CYCLOTRON INSTITUTE
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Looking for states analogous to the ^{12}C Hoyle state in heavier nuclei

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Workshop: Light clusters in nuclei and nuclear matter: Nuclear structure and decay, heavy ion collisions, and astrophysics
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Outline

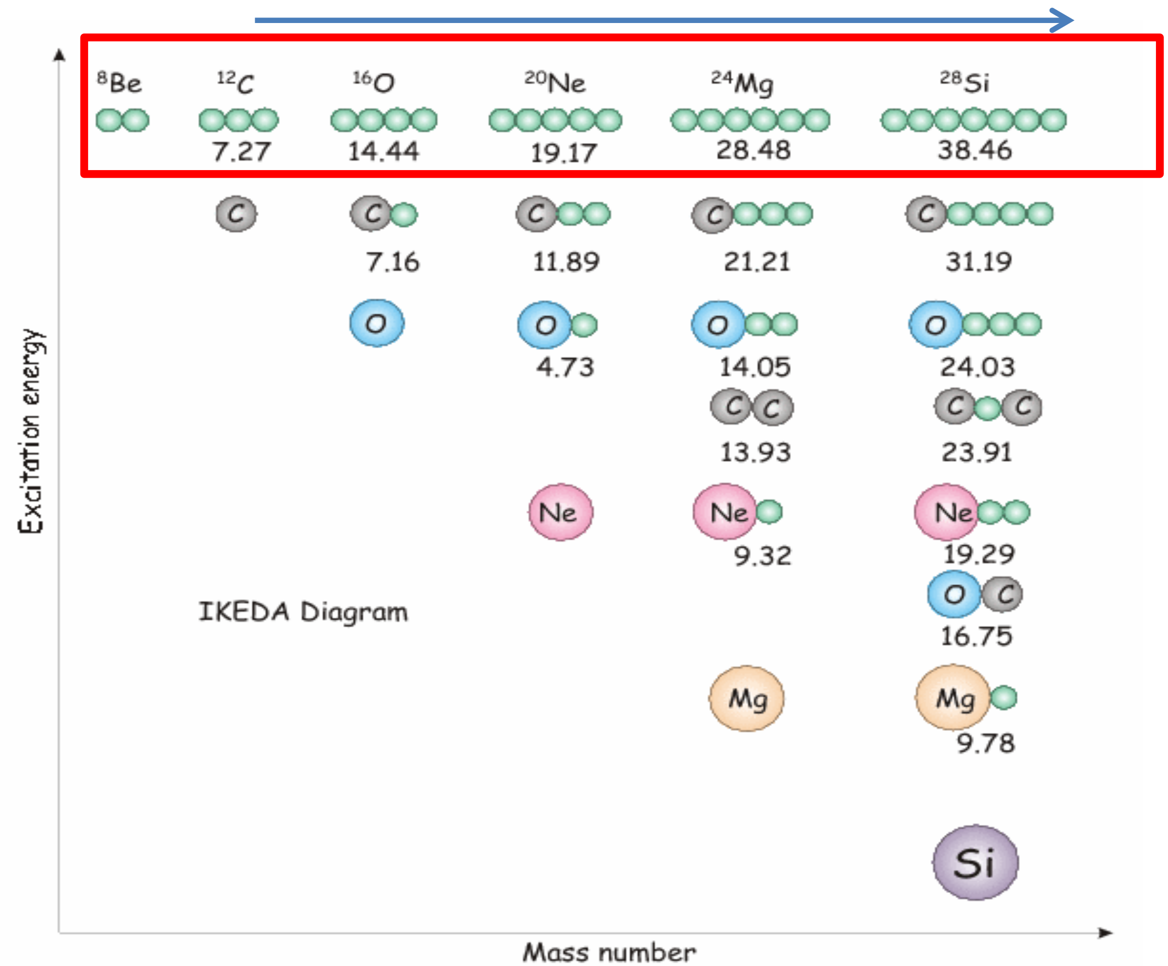
- Motivation
- Why we use a thick target in inverse kinematics
- Experimental setup for the reaction ^{20}Ne + α at 12 AMeV and 9.7 AMeV
- Show that with this technique we can identify states near the threshold in ^{8}Be (α -multiplicity 2) and ^{12}C (α - multiplicity 3)
- Interesting results for ^{16}O (α - multiplicity 4)
- Interesting results for ^{24}Mg

Alpha clustering in nuclei

- **Ikeda diagram** (K. Ikeda, N. Takigawa, and H. Horiuchi, Prog. Theor, Phys. Suppl. Extra Number, 464, 1968.)
- Many **theoretical works** have brought to the picture of alpha cluster nuclei described as a **diluted gas of alphas in the lowest S state.** (PRL 87, 192501; PRC 75, 037303).
- Possible existence of **alpha condensates** in nuclear matter.
- Experimentally **only few not conclusive works are available for ^{16}O or heavier**

Estimated limit N = 7-10α for self-conjugate nuclei

Yamada and Schuck PRC 69, 024309, Bai and Ren PRC 97, 05301



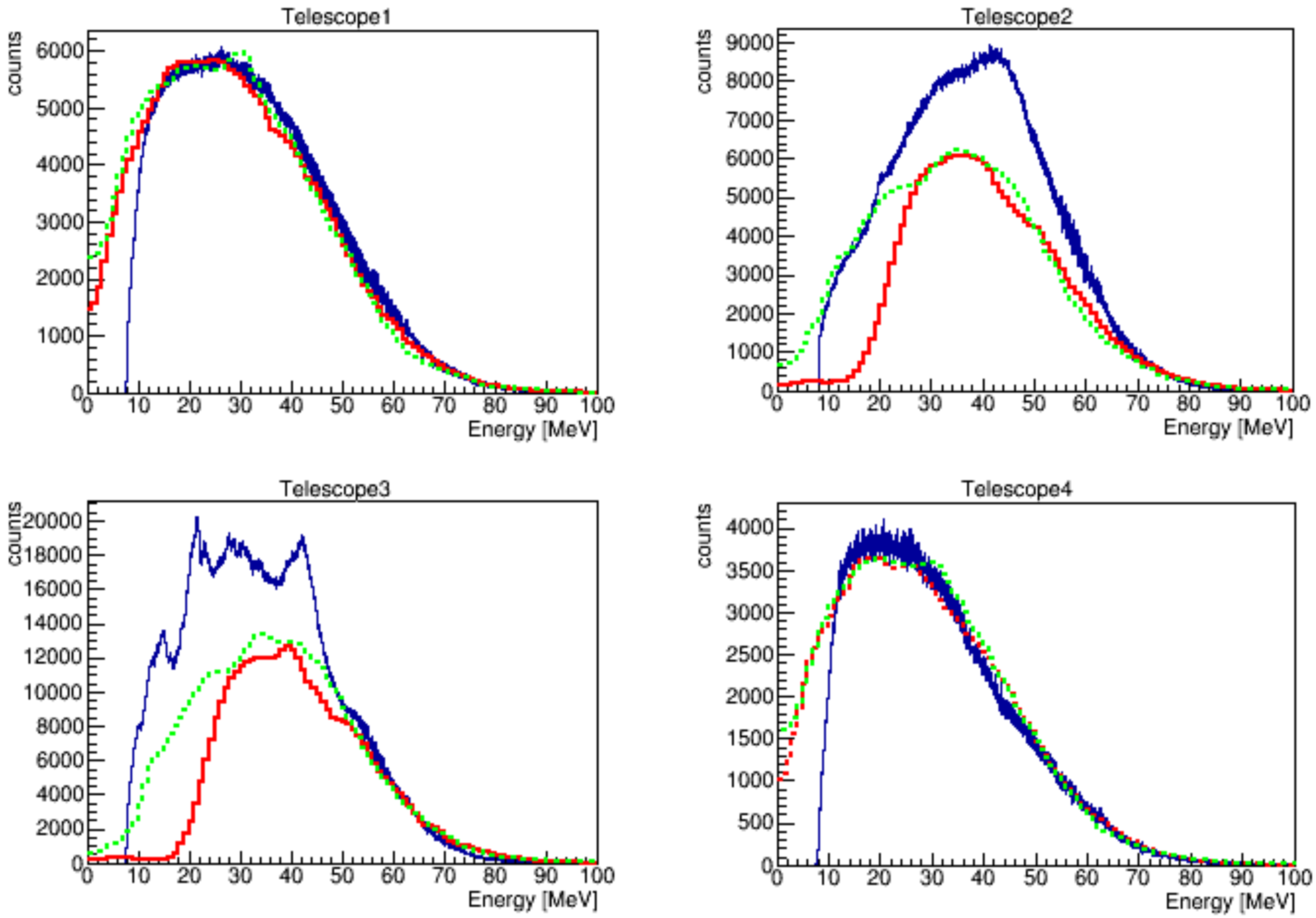
Look for states analogous to the ^{12}C Hoyle state using the thick target inverse kinematics technique

The thick target inverse kinematics technique

- Allows covering a large range of incident energies in the same experiment.
- In the inverse kinematics, the reaction products are focused at forward angles.
- Allows measuring reaction products emitted at 0^o.
- This Method has been used several times to study resonant elastic scattering or transfer reactions and is used here for the first time to detect multiple alpha emission.
- Limit: The position of the interaction point inside the gas has to be reconstructed with some assumptions

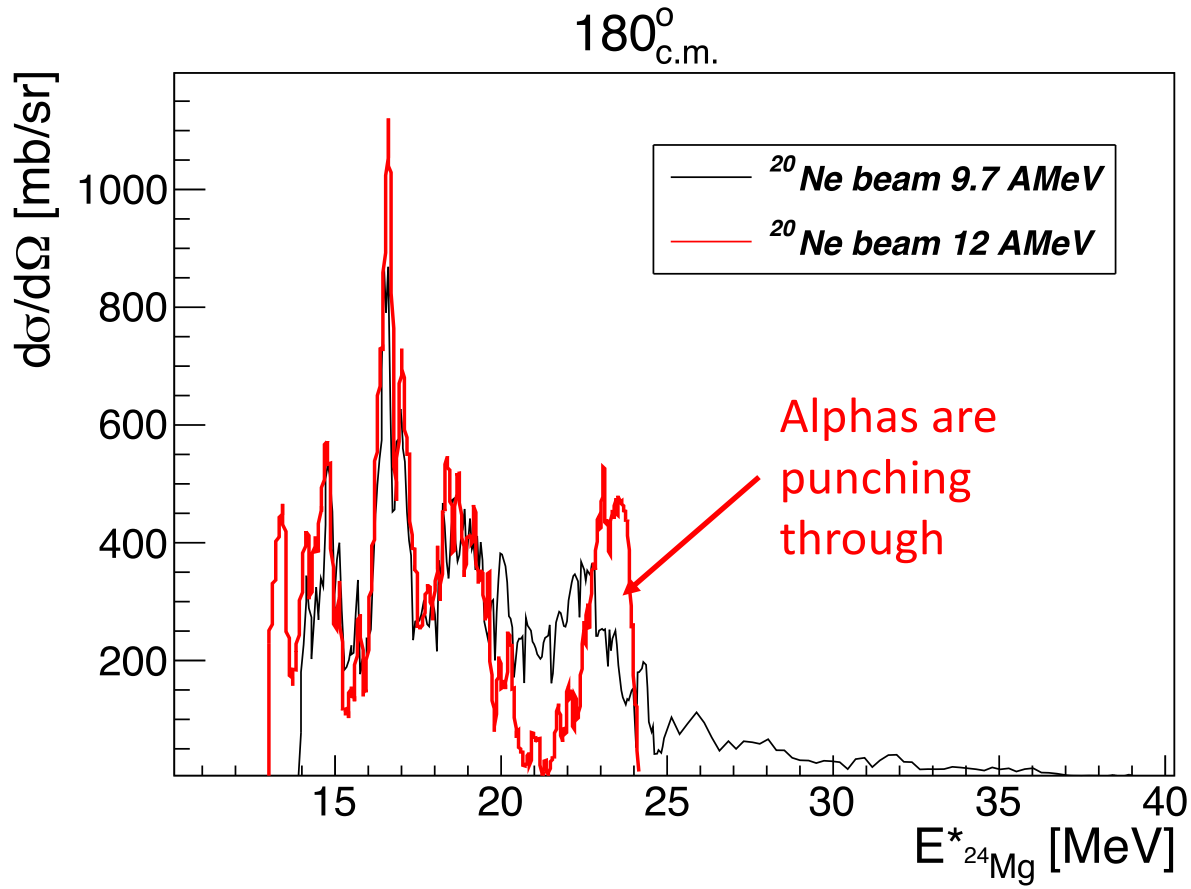
Events with alpha multiplicity 1

At 12AMeV the statistical evaporation plays an important role. This contribution is estimated using the PACE4 code and the HIPSE, both run with beam energy steps of 0.5 MeV/nucleon



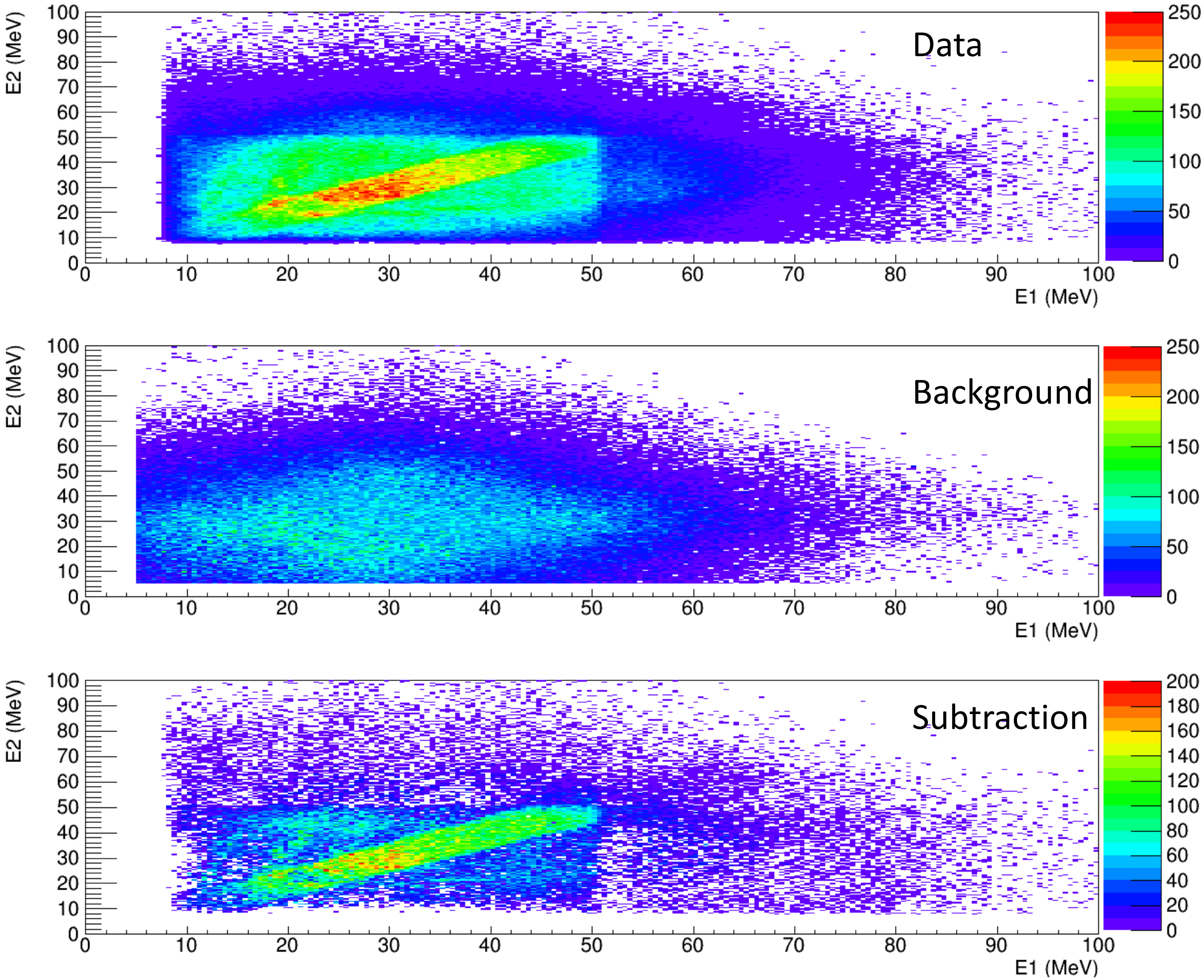
Events with alpha multiplicity 1

The resonant elastic scattering is our reference reaction. We can compare the result with existing cross sections and have a double check for the beam intensity obtained from the monitor.



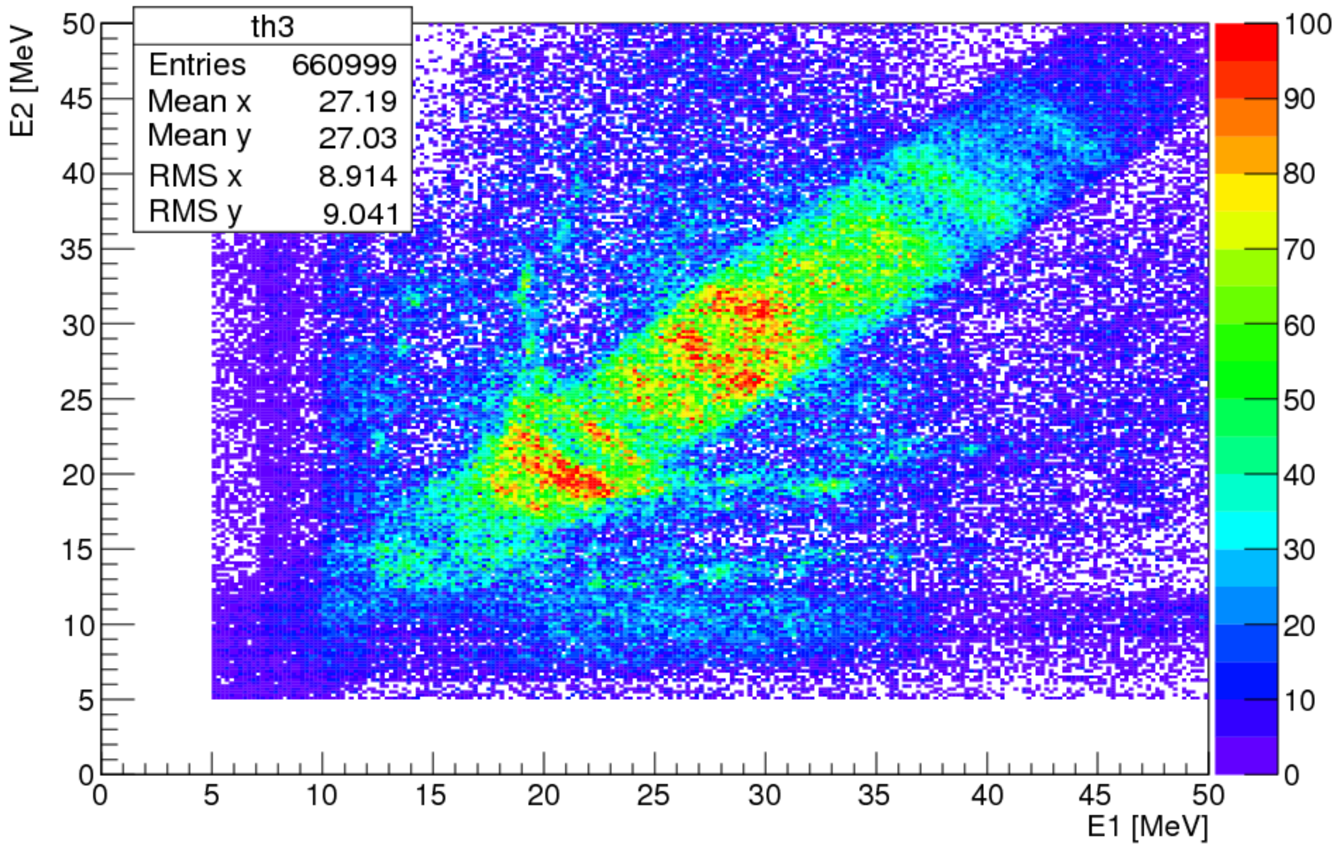
In agreement with the excitation function measured in 10-15 keV energy steps in normal kinematics at 168° in the center of mass By R. Abegg and C.A. Davis

Events with alpha multiplicity 2



12AMeV
Background estimated with HIPSE

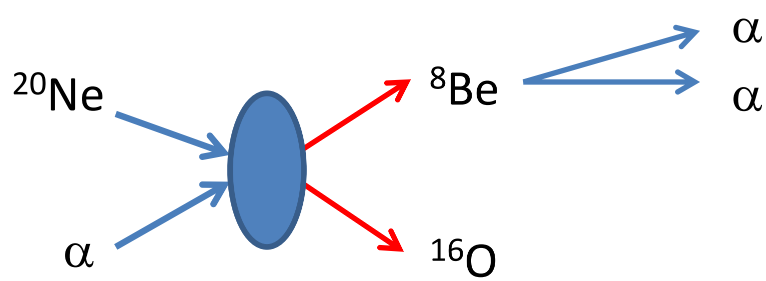
Events with alpha multiplicity 2



9.7 AMeV
After subtracting the background

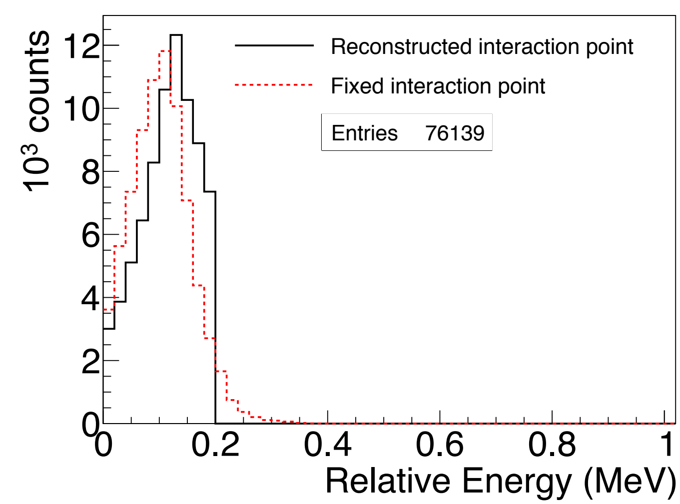
Events with alpha multiplicity 2

^{20}Ne @ 12 and 9.7 AMeV +^{4}He
2 alphas in the same event are correlated in time ΔT<30 ns



Reconstruction of the interaction point with a recursive calculation based on conservation of energy and momentum and the assumptions:

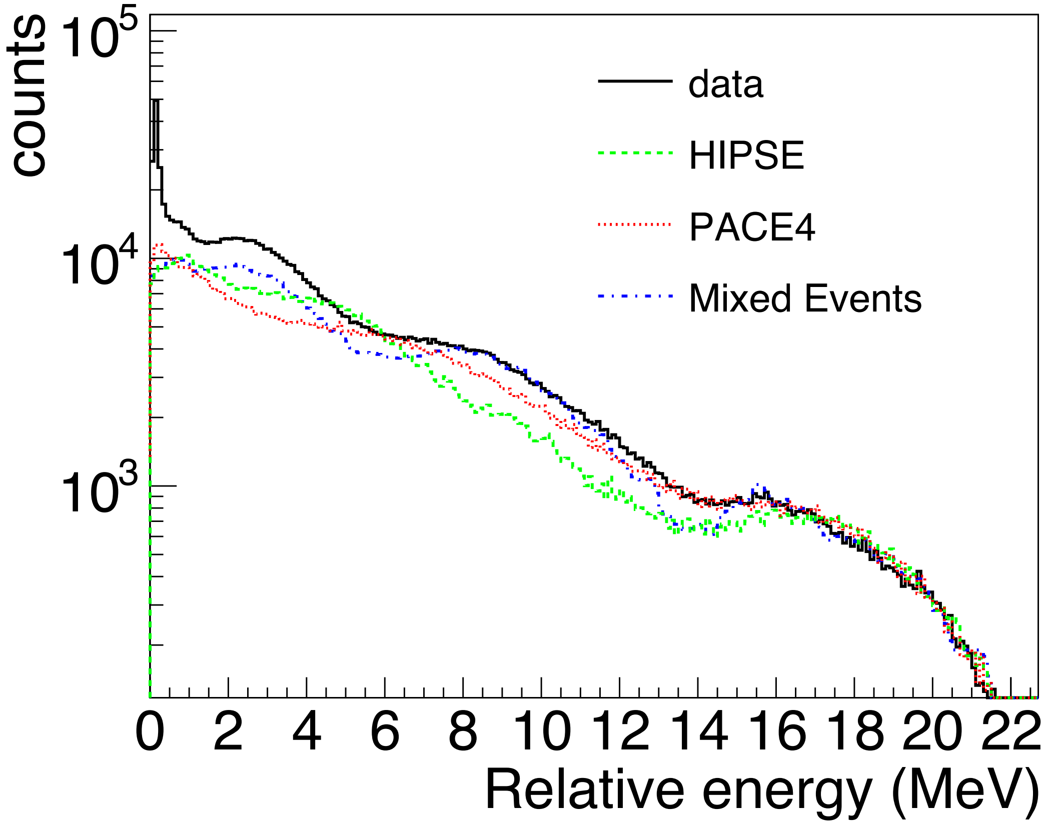
1) The 2 alphas come from a ^{8}Be
2) The ^{16}O is in the ground state

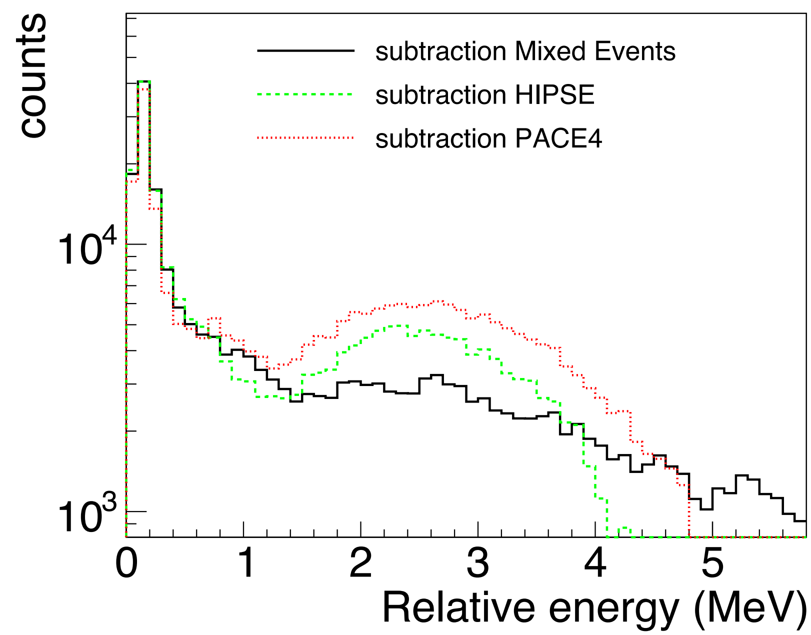


Ek_α_lab -> Ek(^{8}Be)
$E^*(^{8}Be) = E_{cm\_}\alpha_1 + E_{cm\_}\alpha_2 + Qgg$

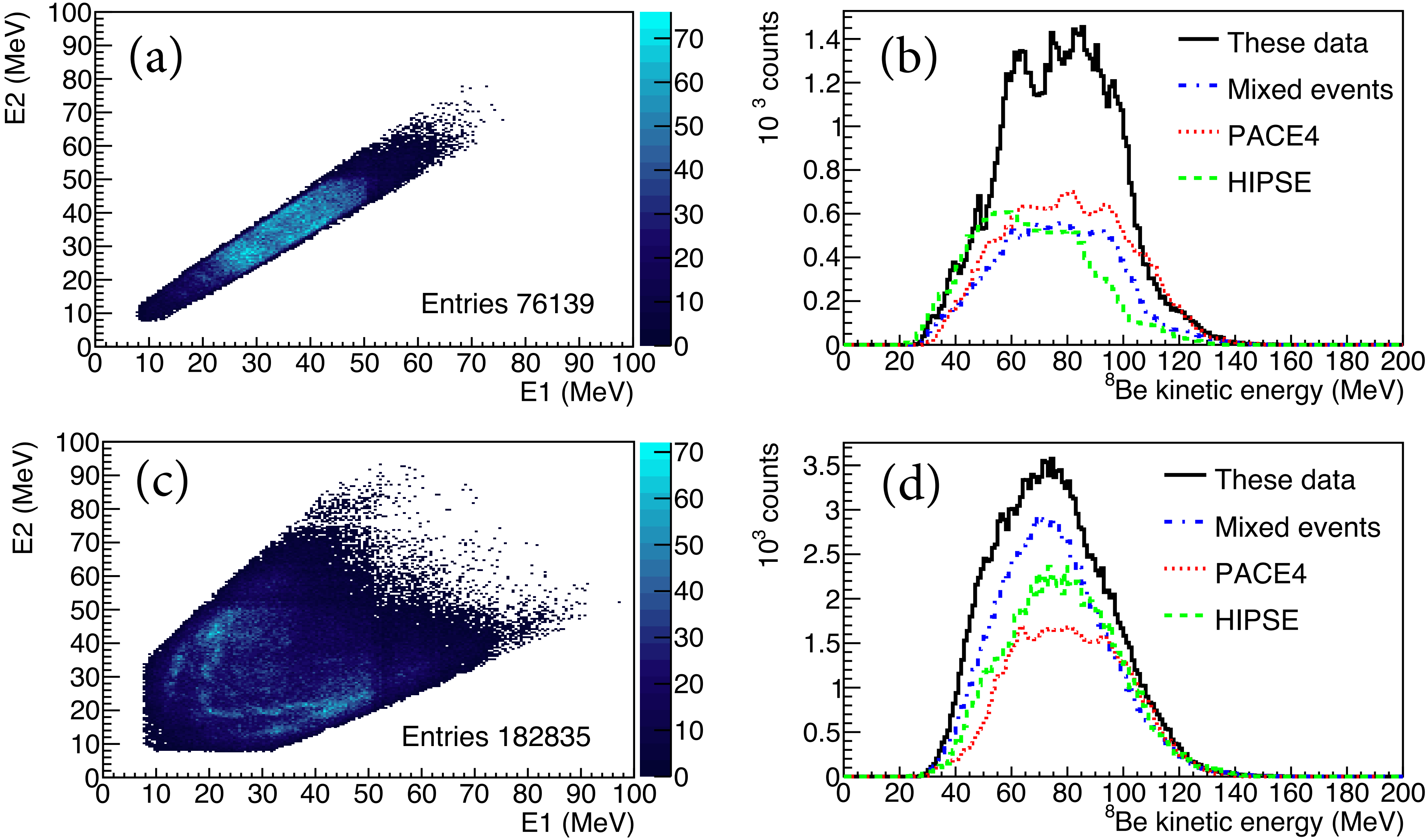
Since the 2 alphas have similar and quite large energy in the laboratory and travel similar flightpaths the energy loss correction almost cancels out when we calculate ^{8}Be excitation energy specially at energies close to the threshold.

Events with alpha multiplicity 2



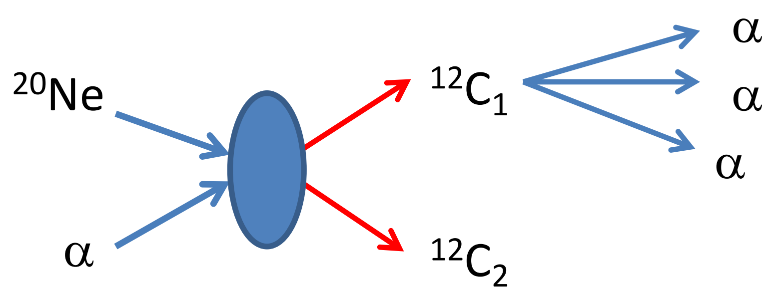


Events with alpha multiplicity 2



Events with alpha multiplicity 3

^{20}Ne @ 12 AMeV +^{4}He
3 alphas in the same event are correlated in time $\Delta T<30$ ns



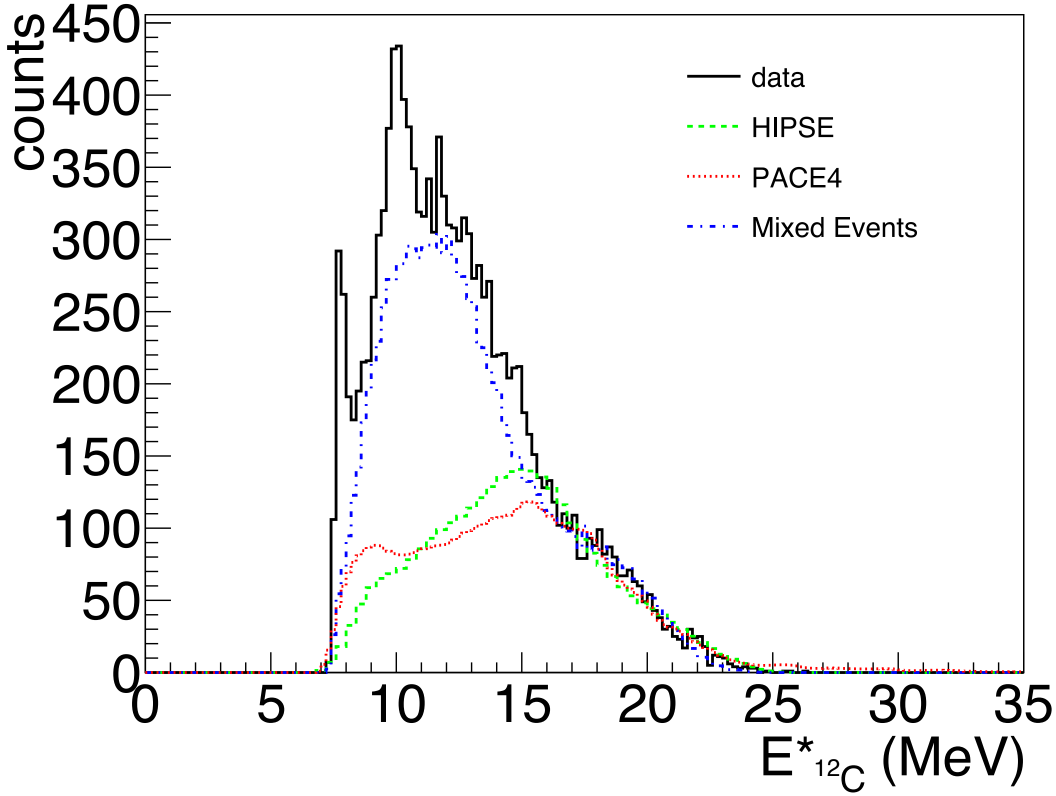
Reconstruction of the interaction point with a recursive calculation based on conservation of energy and momentum and the assumptions:

1) The 3 alphas come from a ^{12}C
2) The other ^{12}C is in the ground state

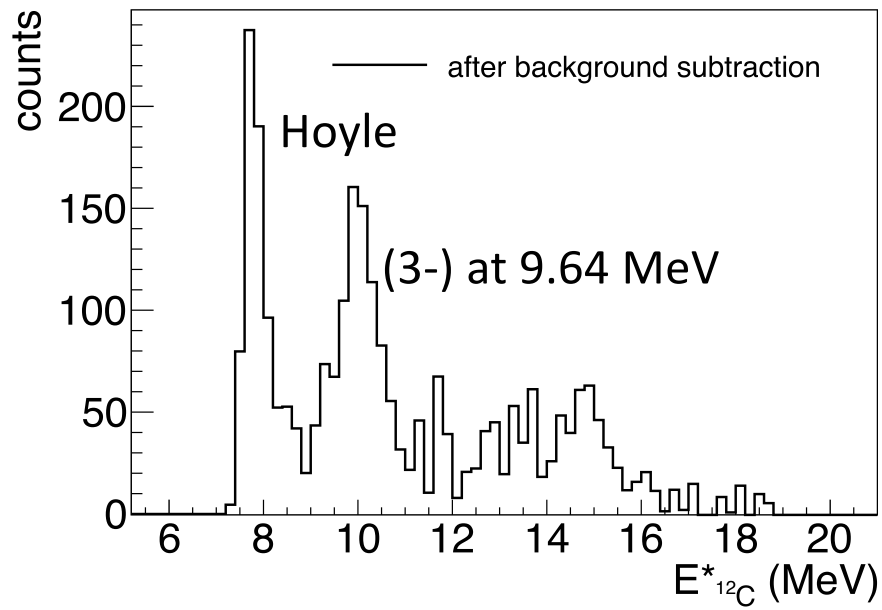
Ek_α_lab -> Ek($^{12}C_1$)
$E^*(^{12}C_1) = E_{cm}\_\alpha_1 + E_{cm}\_\alpha_2 + E_{cm}\_\alpha_3 +$ Qgg (7.26MeV)

Since the 3 alphas have similar and quite large energy in the laboratory and travel similar flightpaths the energy loss correction almost cancels out when we calculate ^{12}C excitation energy specially at energies close to the threshold.

Events with alpha multiplicity 3

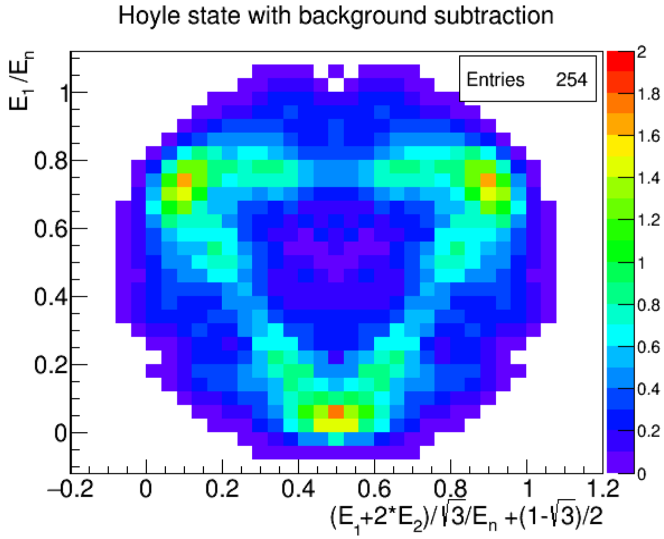


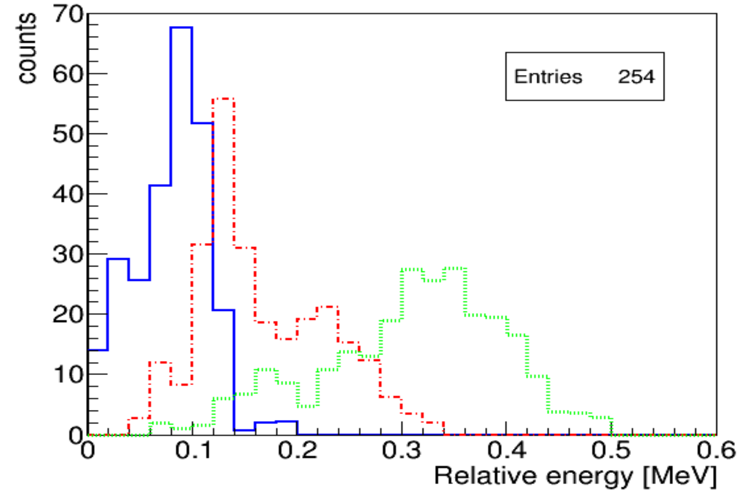
- Relative energy of the three couples of alpha particles -> Tells us if the decay is proceeding through the ^{8}Be ground state.
- Dalitz Plot -> Information about the energy and momentum of the emitted alpha particles.



7.65 MeV (0+) Hoyle State decays through $^{8}Be_{gs}$

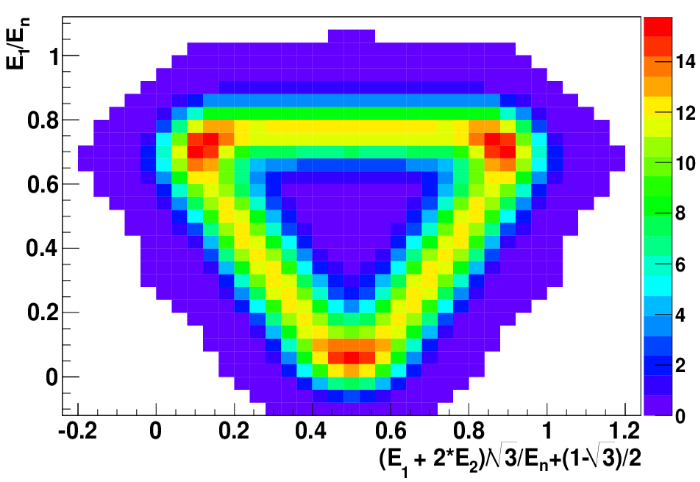
Experiment

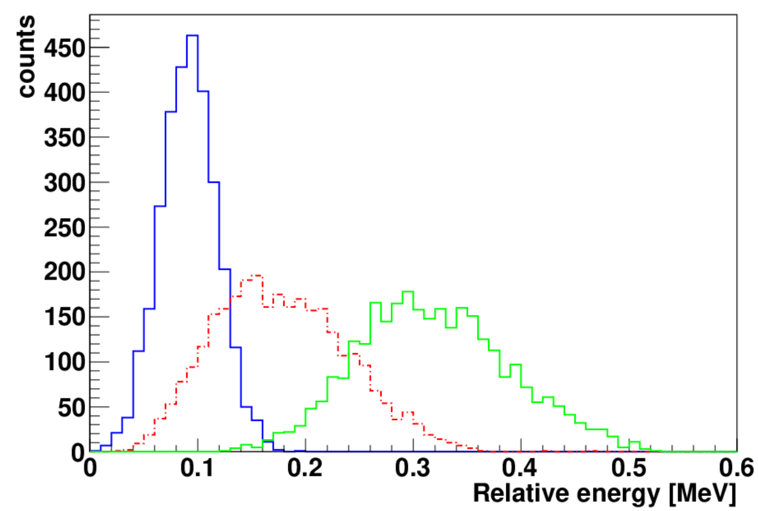




In agreement with Monte Carlo simulation of the Hoyle state decaying through the ^{8}Be ground state

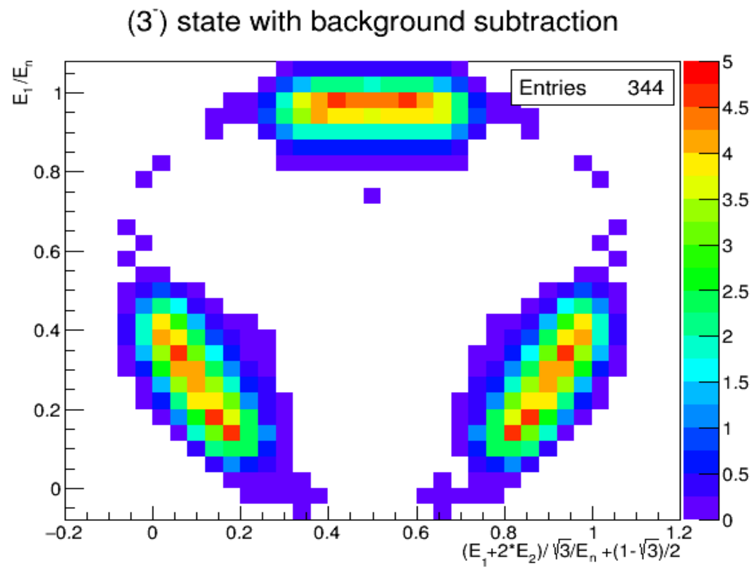
Simulation

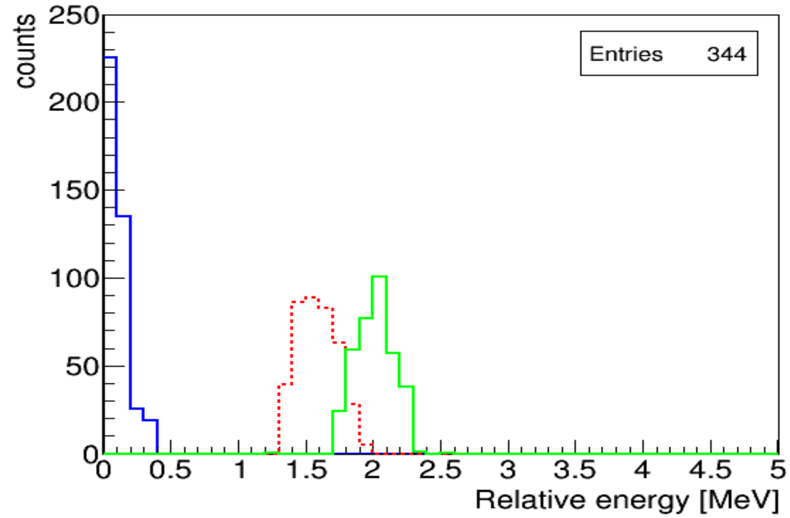




9.64 MeV (3-) decays through $^{8}Be_{gs}$

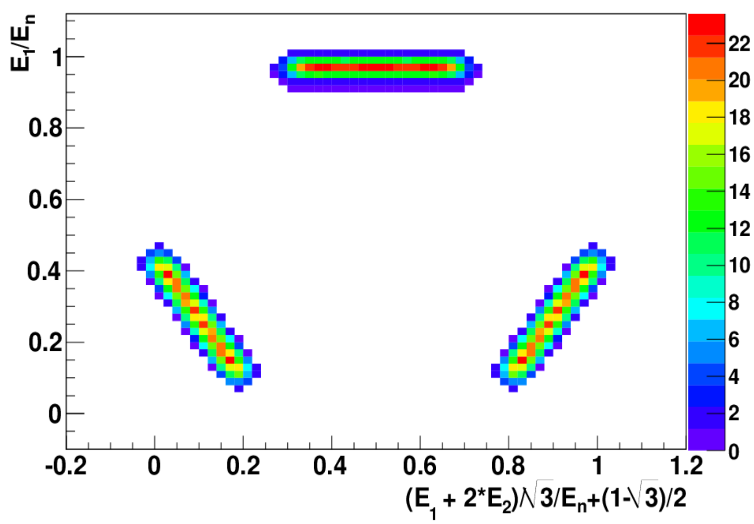
Experiment

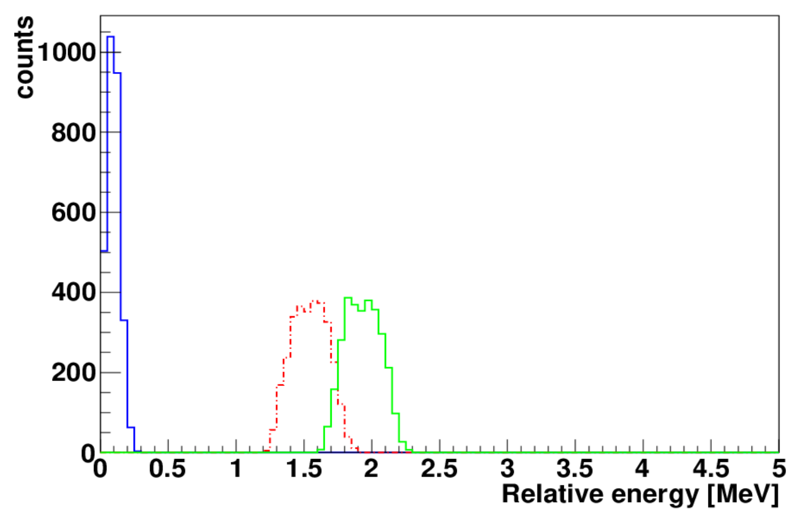




In agreement with Monte Carlo simulation of a 3- state decaying through the ^{8}Be ground state

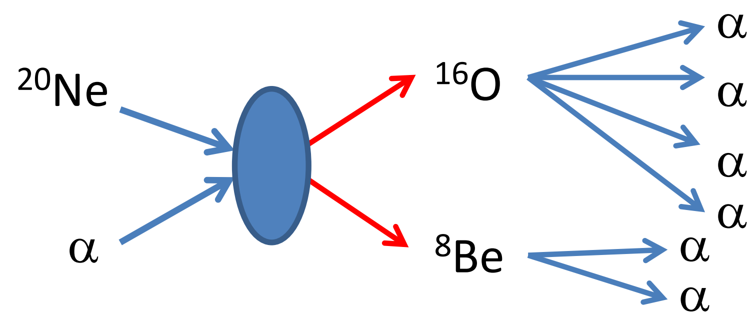
Simulation





Events with alpha multiplicity 4

^{20}Ne @ 12 and 9.7 AMeV +^{4}He
4 alphas in the same event are correlated in time ΔT<30 ns



Reconstruction of the interaction point with a recursive calculation based on conservation of energy and momentum and the assumptions:

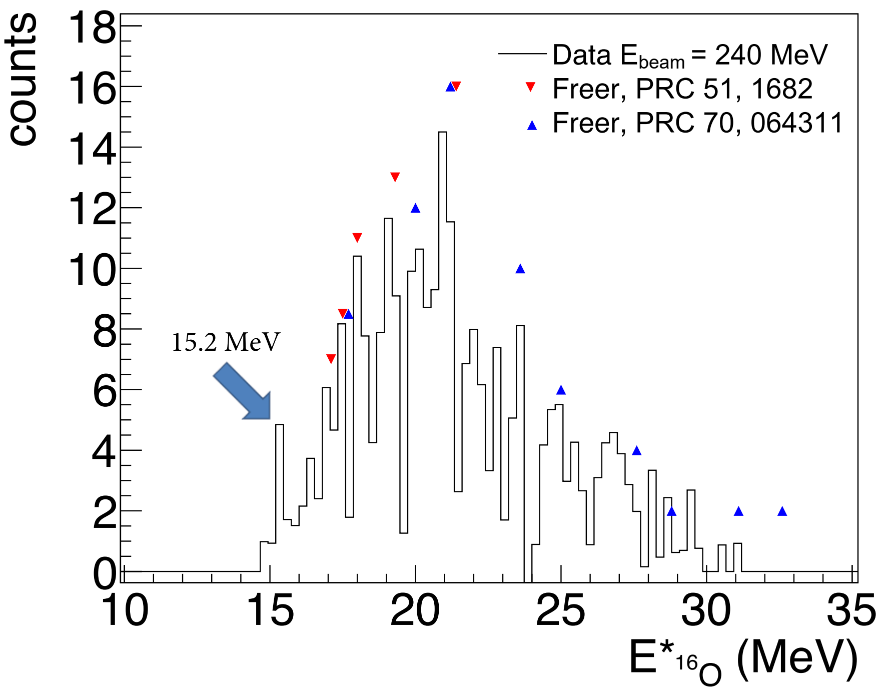
1) The 4 alphas come from a ^{16}O
2) The ^{8}Be is in the ground state

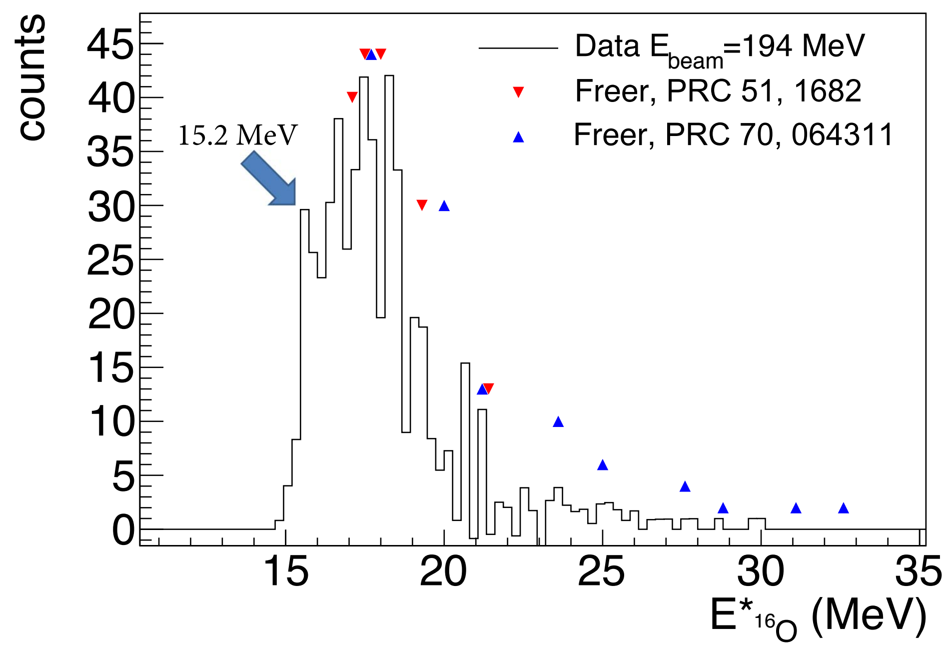
Ek_α_lab -> Ek(^{16}O)

$E^*(^{16}O) = E_{cm}\_\alpha_1 + E_{cm}\_\alpha_2 + E_{cm}\_\alpha_3 + E_{cm}\_\alpha_4 + Qgg\ (14.4\ MeV)$

Only α-particles with energy larger than 13 MeV are selected in order to cut those from the ^{8}Be emitted in opposite direction.

Events with alpha multiplicity 4

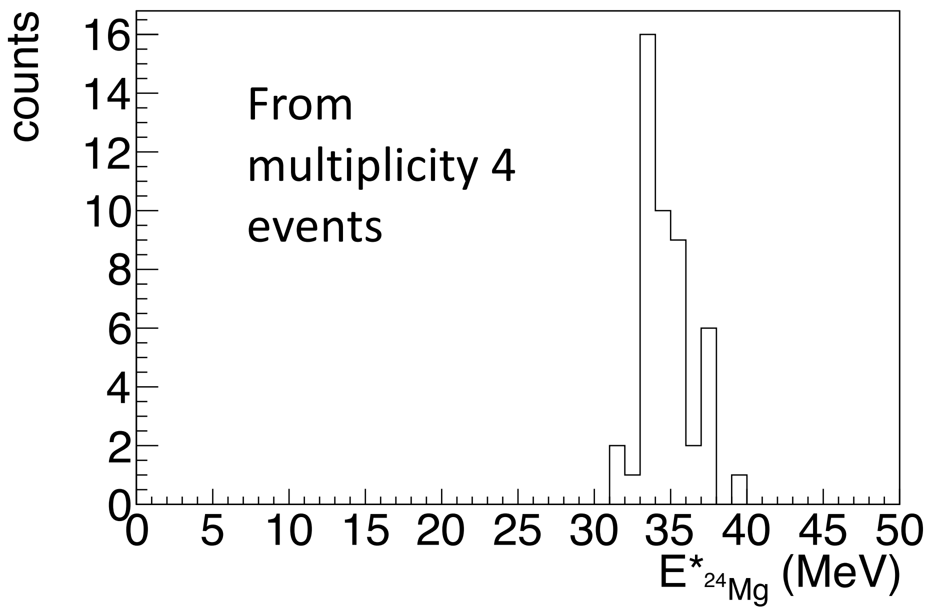




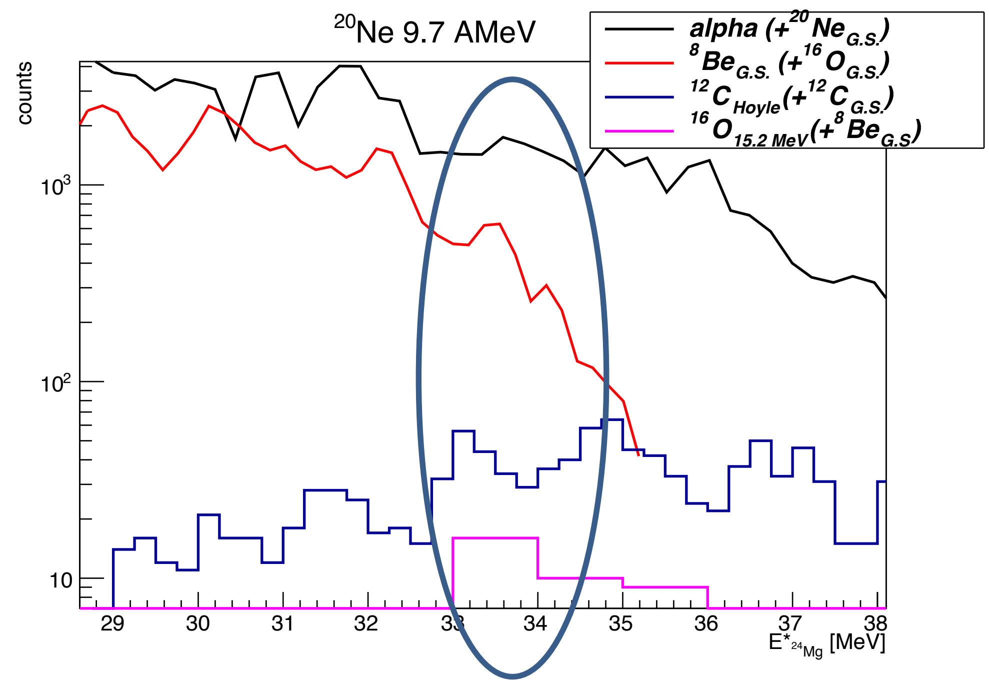
$$\frac{\Gamma_{^8Be}}{\Gamma_{^{12}C(0_2^+)}} = \frac{\text{Yield}(^8\text{Be})}{\text{Yield}[^{12}\text{C}(0_2^+)]}\,\frac{\text{Efficiency}[^{12}\text{C}(0_2^+)]}{\text{Efficiency}(^8\text{Be})}.$$

Energy	Γ(Be)/ Γ(Hoyle) This work 12 AMeV	Γ(Be)/ Γ(Hoyle) This work 9.7 AMeV	Γ(Be)/ Γ(Hoyle) Freer et al. PRC 51, 1662
15.2±0.2	1±0.7	0.96 ± 0.3	
17.1	0.6±0.3	0.7 ± 0.3	0.65 ± 0.16
17.5		0.6 ± 0.3	0.72 ± 0.18
19.7	0.43±0.2	0.6 ± 0.5	0.47 ± 0.15
21.4	5.3±2.8	3 ± 1	>3 ± 1.1

^{24}Mg Excitation energy



Possible state at around 34 MeV decaying into 6 alpha particles. This energy is close to the 33.4 MeV predicted by Yamada and Schuck for a state analogous to the Hoyle state in ^{12}C.



Conclusions

- Using the suggested technique it is possible to identify states near the alpha decay threshold in ^{8}Be and ^{12}C.
- 4α events -> show a structure at 15.2 MeV possible candidate for a state analogous to the Hoyle state in ^{16}O (candidate 0+ state predicted at Ex 15.1 MeV). The few events in this peak decay equally into

  - alpha + $^{12}C_{(Hoyle)}$

  - 2 $^{8}Be_{(gs)}$
- Possible state in ^{24}Mg decaying into 6 alpha particles at around 34 MeV.

Thank you for your attention!

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