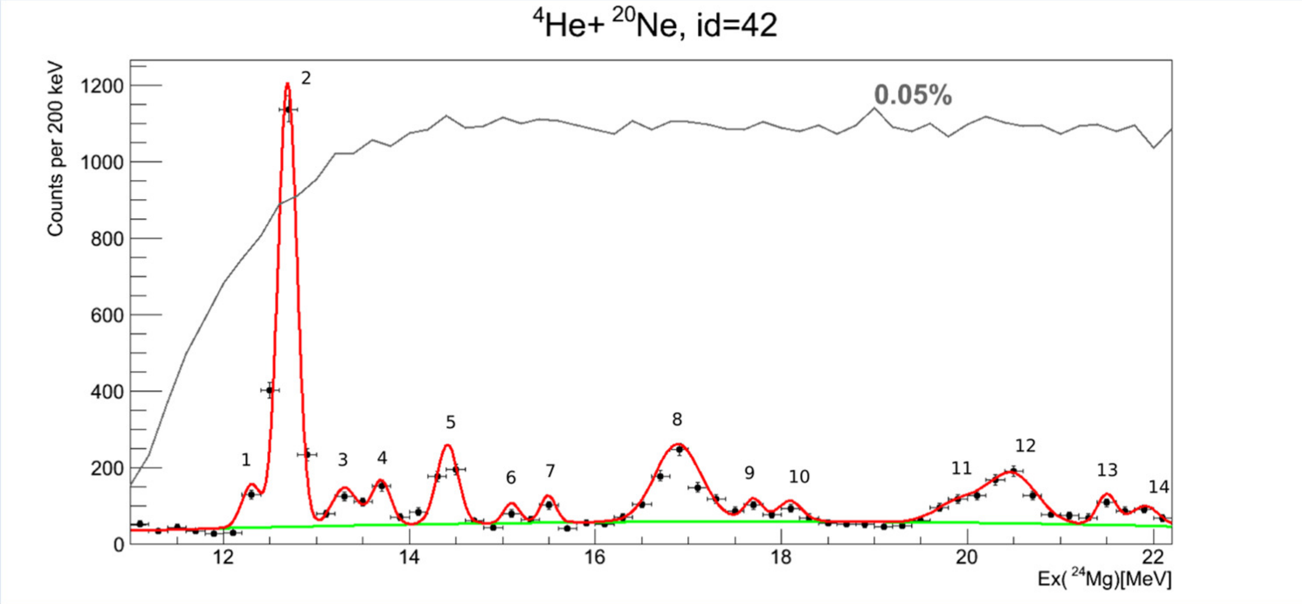




Relative energy plots for the ^{20}Ne ground state decay







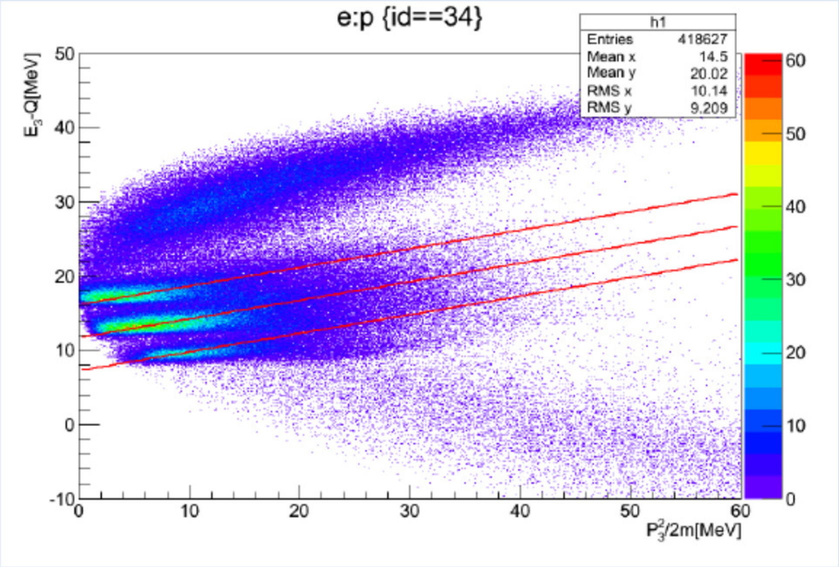
T2-T4

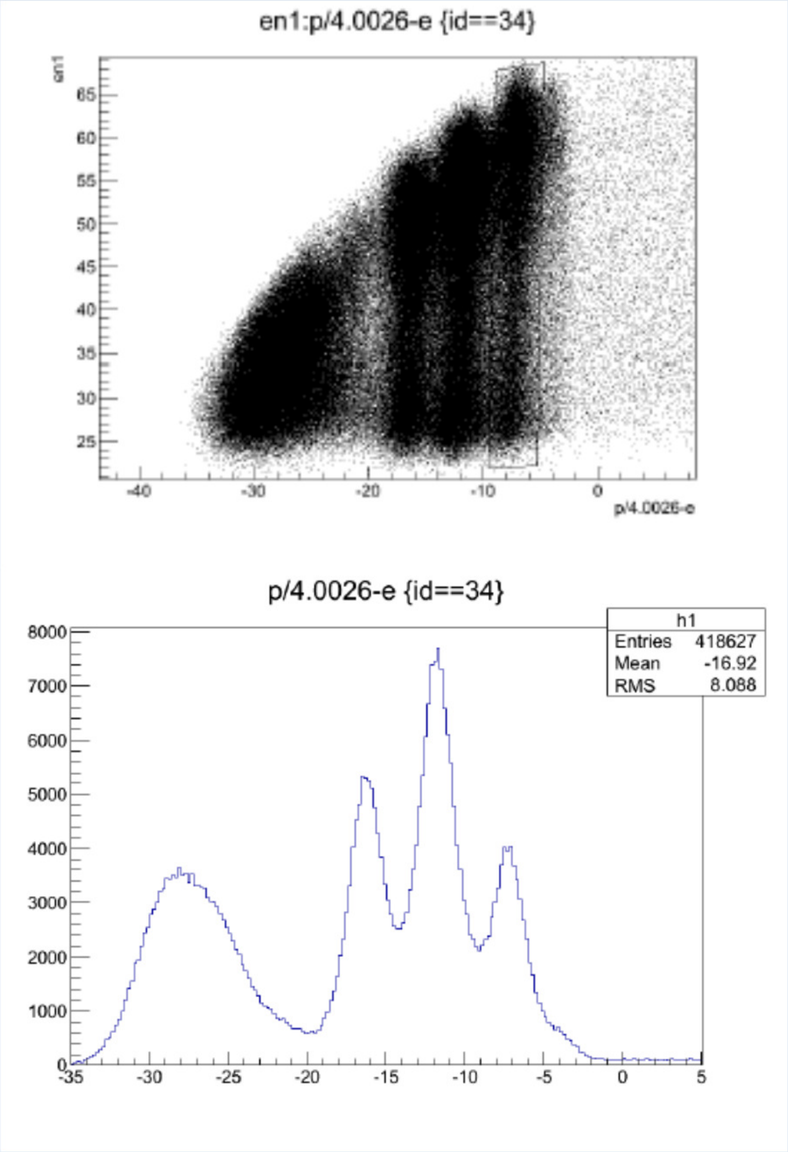
^{4}He+ ^{20}Ne, id=31
0.07%
Counts per 200 keV
Ex(^{24}Mg)[MeV]
^{4}He+ ^{20}Ne, id=32
0.04%
Counts per 200 keV
Ex(^{24}Mg)[MeV]
^{4}He+ ^{20}Ne, id=35
0.04%
Counts per 200 keV
Ex(^{24}Mg)[MeV]
^{4}He+ ^{20}Ne, id=36
0.05%
Counts per 200 keV
Ex(^{24}Mg)[MeV]
^{4}He+ ^{20}Ne, id=41
0.07%
Counts per 200 keV
^{4}He+ ^{20}Ne, id=45
0.03%
Counts per 200 keV
Ex(^{24}Mg)[MeV]
^{4}He+ ^{20}Ne, id=46
0.03%
Counts per 200 keV
Ex(^{24}Mg)[MeV]
^{4}He+ ^{20}Ne, id=25
0.06%
Counts per 200 keV
Ex(^{24}Mg)[MeV]

$^{12}C+^{12}C$ decay

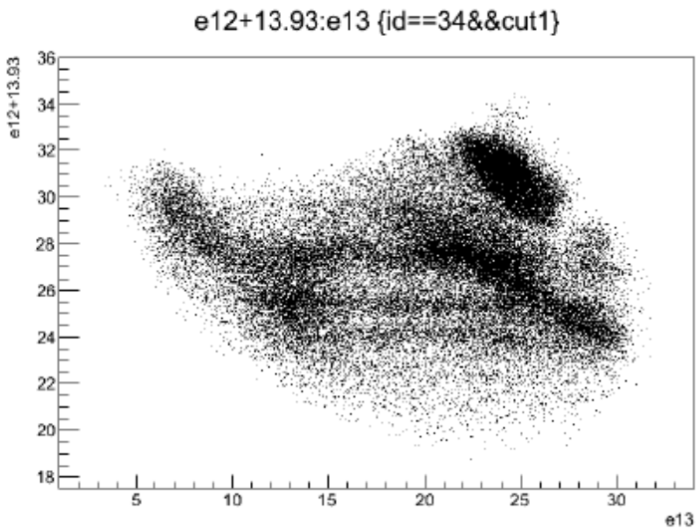
$^{12}C+^{12}C$ coincident events

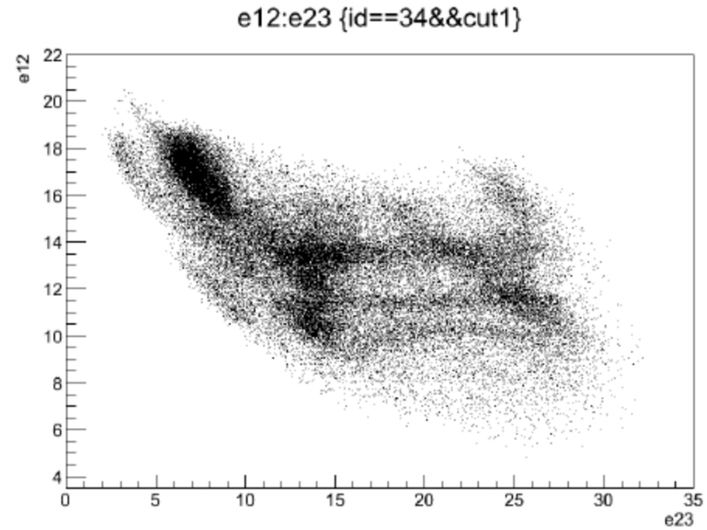
^{12}C detected in T3 & T4 only

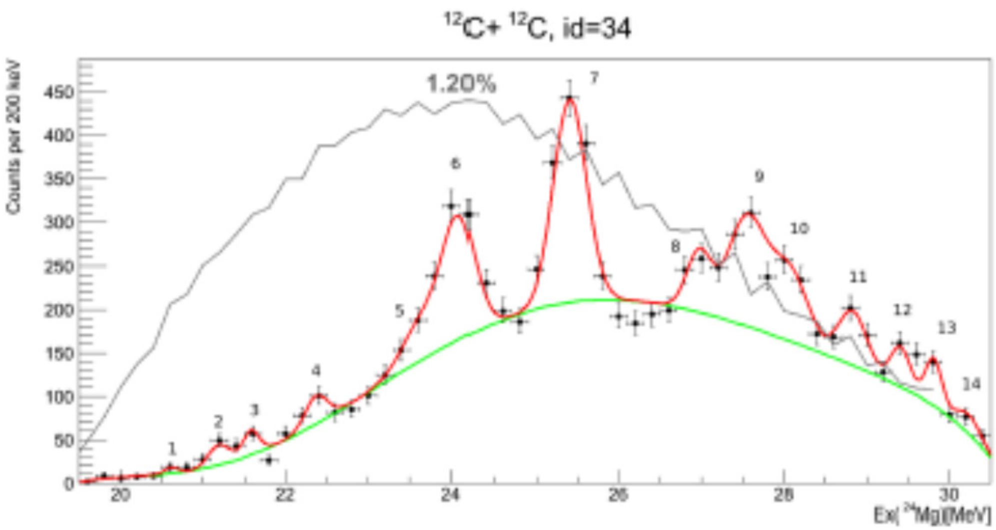




Relative energy plots for the ^{12}C ground state decay

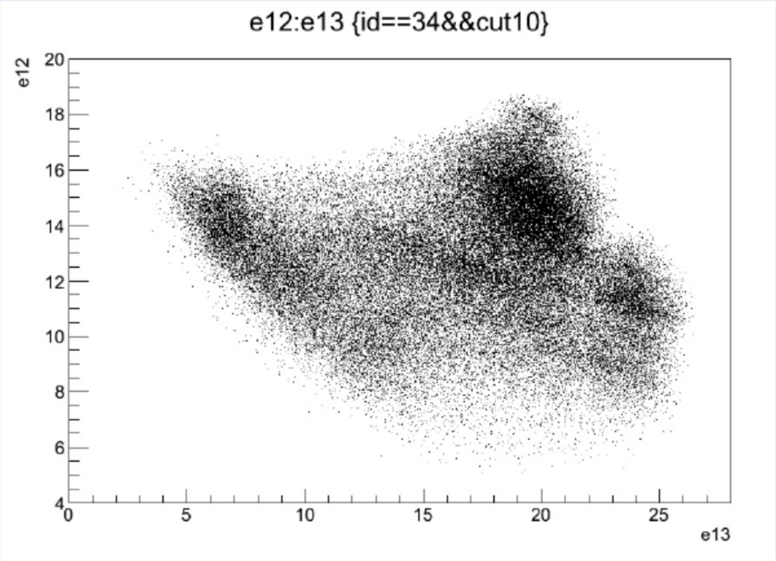


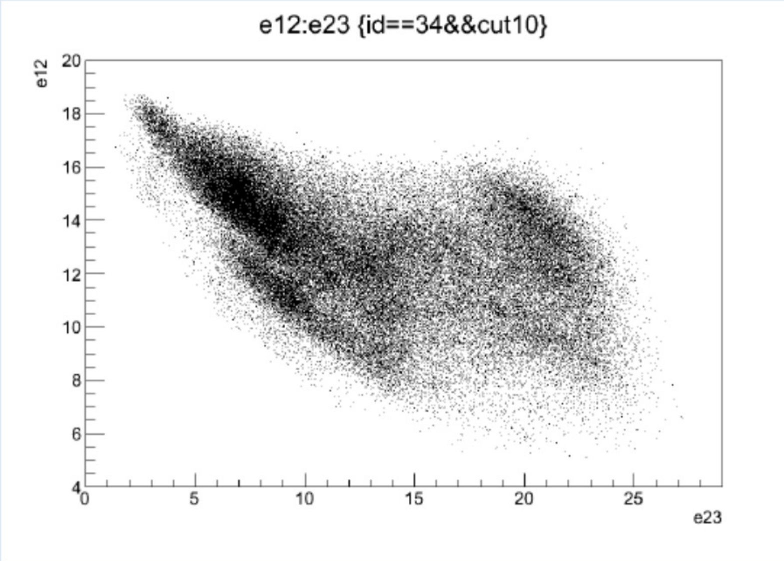


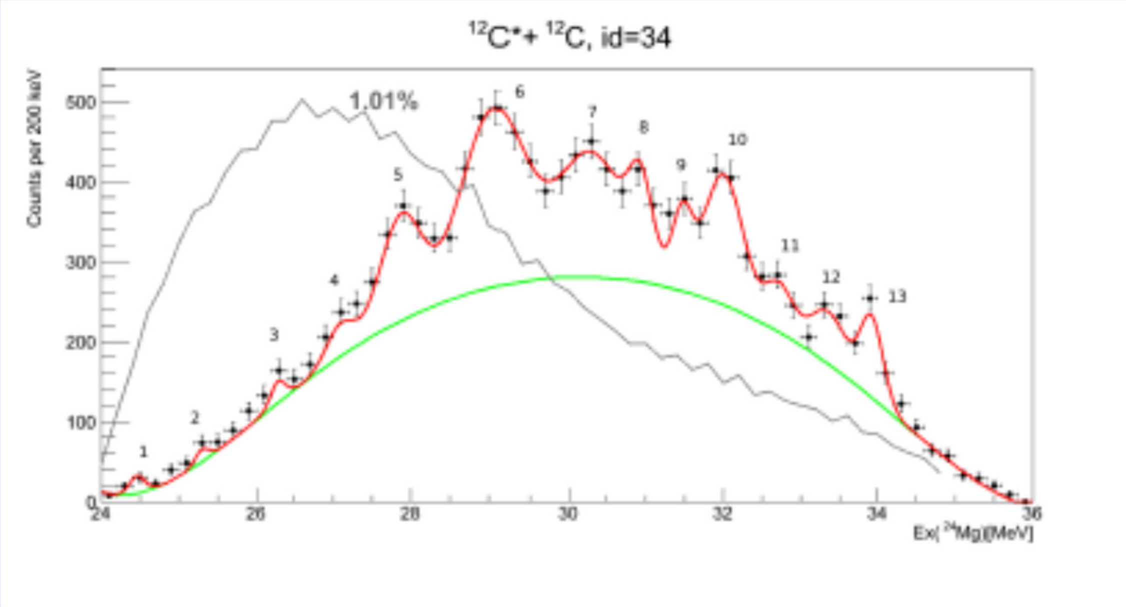


$E_x(^{24}Mg)$: 19.9, 20.9, 21.3, 21.7, 22.7, 23.8, 24.2, 25.6 (25.0+25.9 ?), 27.0, 27.6 (27.0+28.0 ?), 28.0, 28.8 (28.4+29.2 ?), 29.2, 30.4 MeV

Relative energy plots for the $^{12}C+^{12}C^{*}(4.4\ MeV)$ decay

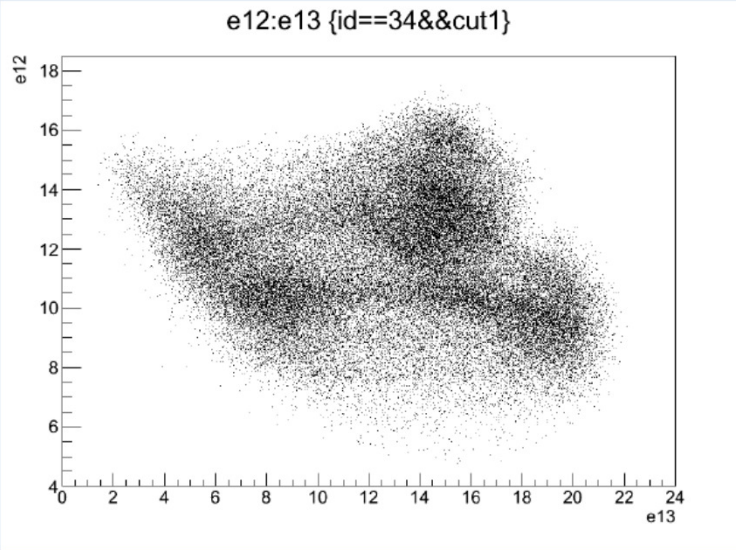


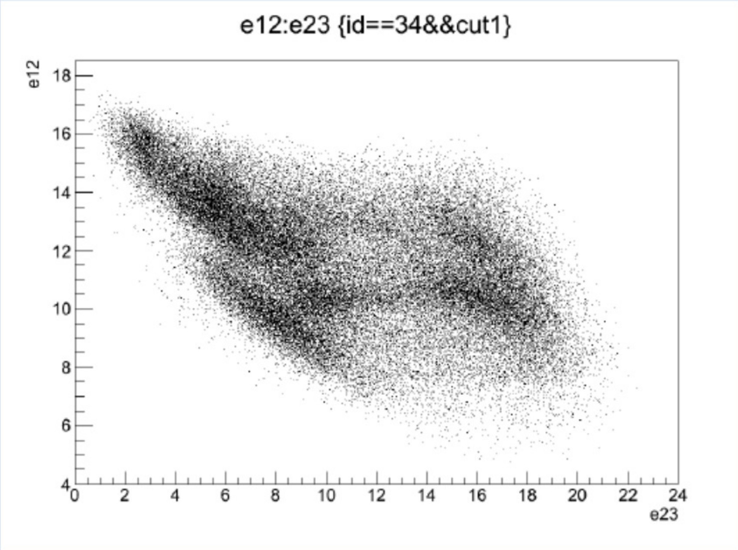


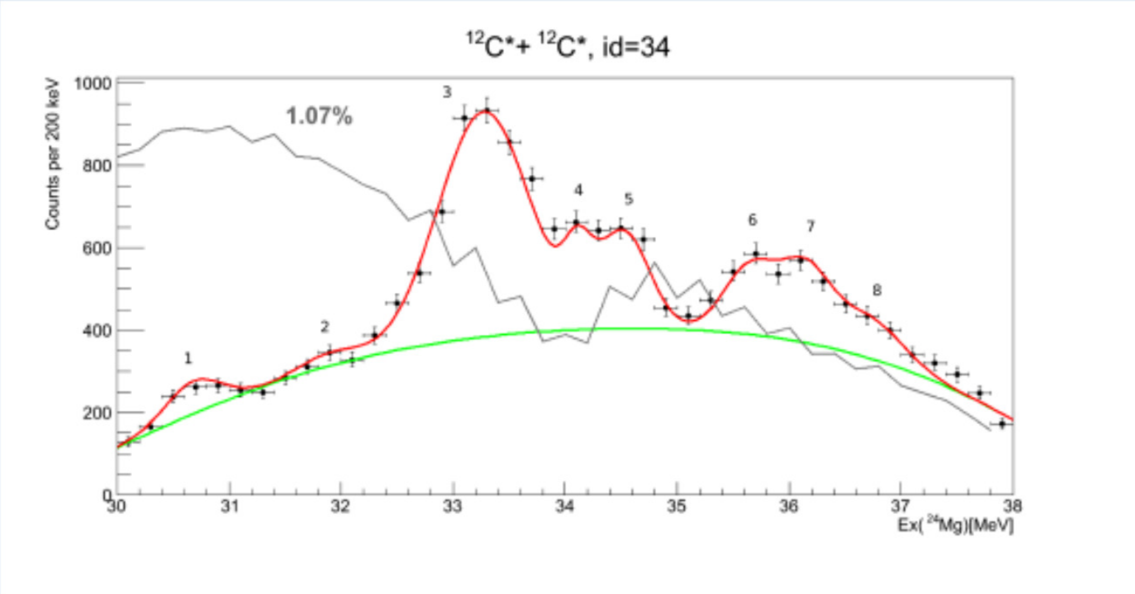


$E_x(^{24}Mg)$: 24.2, 25.0, 25.9, 26.4, 27.6, 28.8 (28.4+29.2), 30.0, 30.8, 31.2, 31.9, 32.5, 33.2, 33.8 MeV

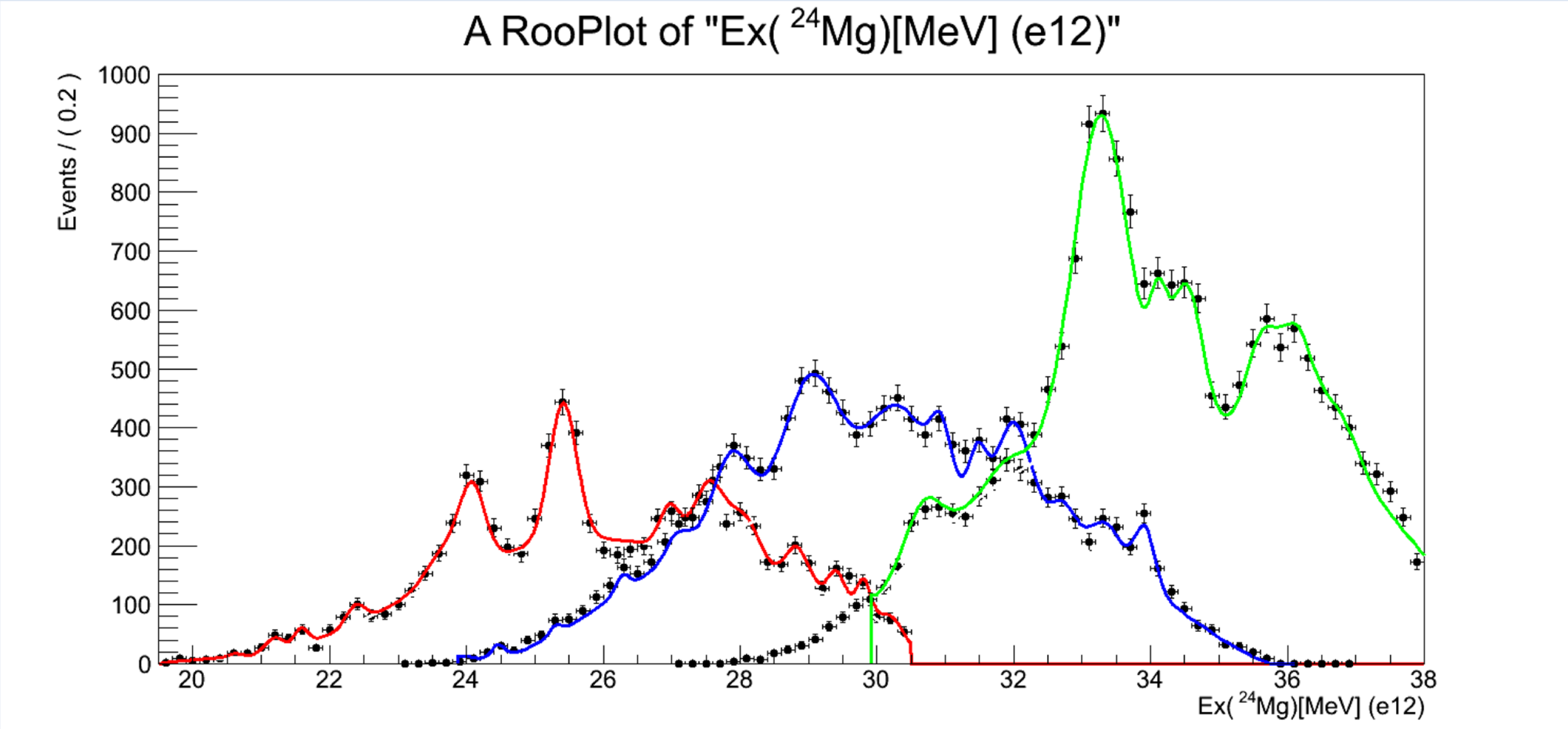
Relative energy plots for the $^{12}C^*(4.4\ MeV)+^{12}C^*(4.4\ MeV)$ decay





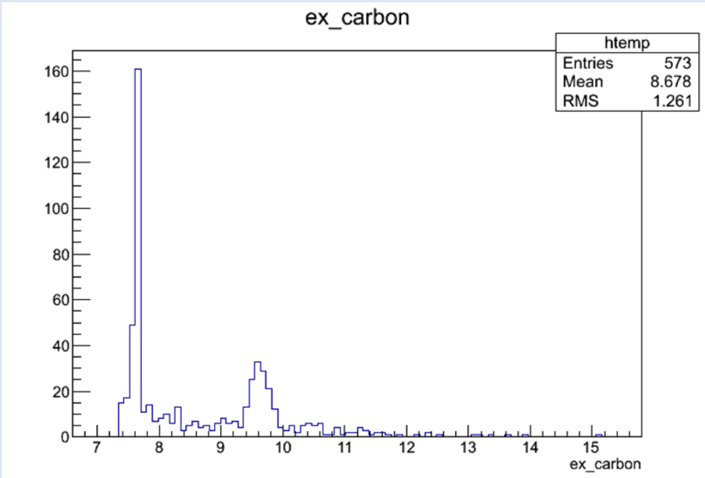


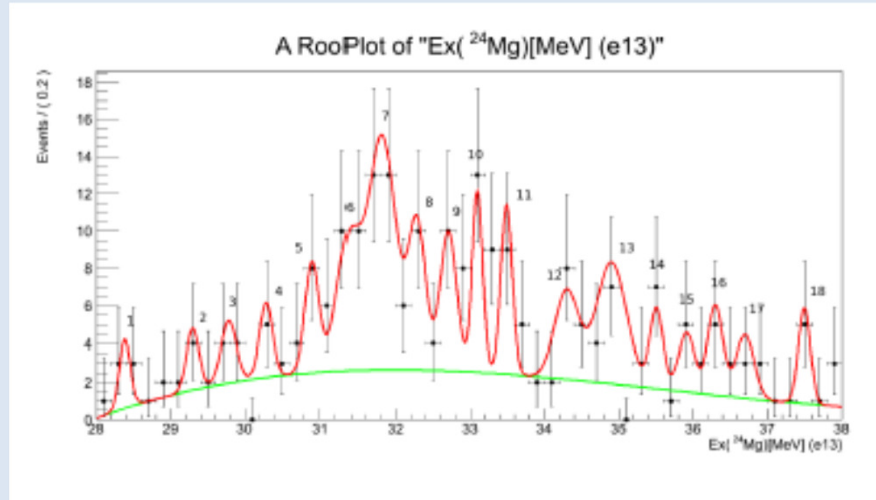
$E_x(^{24}Mg)$: 30.4, 33.2, 34.1, 35.7 MeV



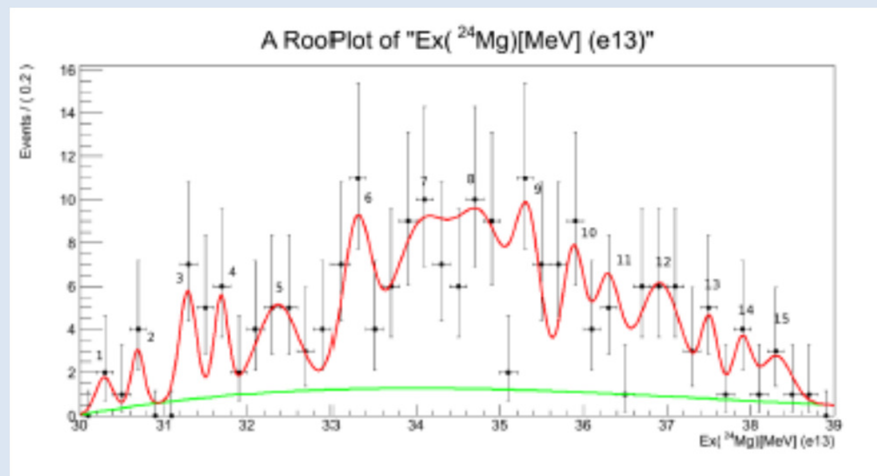
$E_x(^{24}Mg)$: 19.9, 20.9, 21.3, 21.7, 22.7, 23.8, 24.2, 25.0, 25.6, 25.9, 26.4, 27.0, 27.6, 28.0, 28.8, 29.2, 30.4, 30.8, 31.2, 31.9, 32.5, 33.2, 33.8, 34.1, 35.7 MeV

Relative energy plots for the ^{12}C+$^{12}C^*$(7.6, 9.6 MeV) decay





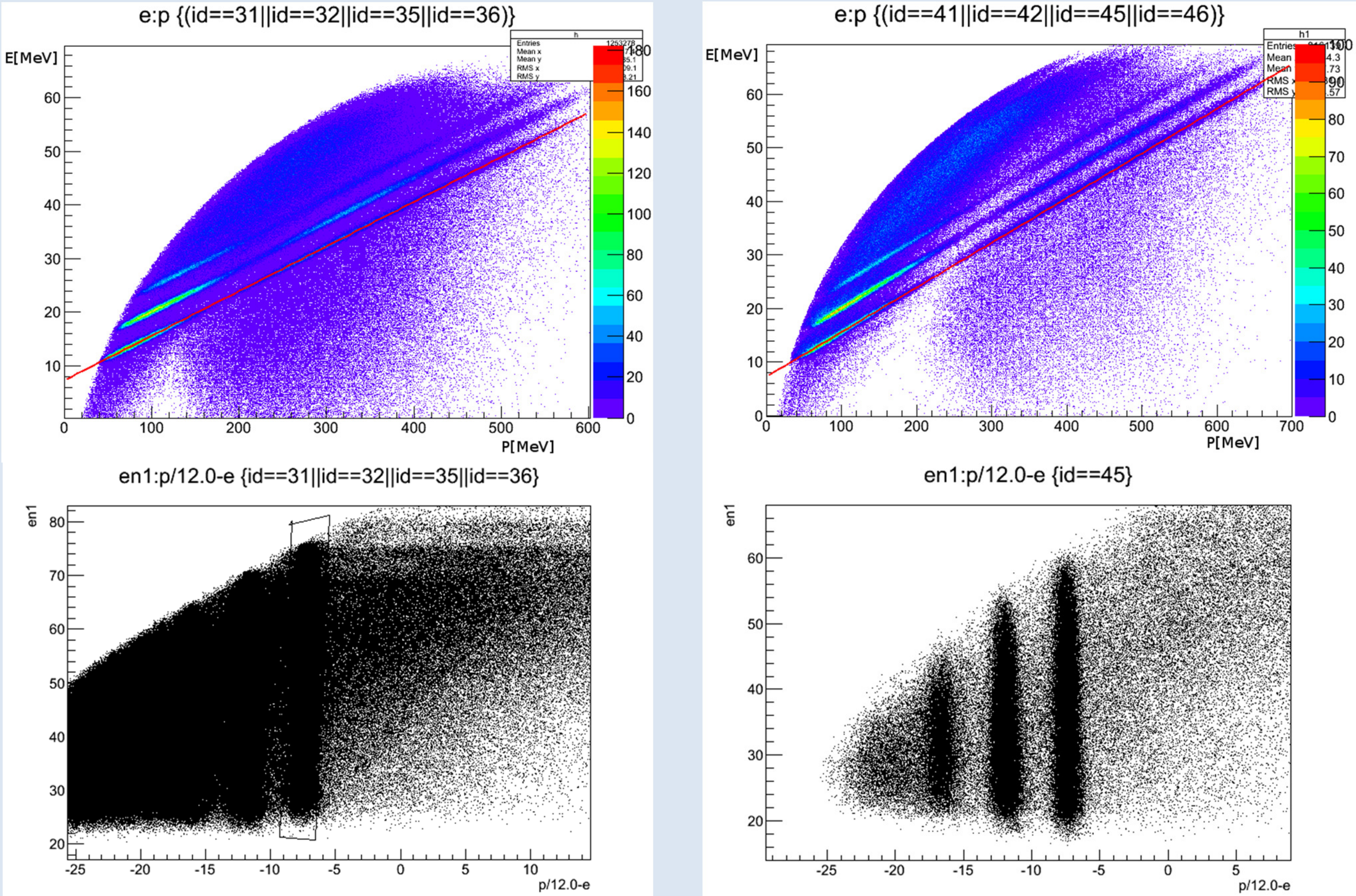
$E_x(^{24}Mg)$: 28.4, 31.9, 33.2, 34.6 MeV – 7.6 MeV



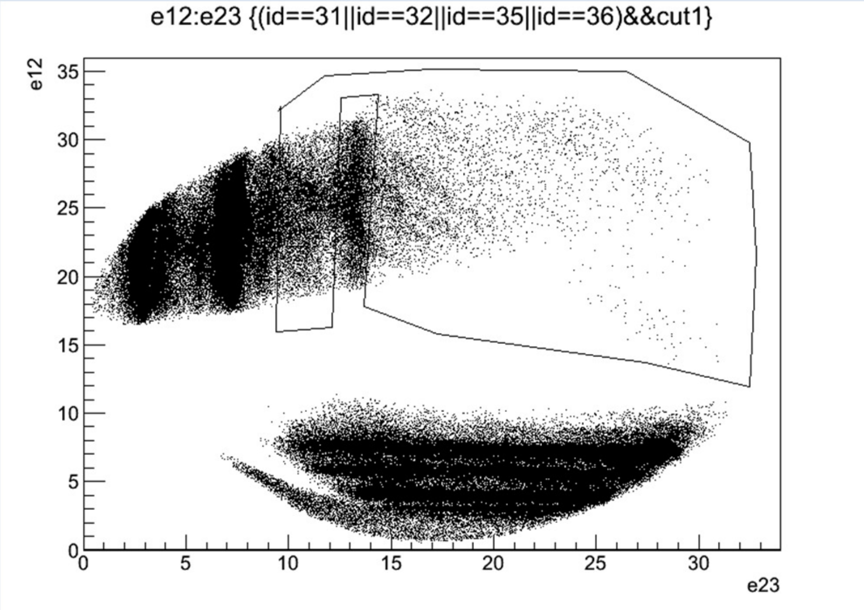
$E_x(^{24}Mg)$: 31.9, 32.5, 33.2, 34.6, 37.0 MeV – 9.6 MeV

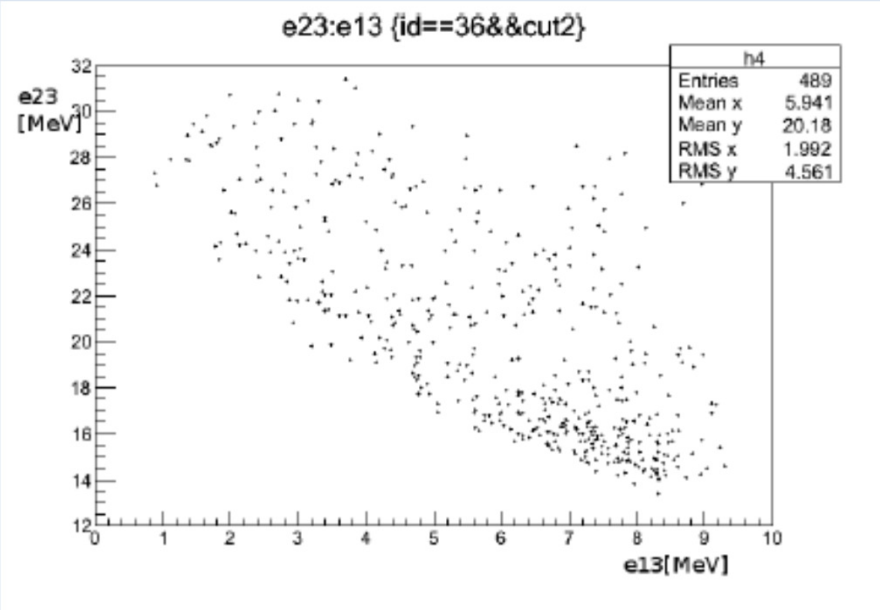
$^{12}C+^{12}C$ decay

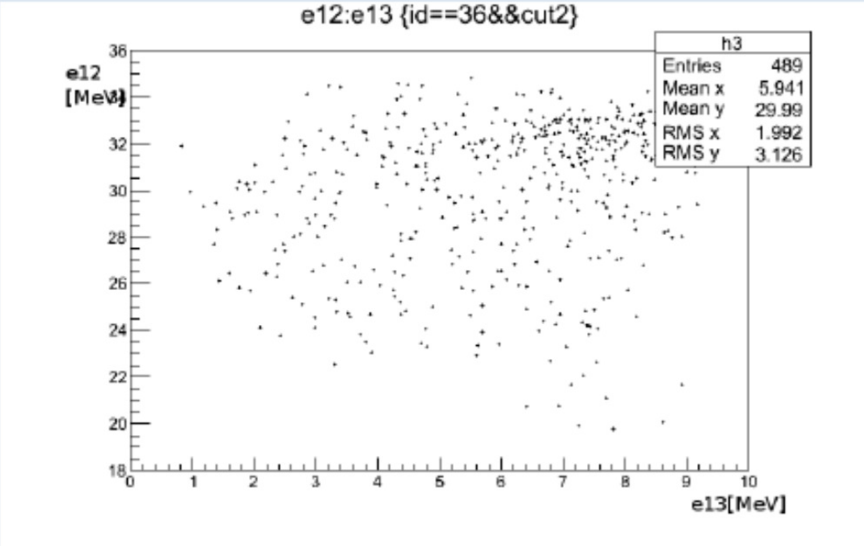
$^{12}C+\alpha$ coincident events

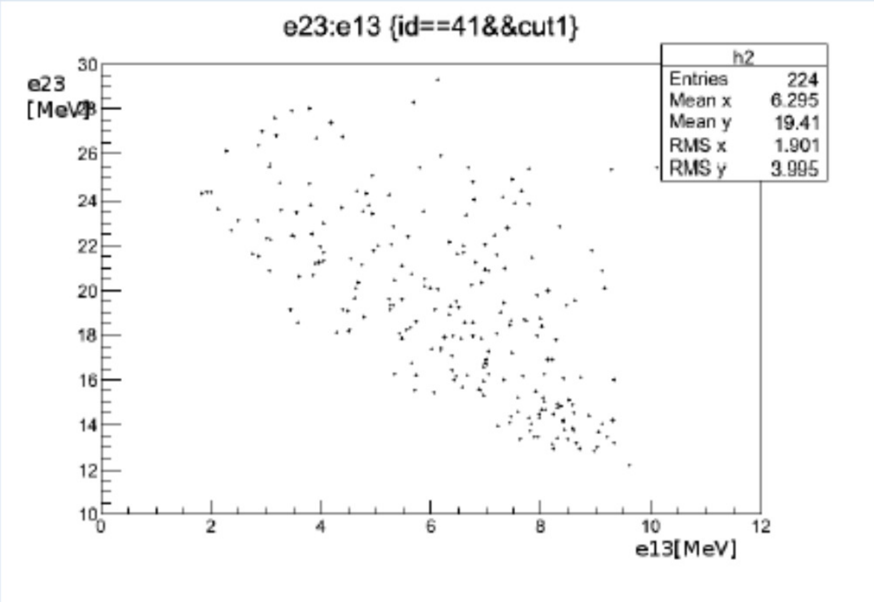


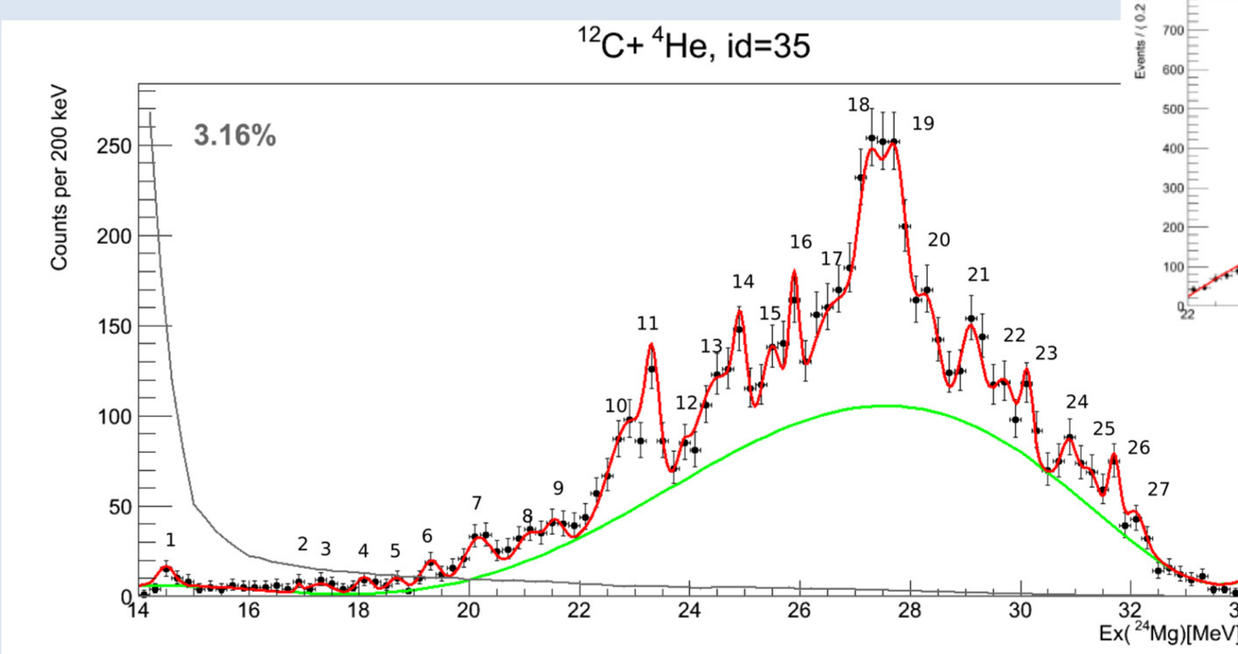
Relative energy plots for the ^{12}C ground state decay

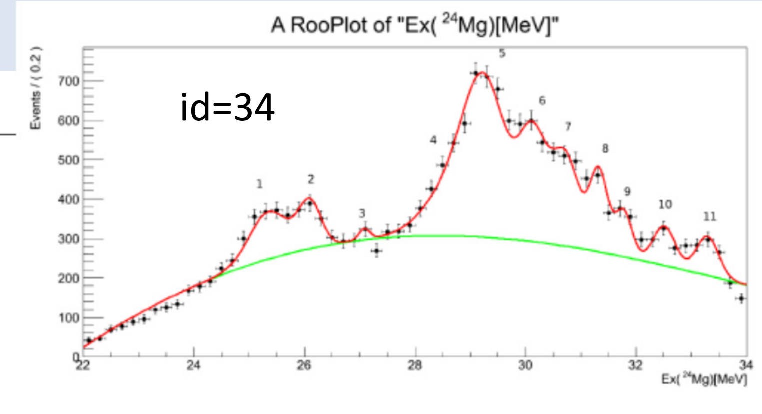


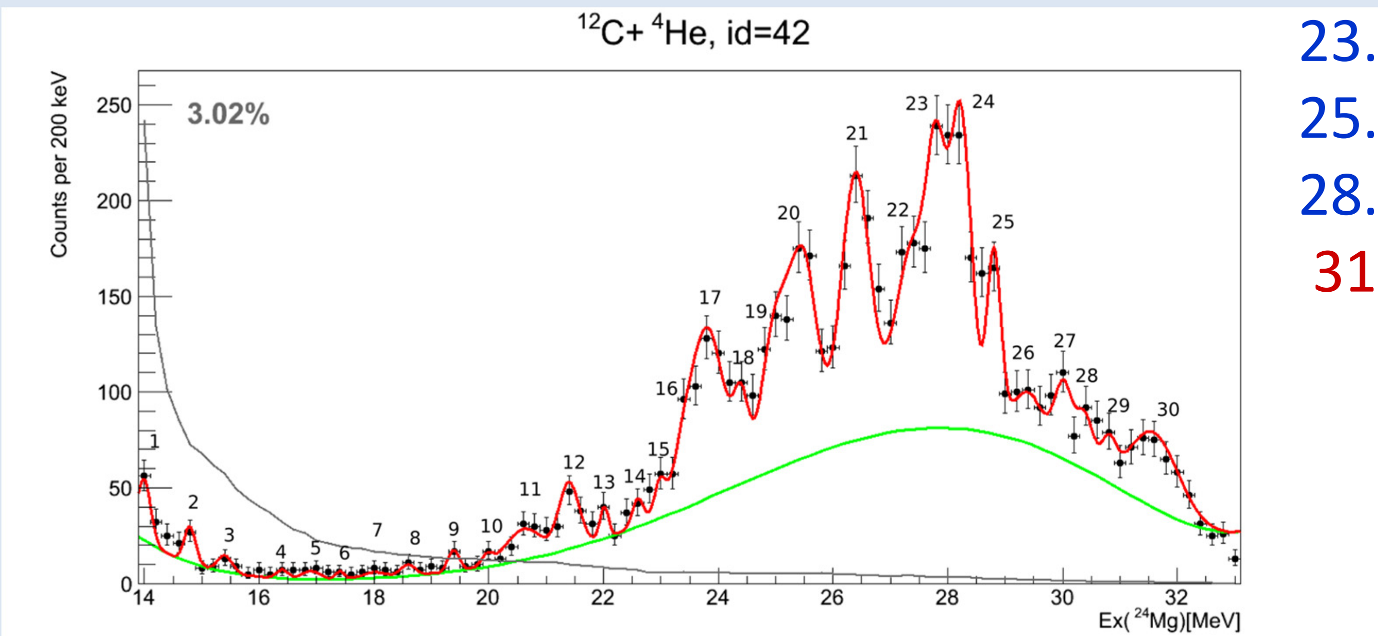






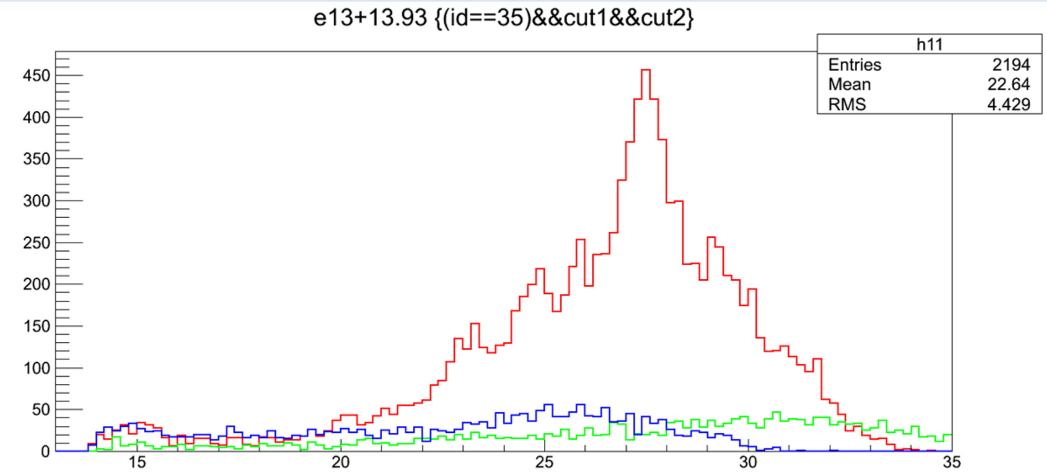


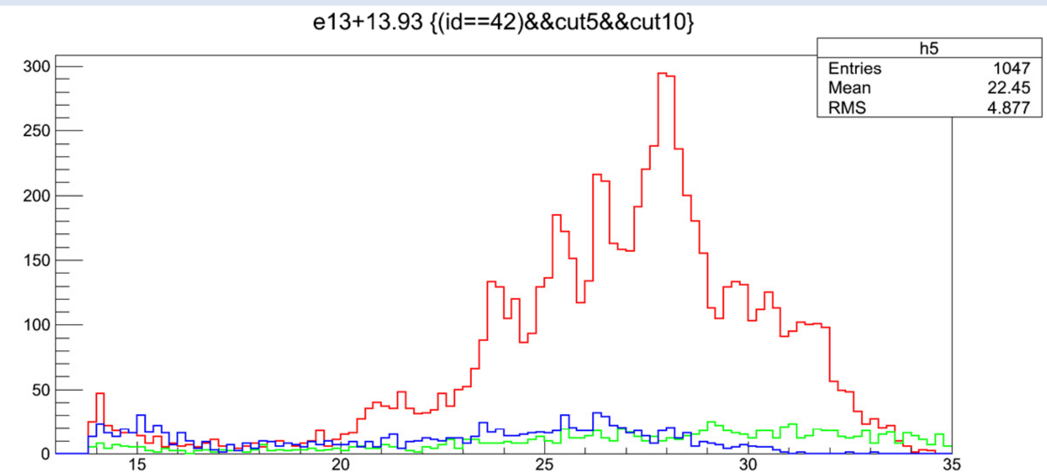


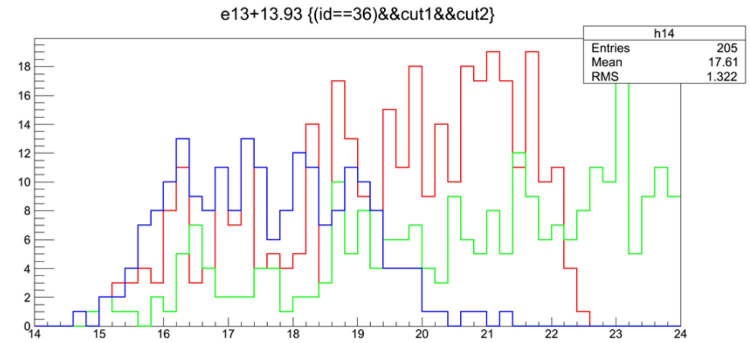


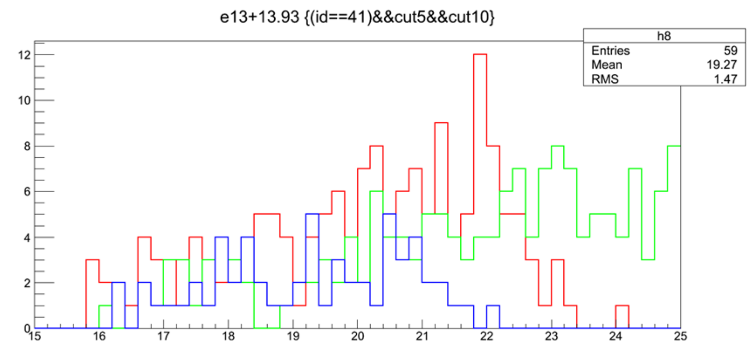
$E_x(^{24}Mg)$: 19.9, 20.9, 21.3, 21.7, 22.7, 23.1, 23.8, 24.2, 25.0, 25.6, 25.9, 26.4, 27.0, 27.6, 28.0, 28.8, 30.0, 30.8, 31.2, 31.7, 31.9 MeV

Right Q-value, higher Q, lower Q









PHYSICAL REVIEW C 73, 064601 (2006)

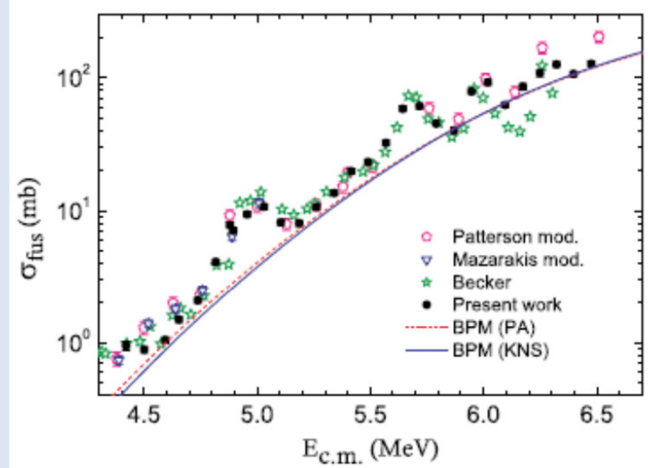
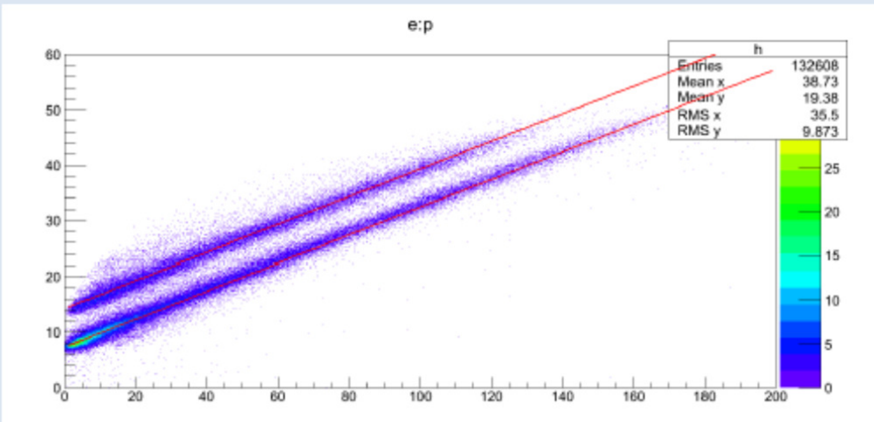


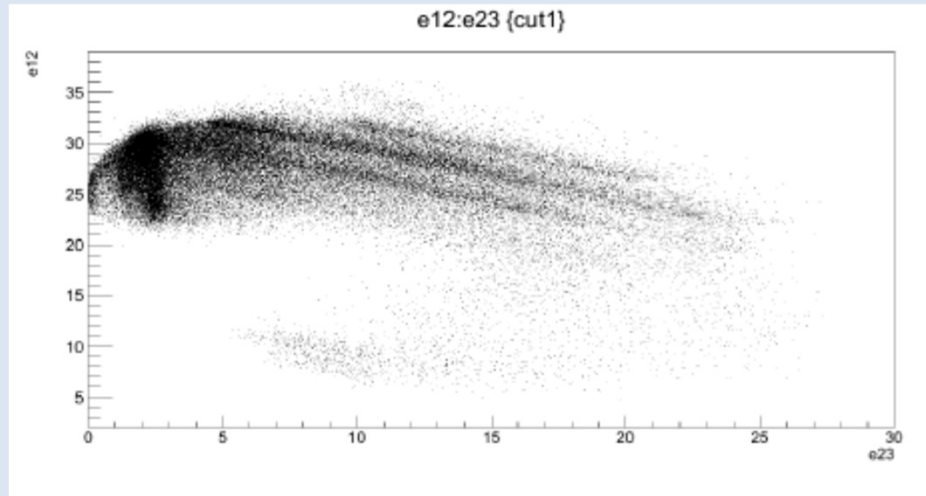
FIG. 6. (Color online) Excitation functions obtained with particle techniques, transformed with the energy shift and the scale factor indicated in the text. Our data are also shown for comparison. The curves are BPM calculations using the proximity adiabatic (PA) and Krappe-Nix-Sierk (KNS) potentials.

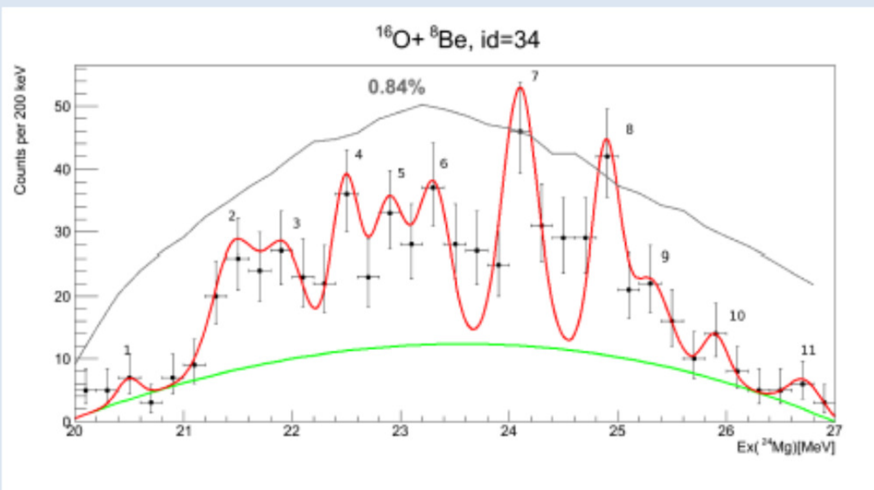
Observed only already known resonances at 18.9, 19.6 and 19.9 MeV

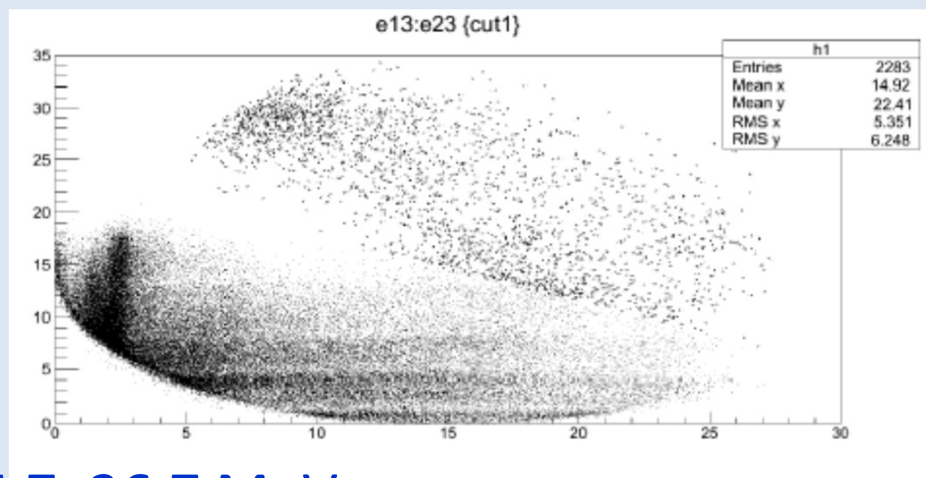
$^{16}O+^{8}Be$ decay

$^{16}O+^{8}Be$ coincident events



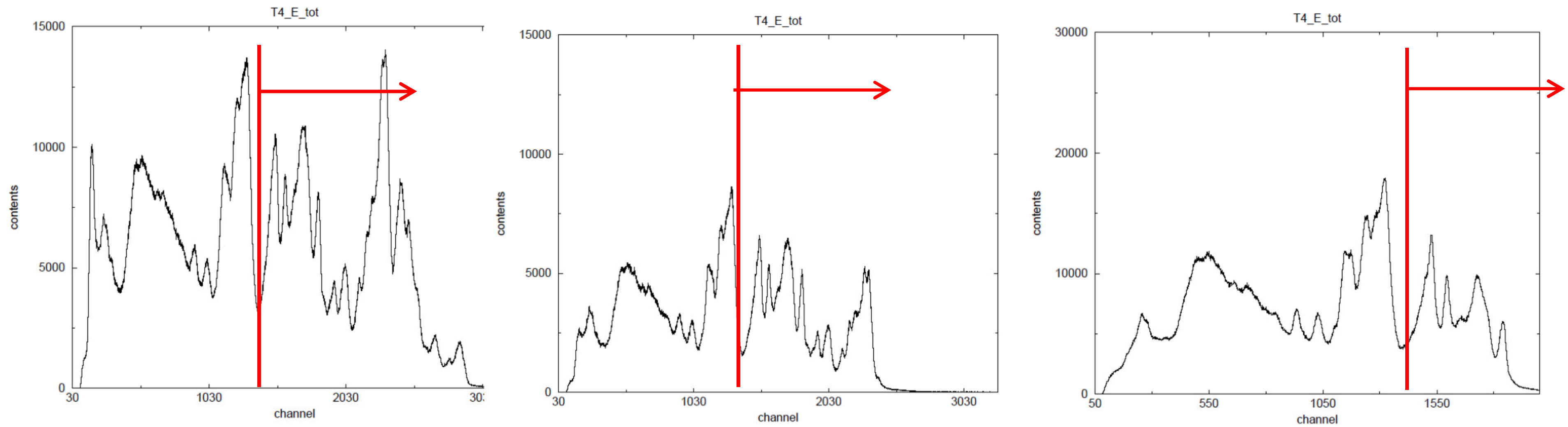






$E_x(^{24}Mg)$: 21.7, 23.1, 24.2, 24.8, 25.7, 26.7 MeV

^{20}Ne+α resonant scattering experiment



Beam energy

Thick gas target measurements: detector telescope at 0 deg
R-matrix calculations: spin and parity of the resonances

Summary

- a number of states at the ^{24}Mg excitations above 20 MeV have been observed – some are new, some new decay modes observed
- $^{12}C+^{12}C$ decay of known states at 18.9, 19.6 and 19.9 MeV observed – they all also observed to decay into the $^{20}Ne+\alpha$ channel
- limitations of the experimental setup/DAQ system – large rate of accidental coincidence events due to large elastic scatering rate – limited sensitivity obstructs observation of the $^{12}C+^{12}C$ decay of the states below 18.9 MeV
- another approach: the $^{20}Ne+\alpha$ resonant scattering + R-matrix fit – search for 0^+ state(s) below 18.9 MeV

THANK YOU !

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