Search for Toroidal Nuclear Resonances in the Cluster Disassembly of 28Si

A.B. McIntosh

Workshop on Particle Correlations and Femtoscopy
2024 November 4-8
Toulouse, France

CYCLOTRON INSTITUTE
TEXAS A&M UNIVERSITY

THE Welch FOUNDATION

U.S. Dept. of Energy, Nuclear Physics: DE-FG02-93ER40773
Welch Foundation: A-1266

Andy Hannaman
(thesis work)

Bryan Harvey

A. Hannaman,[1,2,*] B. Harvey,[1,3] A. B. McIntosh,[1,†] K. Hagel,[1] A. Abbott,[1,2] A. Fentress,[1,2] J. Gauthier,[1] T. Hankins,[1,2] Y.-W. Lui,[1] L. McCann,[1,2] L. A. McIntosh,[1] S. Regener,[1] R. Rider,[1,2] S. Schultz,[1,2] M. Q. Sorensen,[1,2] J. Tobar,[1,2] Z. N. Tobin,[1,2] and S. J. Yennello[1,2]

PHYSICAL REVIEW C **109**, 054615 (2024)

History of Doughnut-shaped Nuclei

Nobel Prize in Physics (1975)
Bohr, Mottelson, Rainwater

"…for the discovery of the connection between collective motion and particle motion in atomic nuclei…"

Wheeler (1950) Take-Home Exam (1963)

PRINCETON UNIVERSITY
Physics Department

Physics 576 -- Nuclear Models 22 May 1963

Final "Take-Home" Examination for Those Taking Course for Credit

DOUGHNUT NUCLEI

...ow's recent book, The Biography of Physics, refers in a few passing sentences to unpublished Princeton work on the theory of doughnut shaped nuclei. (1) Develop this theory in the approximation in which the minor radius b of the torus is treated as very small in comparison with the major radius a , and in which the effect of the electrons is neglected.
(Hint: The coulomb energy is the integral over the bent cylinder of the quantity $\frac{1}{2}\rho V$, where ρ is idealized as constant. The charge density per unit length of the ring is $\lambda = \pi b^2 \rho$. Outside the ring treat its electrical potential as if caused by a wire; thus (in e.s.u.),

The Nobel Prize in Physics 1975. NobelPrize.org. Nobel Prize Outreach AB 2023. Sun. 16 Apr 2023. <https://www.nobelprize.org/prizes/physics/1975/summary/>

J.A. Wheeler, Nucleonics Notebook (1950) unpublished
J.A. Wheeler Princeton Graduate Course Physics 576 Take-Home Exam Problem 2, May 22, 1963

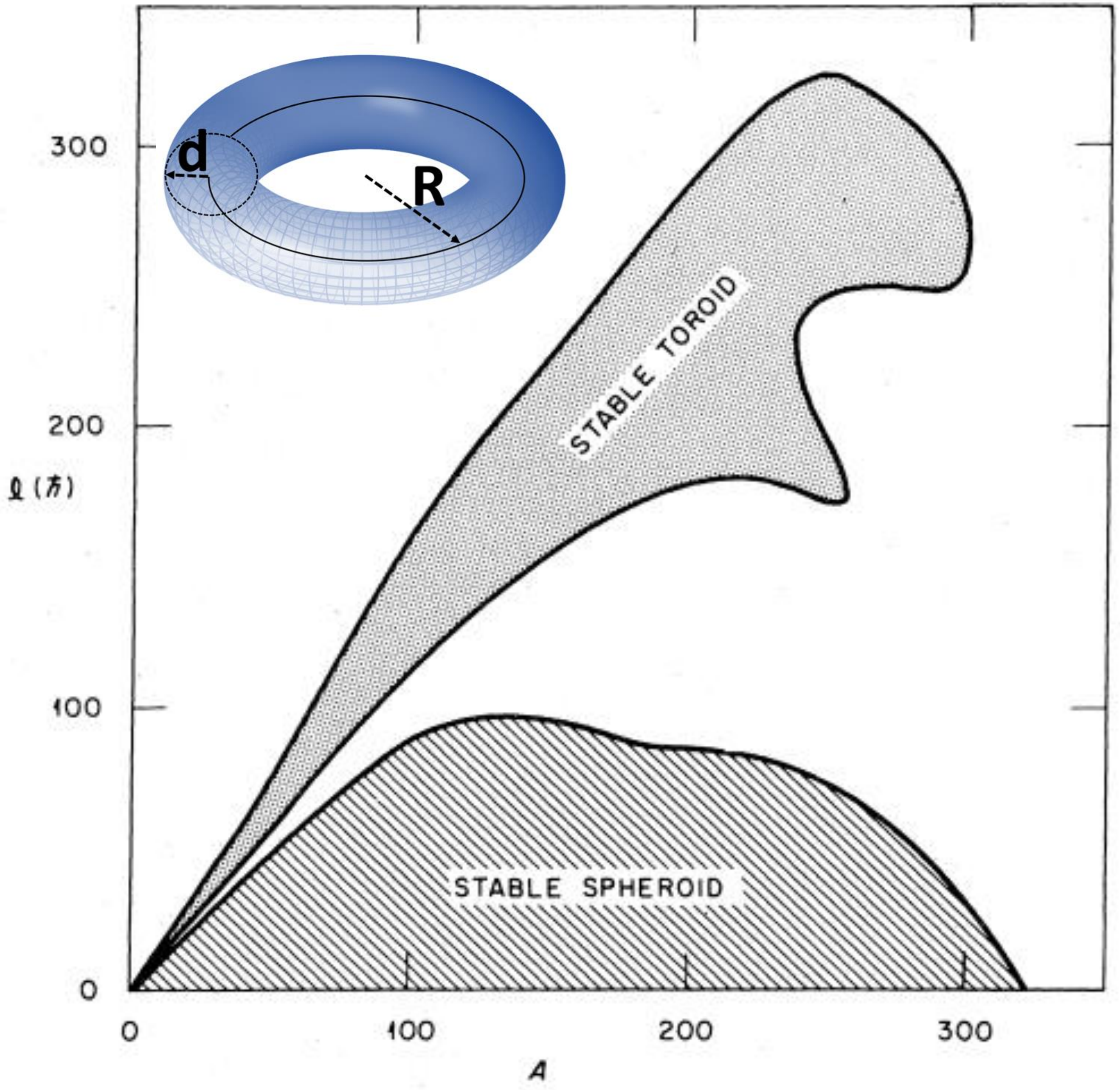
History of Doughnut-shaped Nuclei

Nuclei could take toroidal shapes under certain conditions
"We phycists should think about where such behavior might occur and look for it."
Wheeler, 1963

Excited toroidal shapes for 40 < A < 70
Wong 1972, 1973

Stable toroidal configurations predicted for high angular momentum
Wong 1978

Classical Deformed LDM



C.Y. Wong, Phys Lett. B, 41, 446-450 (1972)
C.Y. Wong, Phys. Rev. C, 17, 331-340 (1978)
T. Ichikawa, Phys. Rev. Lett., 109, 232503 (2012)

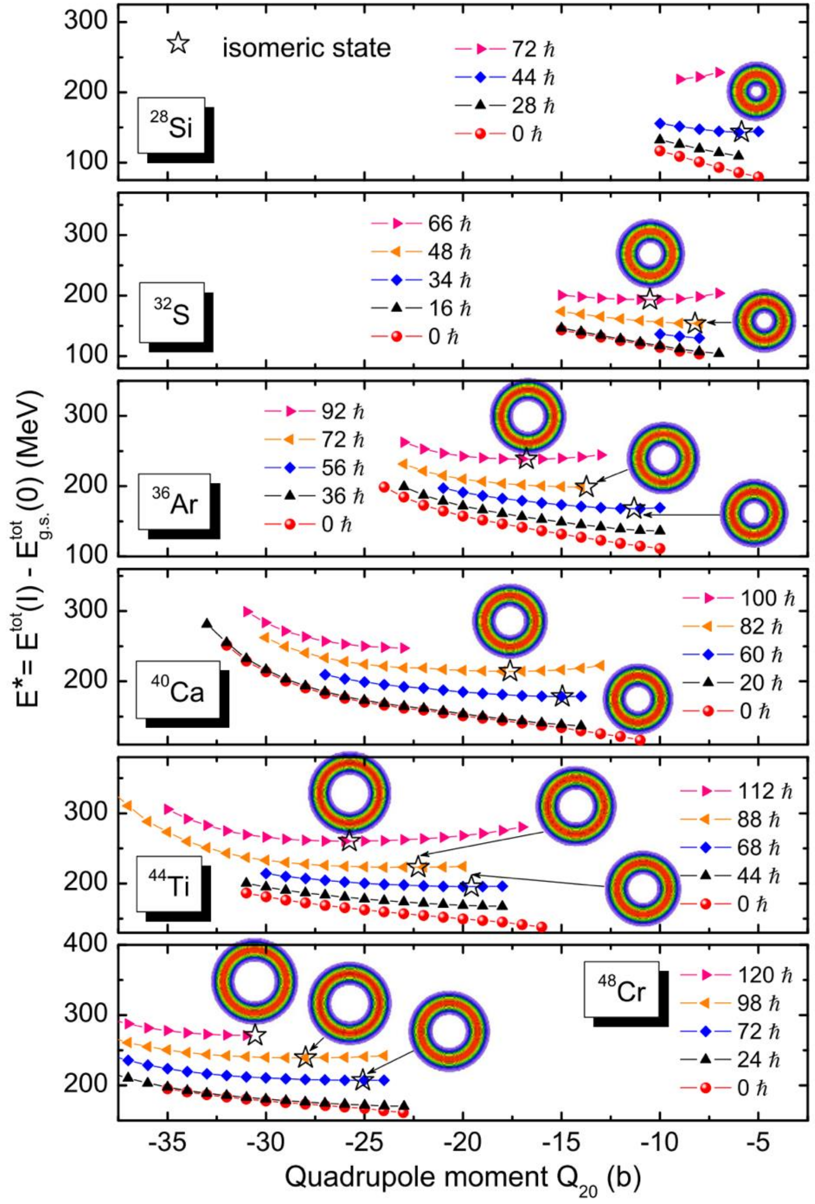
History of Doughnut-shaped Nuclei

Nuclei could take toroidal shapes under certain conditions
"We phycists should think about where such behavior might occur and look for it."
Wheeler, 1963

Excited toroidal shapes for 40 < A < 70
Wong 1972, 1973

Stable toroidal configurations predicted for high angular momentum
Wong 1978

Microscopic calculations predict existence of toroidal isomers in light nuclei
Focus on alpha conjugate nuclei
Ichikawa, et al.
Staszczak and Wong (2014)



Cranked self-consistent Skyrme Hartree Fock

A. Staszczak and C.Y. Wong, Phys. Lett. B, 738, 401 (2014).

History of Doughnut-shaped Nuclei

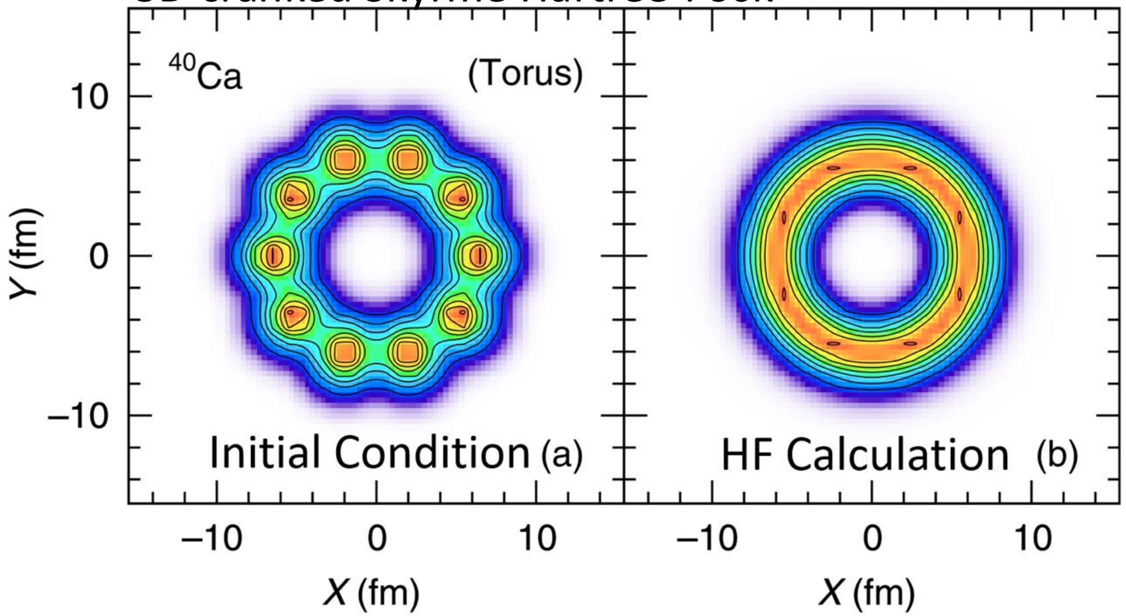
Alpha-conjugate nuclei have
states composed of alpha clusters

- High binding energy of 4He
- High excitation to first excited 4He state

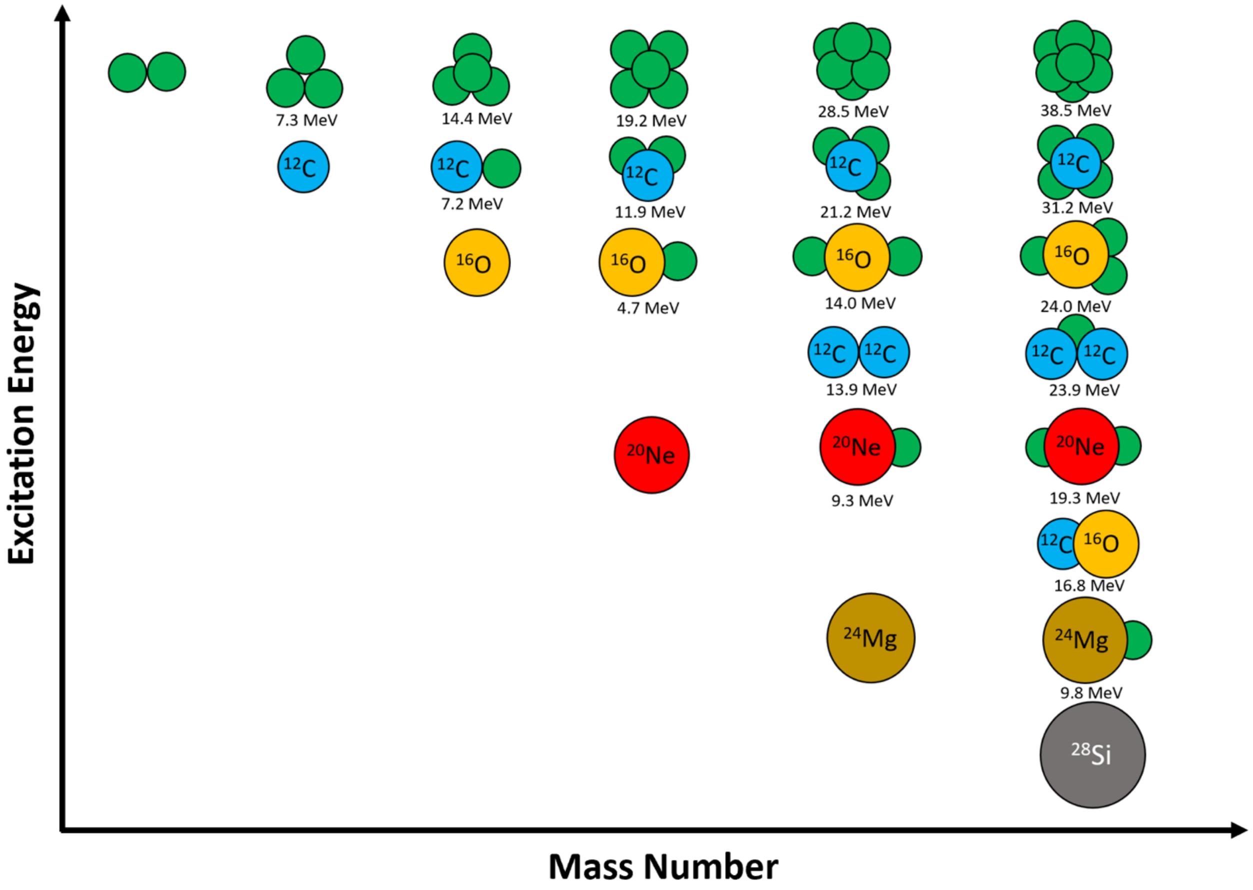
Cluster degrees of freedom are accessible at
sufficiently high excitation

- Cluster, multi-cluster breakup is allowed

3D cranked Skyrme Hartree-Fock



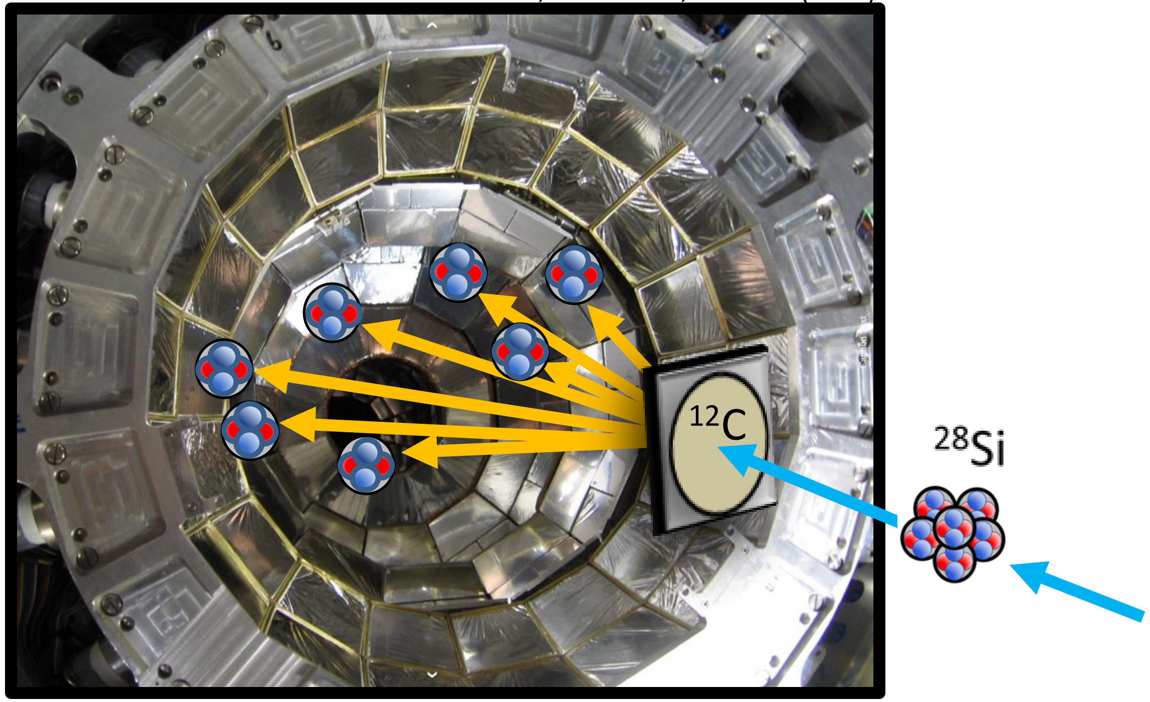
T. Ichikawa, Phys. Rev. Lett., 109, 232503 (2012)



NIMROD

Experiment at Texas A&M University
28Si + 12C @ 35 MeV/u

S. Wuenschel et al., NIM A 604, 578-583 (2009)



Measure Energy, Z, A

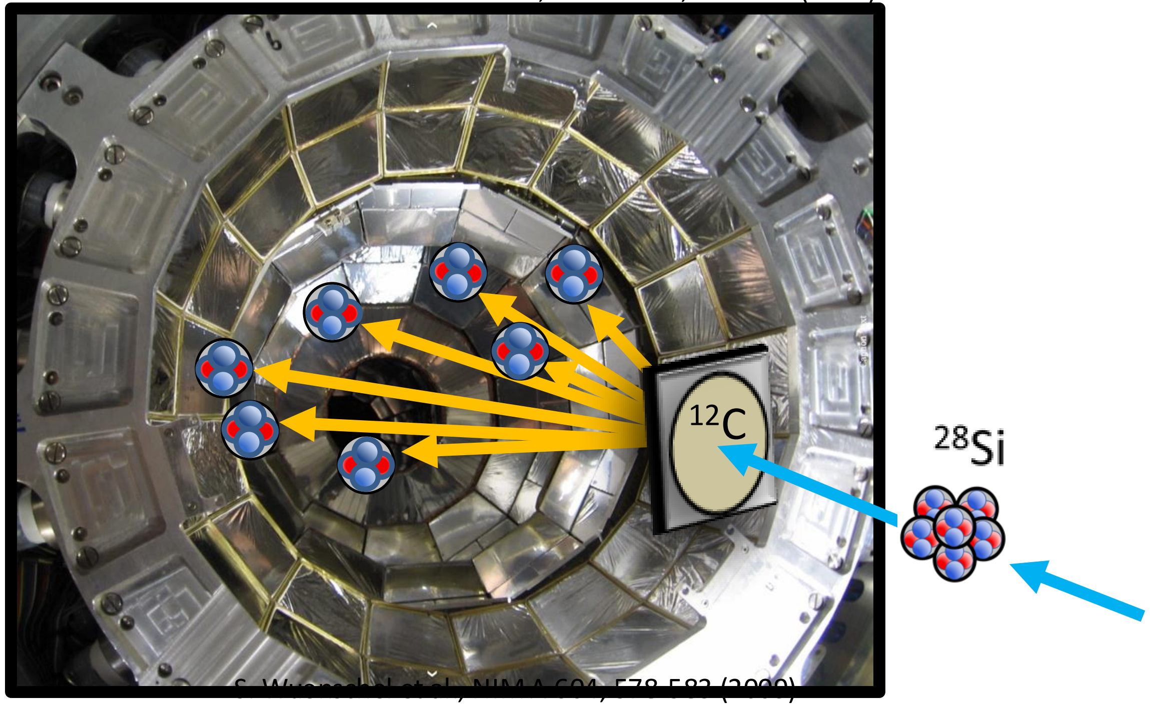
NIMROD

Experiment at Texas A&M University
28Si + 12C @ 35 MeV/u

Reconstruct excited 28Si from products

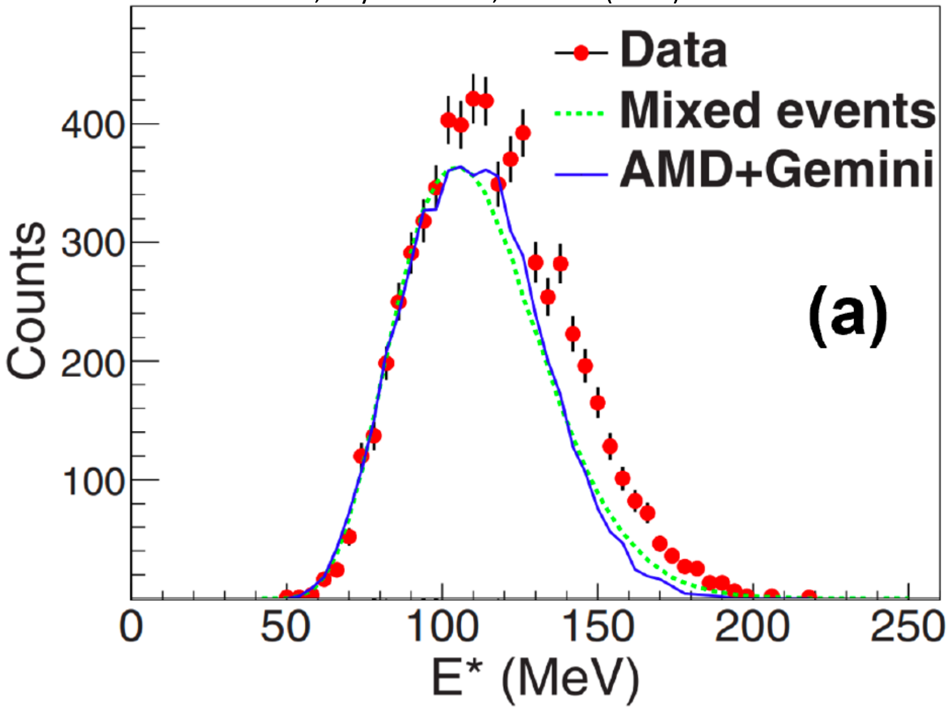
$$E^* = \sum_i E_i + Q$$

S. Wuenschel et al., NIM A 604, 578-583 (2009)



Measure Energy, Z, A

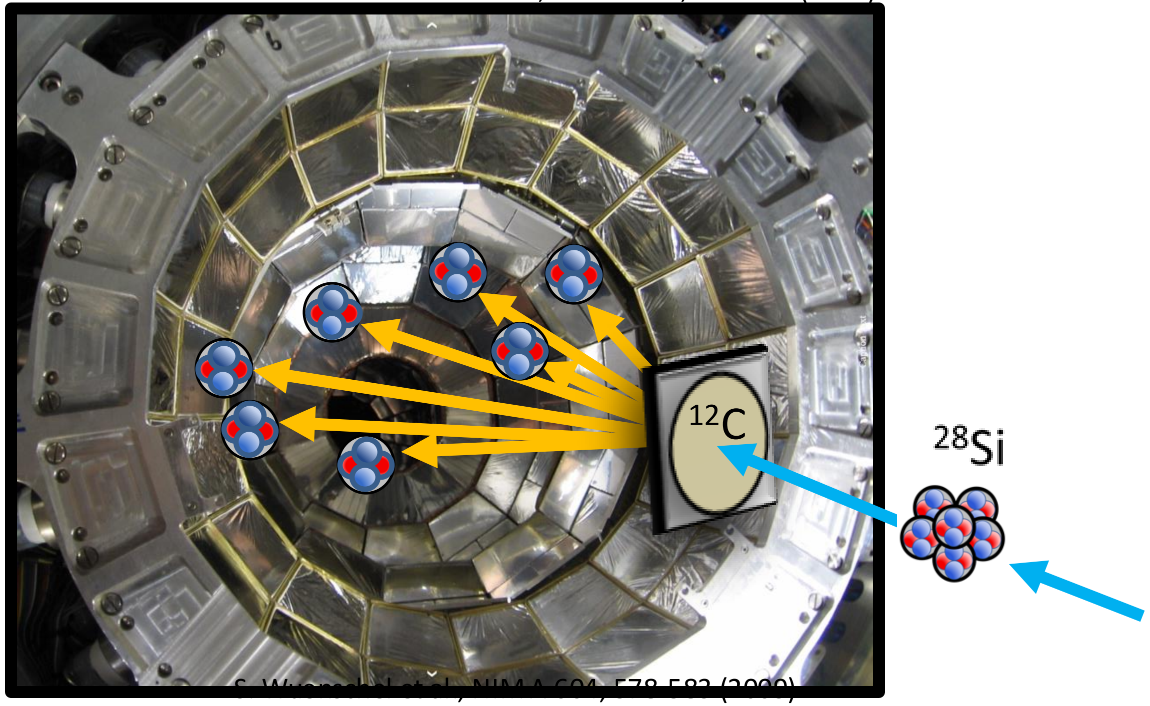
X.G. Cao et al., Phys Rev C 99, 014606 (2019)



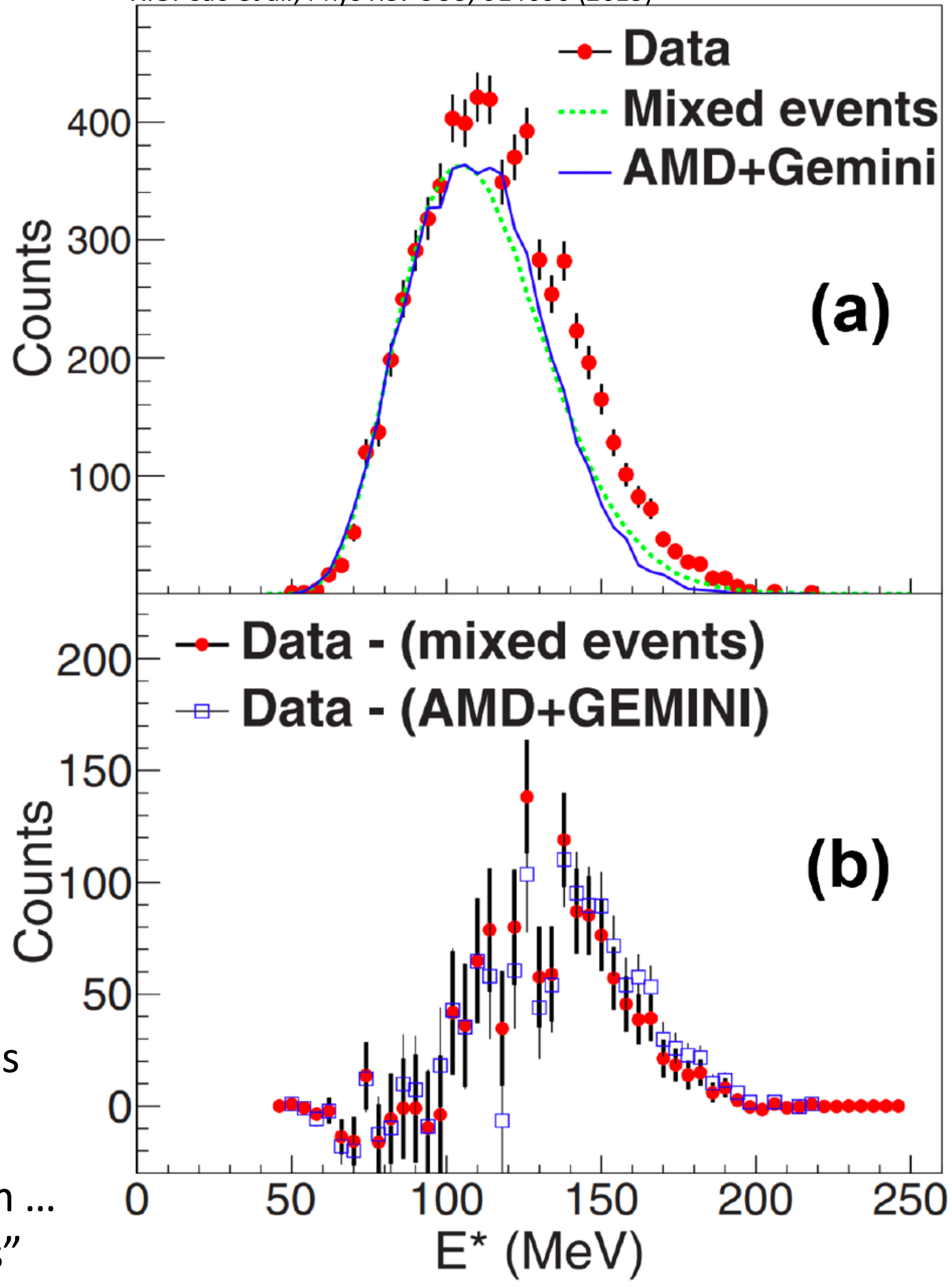
NIMROD

Experiment at Texas A&M University
28Si + 12C @ 35 MeV/u

S. Wuenschel et al., NIM A 604, 578-583 (2009)



X.G. Cao et al., Phys Rev C 99, 014606 (2019)



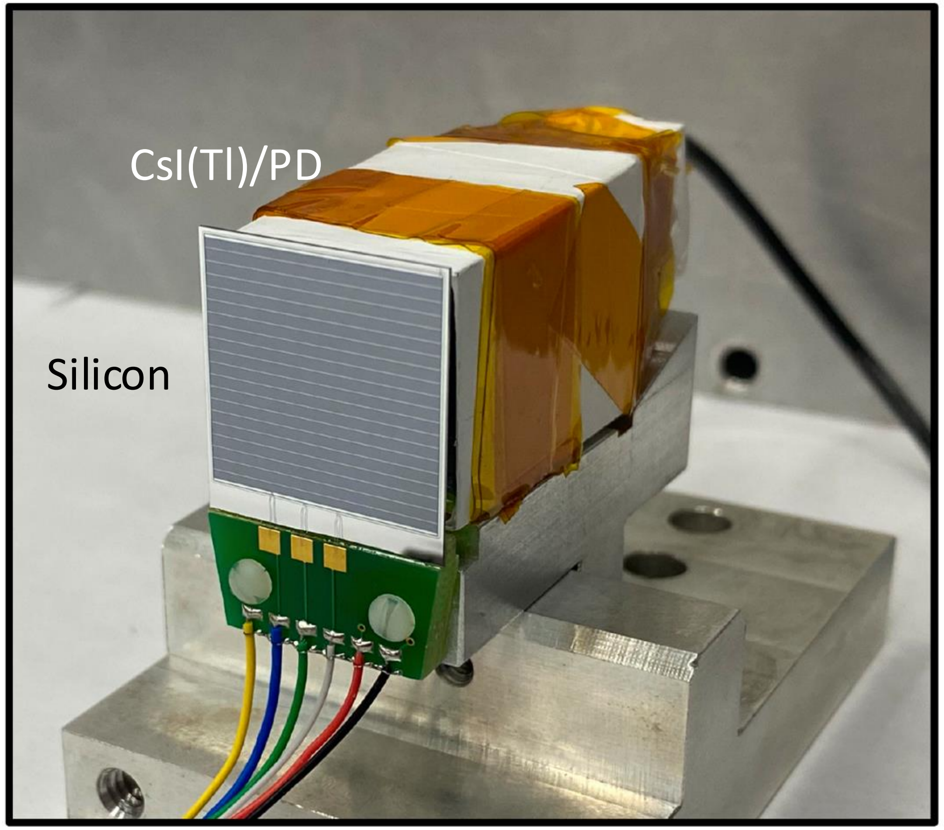
Measure Energy, Z, A

Yield above estimated background suggests existence of high-energy resonances.

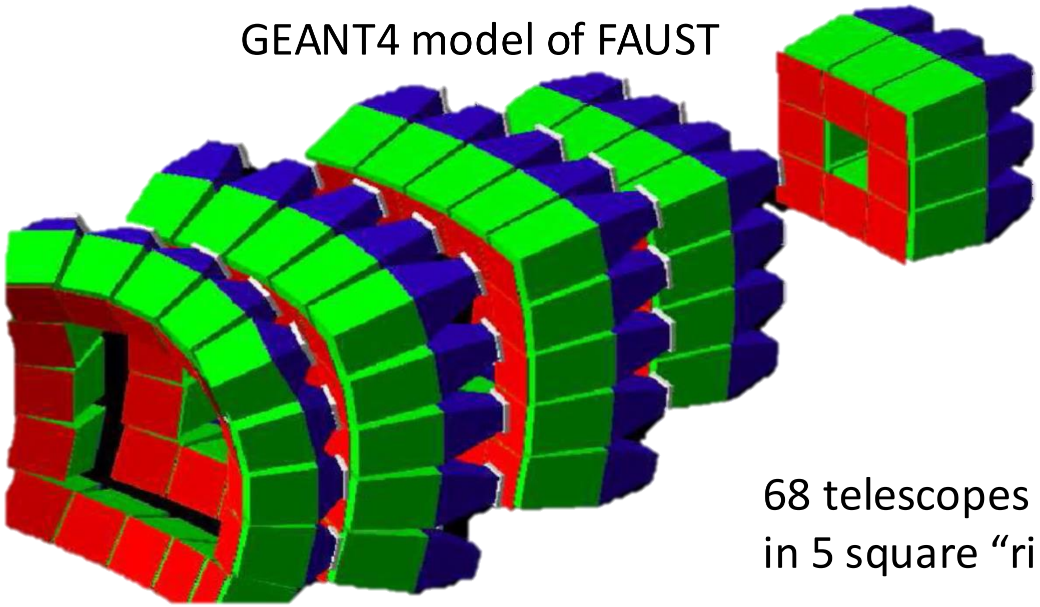
"A higher granularity detector system … could offer significant improvements"

FAUST

1 of 68 FAUST detectors



GEANT4 model of FAUST

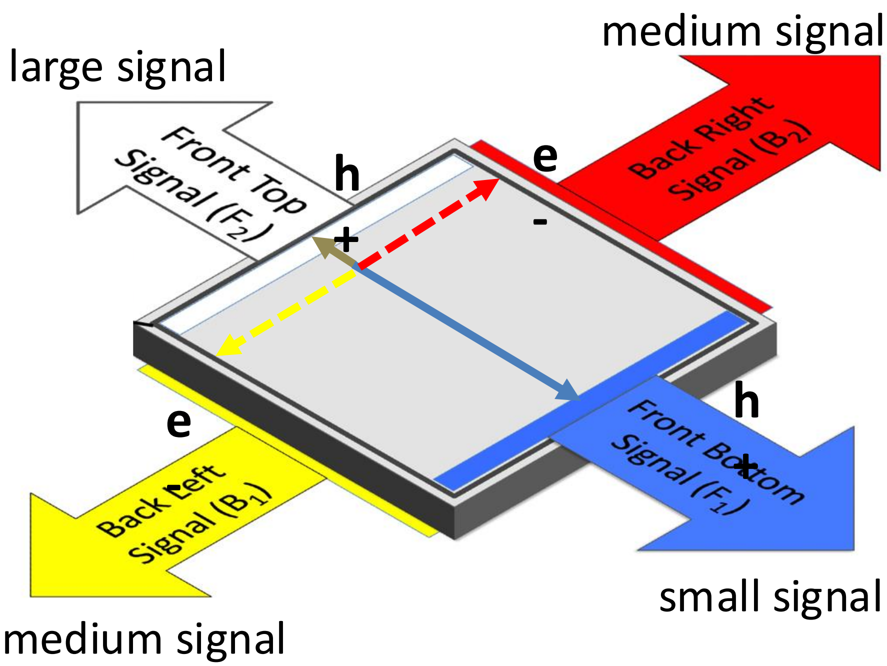


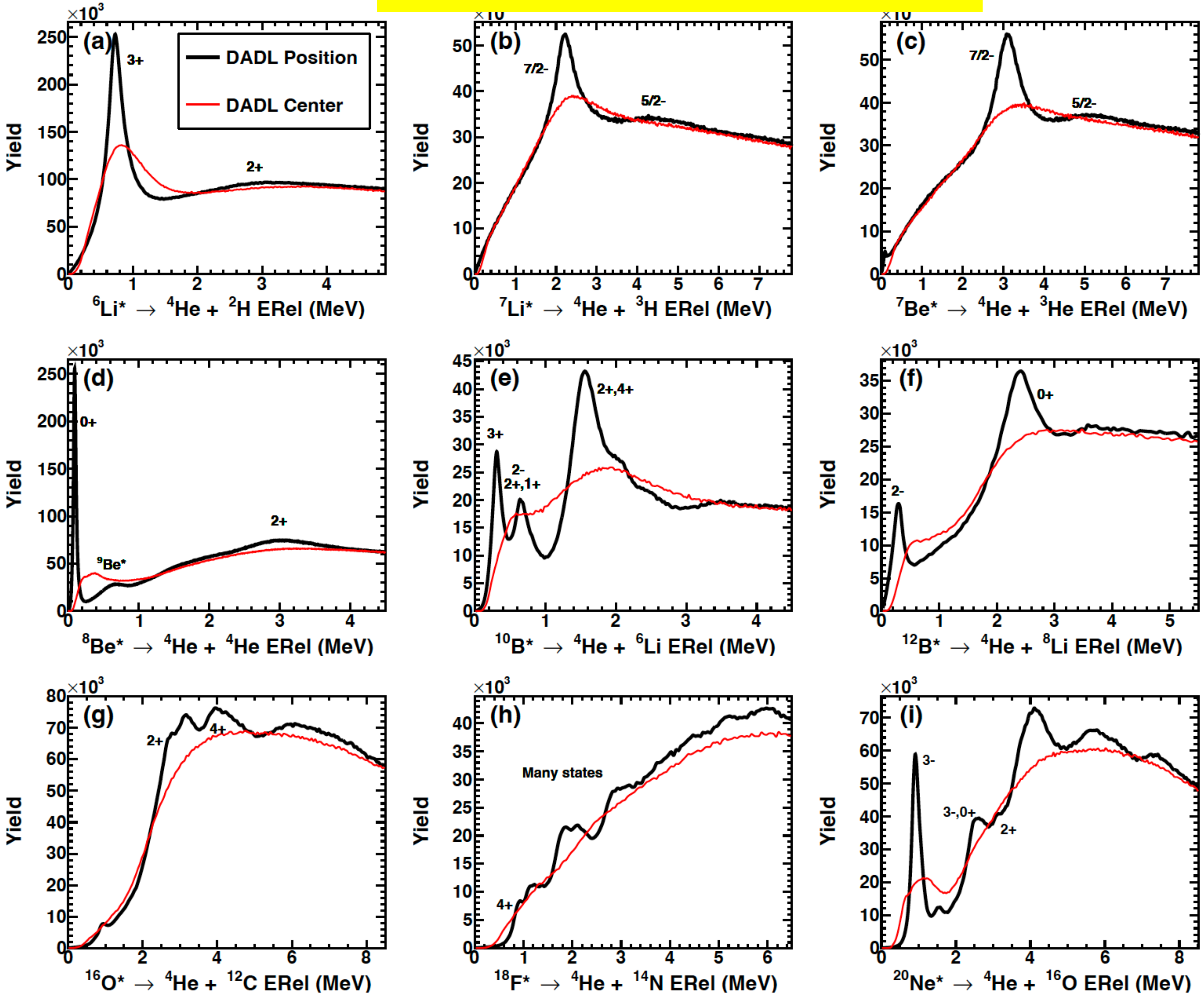
68 telescopes
in 5 square “rings”

Coverage from 1.6 to 45 degrees
Energy in Si & CsI
Particle ID in Si vs CsI
Position in the Dual-Axis Duo-Lateral Silicon (DADL)

FAUST: Position Resolution with DADL

Excellent position resolution leads to excellent excited state resolution





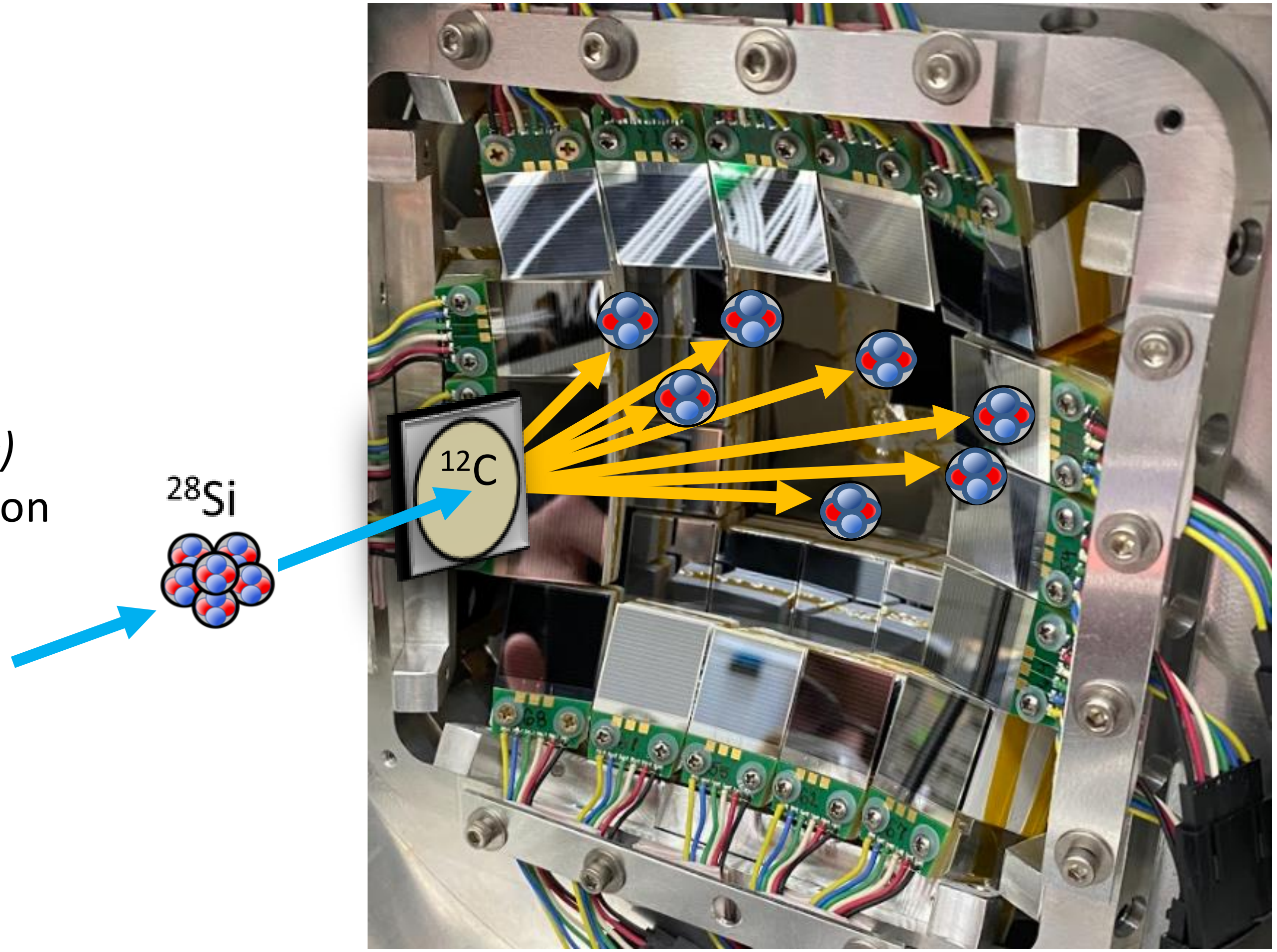
Angular resolution < 1 degree for alphas around 30 MeV/u

FAUST

Measurement with FAUST in 2021

Measure 28Si + 12C @ 35 MeV/u *(same system as before)*
with excellent position resolution → excellent E* resolution
with improved statistical errors (20x more events)

With an improved measurement, can we observe more clearly the resonances suggested by Cao et al in the alpha disassembly of 28Si?



28Si E* distribution

In our new experiment with FAUST, with

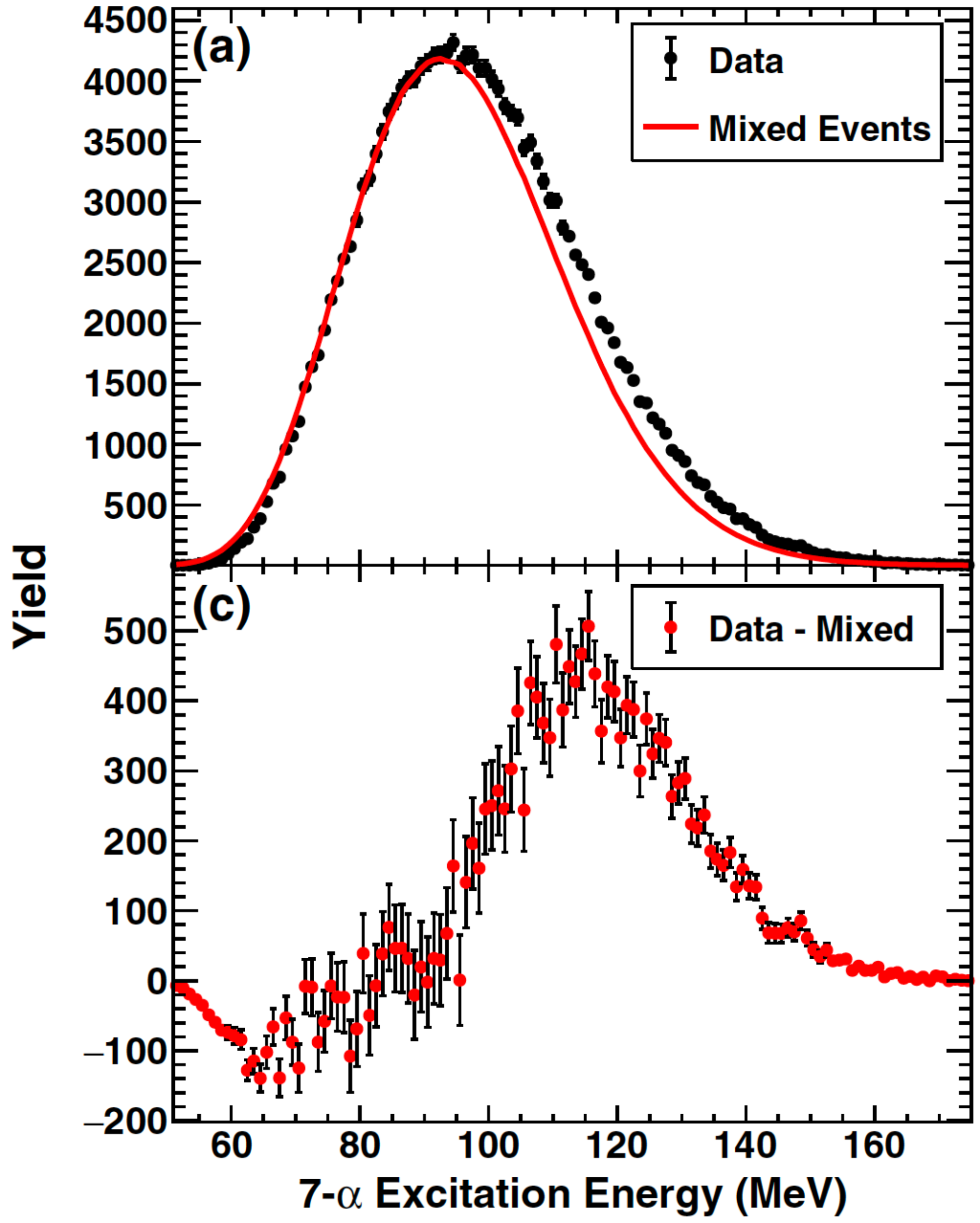
- improved position resolution, and
- improved statistical uncertainty

→ no resolved peaks

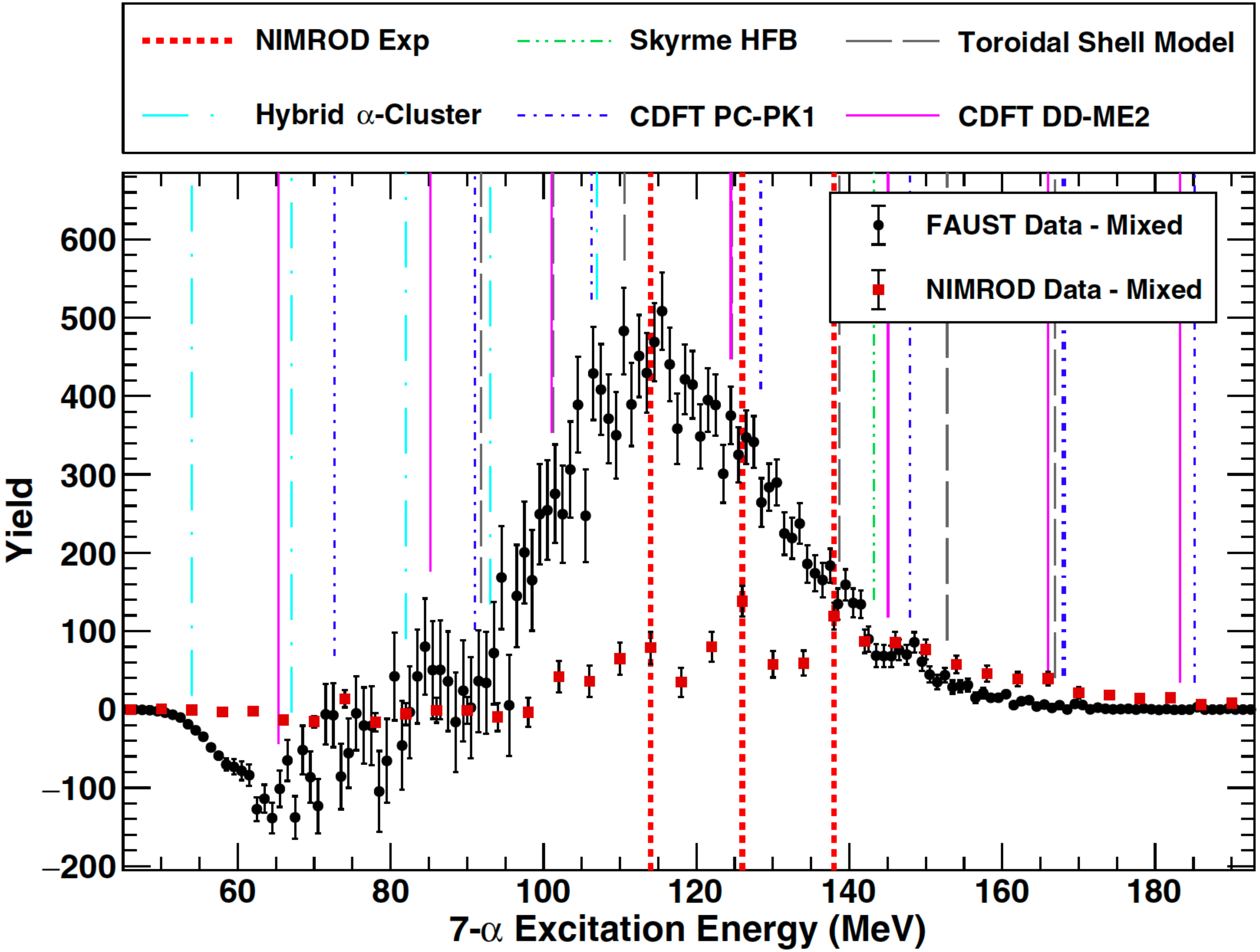
Mixed events:

- agreement at low E*
- underprediction at high E*

→ No obvious resonant structure in excess yield



Comparison:
FAUST & NIMROD measurements



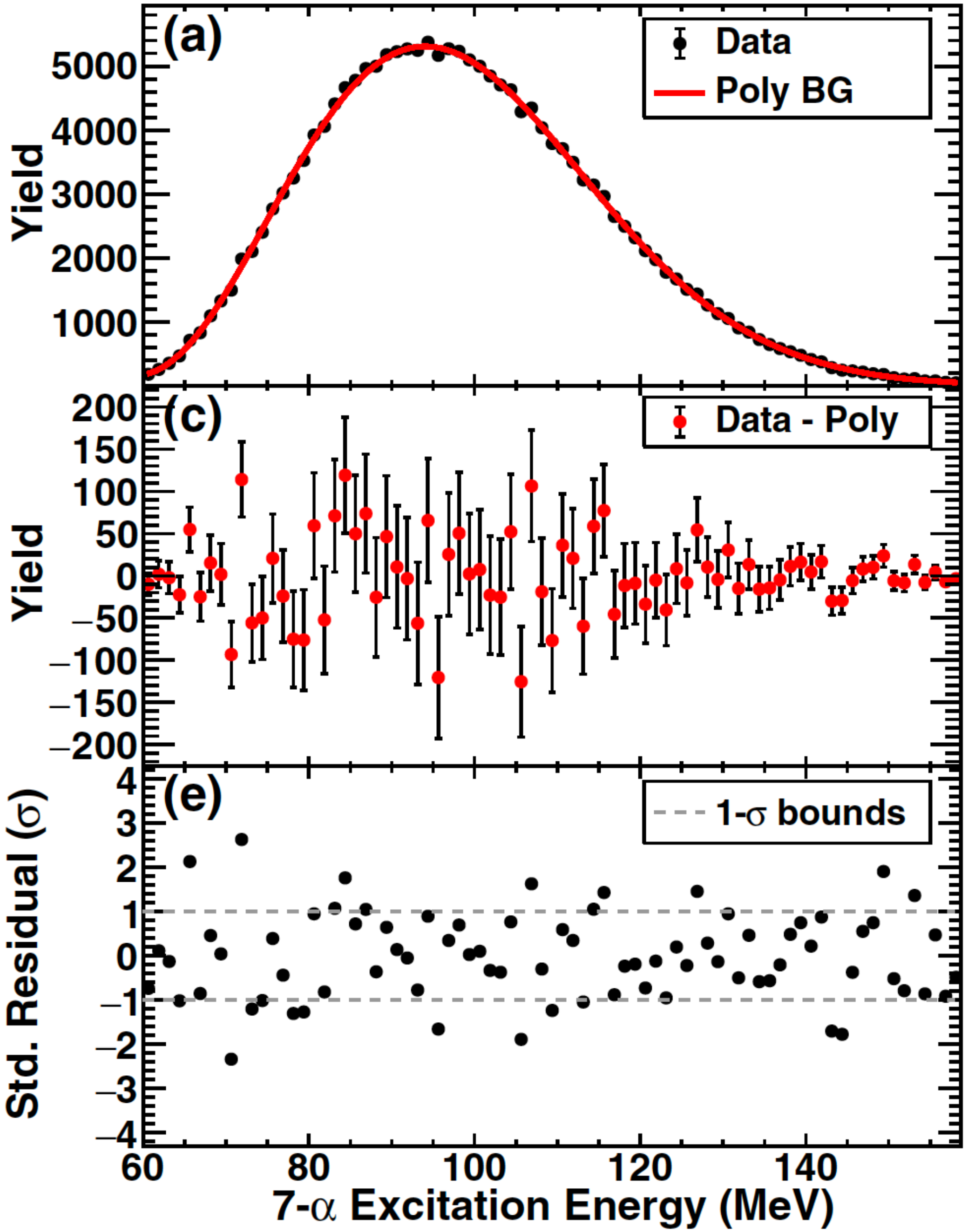
Statistical Analysis
Structure in the E* distribution?

1) Fit a smooth polynomial to the data
2) Take the difference between data and fit
3) Calculate standard residuals
   (difference normalized by uncertainty)

68% of the data should lie within 1σ,
95% should like within 2σ.

It does.
→ There are no narrow resonances.

There may be very broad resonances
which the polynomial captures.



No strong evidence of resonances in
28Si + 12C@ 35 MeV/u with FAUST.

Can we set upper limits on the cross sections
for populating resonant states?

How do these compare to the
candidate states suggested by NIMROD?

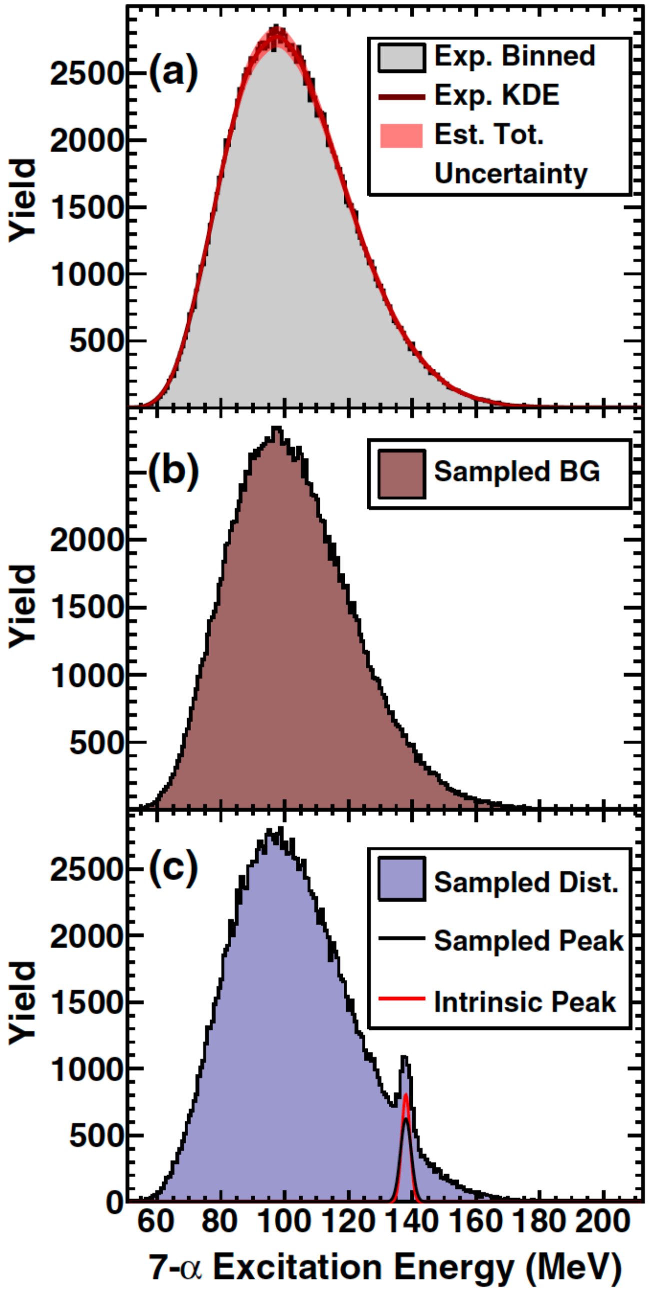
Modeling to set upper limits

1) Take experimental distribution, including uncertainties
2) Extract Kernel Density Estimate (KDE) so you have a smooth distribution to sample

3) Sample the KDE (it should look like the measured distribution)

4) Sampling the KDE and a narrow, intense Gaussian gives a distribution like the data, but with a peak on it

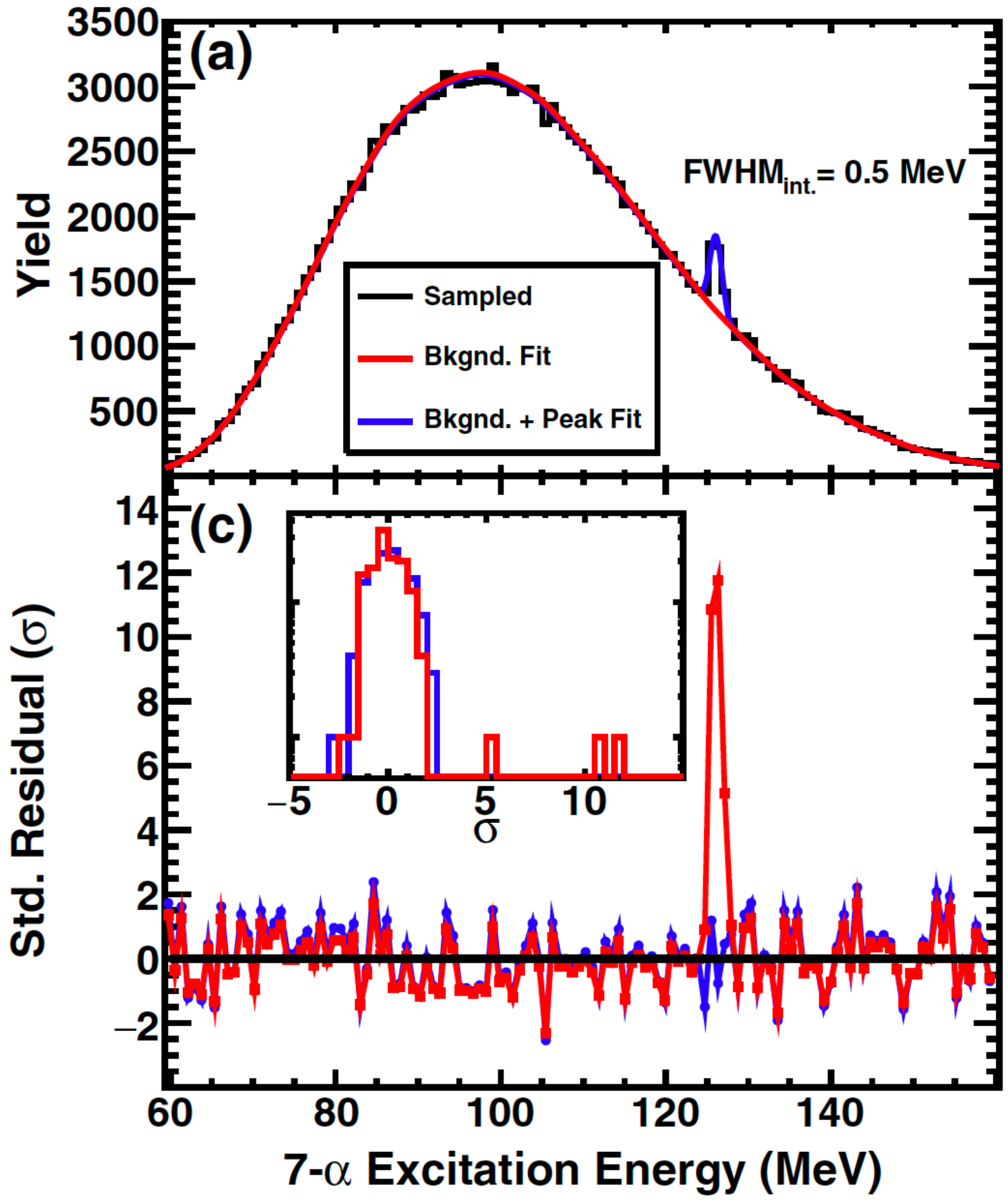
We can vary the intensity and width of the added Gaussian until it disappears; upper limits.



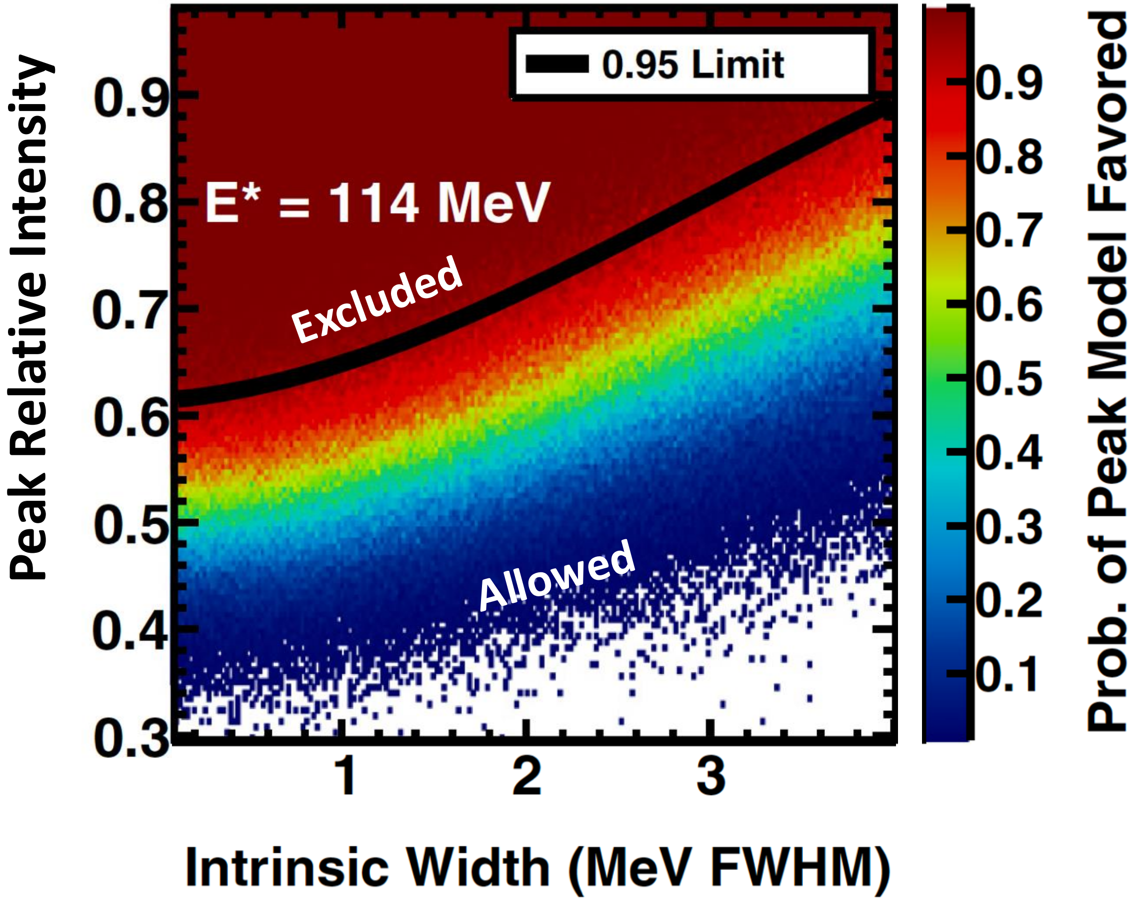
Modeling to set upper limits

5) Try fitting the distribution with the added peak with
   a) background plus peak
   b) background only
6) Calculate standard residuals: the better fit has better standard residuals

Repeat for many
a) peak intensities
b) peak widths



Modeling to set upper limits



Excluded region:
The standard residuals are smaller if
a peak is included in the fit.
A peak would be resolvable.

Allowed region:
The standard residuals are smaller if
a peak is not included in the fit.
A peak would not be resolvable.

Therefore
(given the measured E* distribution,
and the detector resolution)
the distribution shows the probability that a peak could exist at a particular E* (114 MeV) for any particular intensity and width.

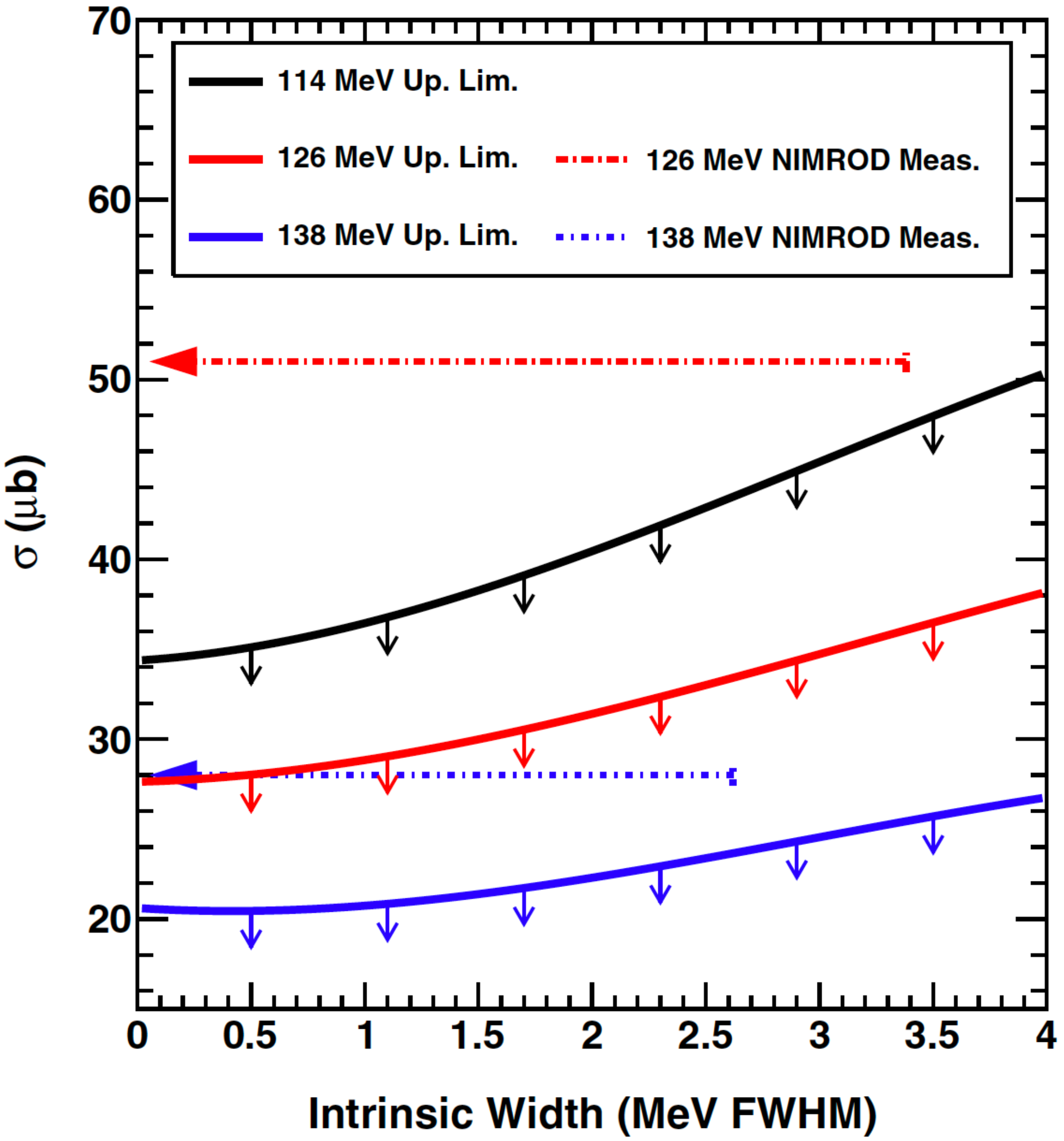
A limit at 95% confidence is established.

Upper limits on the cross section

Cao et al (NIMROD) reported three possible resonances.
For two, cross sections were reported.
The dashed lines show the allowable resonance width, given the measured distribution and the detector resolution.

Hannaman et al (FAUST),
via the analysis described,
does not observe distinguishable peaks,
and sets upper limits on the cross section
as a function of width.

The FAUST upper limits exclude the NIMROD candidates.



Summary

Model calculations suggest that spin-stabilized toroidal resonances may exist.
In alpha conjugate nuclei, these could break up into alpha clusters.

Cao et al sought to observe this in NIMROD data, and found possible candidates,
though the detector was not optimized for this measurement.

We (Hannaman et al) sought to observe this using FAUST,
with excellent angular resolution and improved statistical uncertainty.
There is no strong evidence for high E* resonances.
Upper limits are established.

The existence of toroidally deformed nuclei remains unconfirmed.
Perhaps they do not exist.
Perhaps their production is extremely rare.
Perhaps their decays pathways are of a different sort.

Collective motion, nucleon motion, deformation, and cluster breakup
remain important and active topics in nuclear science.

And we have tools to address this.

PHYSICAL REVIEW C **109**, 054615 (2024)

Experimental search for toroidal high-spin isomers in collisions of $^{28}Si + ^{12}C$ at 35 MeV/nucleon with the Forward Array Using Silicon Technology

A. Hannaman,[1,2,*] B. Harvey,[1,3] A. B. McIntosh,[1,†] K. Hagel,[1] A. Abbott,[1,2] A. Fentress,[1,2] J. Gauthier,[1] T. Hankins,[1,2] Y.-W. Lui,[1] L. McCann,[1,2] L. A. McIntosh,[1] S. Regener,[1] R. Rider,[1,2] S. Schultz,[1,2] M. Q. Sorensen,[1,2] J. Tobar,[1,2] Z. N. Tobin,[1,2] and S. J. Yennello[1,2]

[1]*Cyclotron Institute, Texas A&M University, College Station, Texas 77843, USA*
[2]*Chemistry Department, Texas A&M University, College Station, Texas 77843, USA*
[3]*Physics Department, Texas A&M University, College Station, Texas 77843, USA*

(Received 12 November 2023; revised 24 March 2024; accepted 17 April 2024; published 16 May 2024)

EXPERIMENTAL SEARCH FOR TOROIDAL HIGH-SPIN ISOMERS IN COLLISIONS OF $^{28}\mathrm{Si} + ^{12}\mathrm{C}$ AT 35 MEV/NUCLEON USING FAUST

A Thesis

by

ANDREW J. HANNAMAN