Study of $^{4}He(^{4}He,^{4}He)^{4}He^{*}$ inelastic scattering at the MAGNEX facility

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Outline

- ❖Introduction
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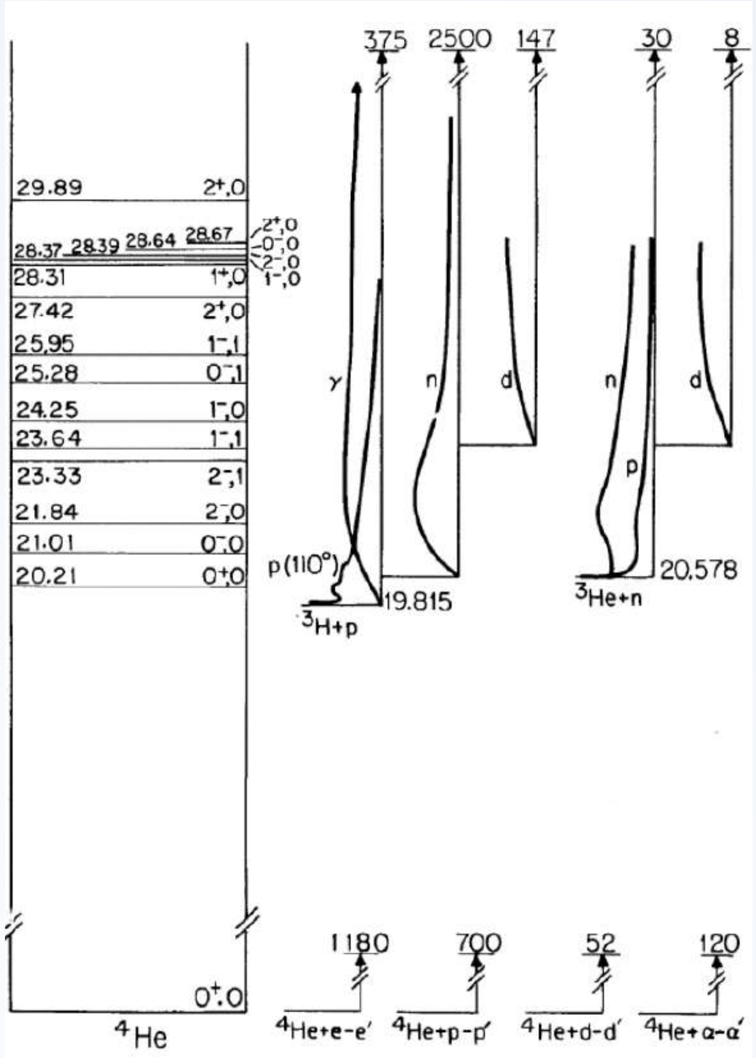
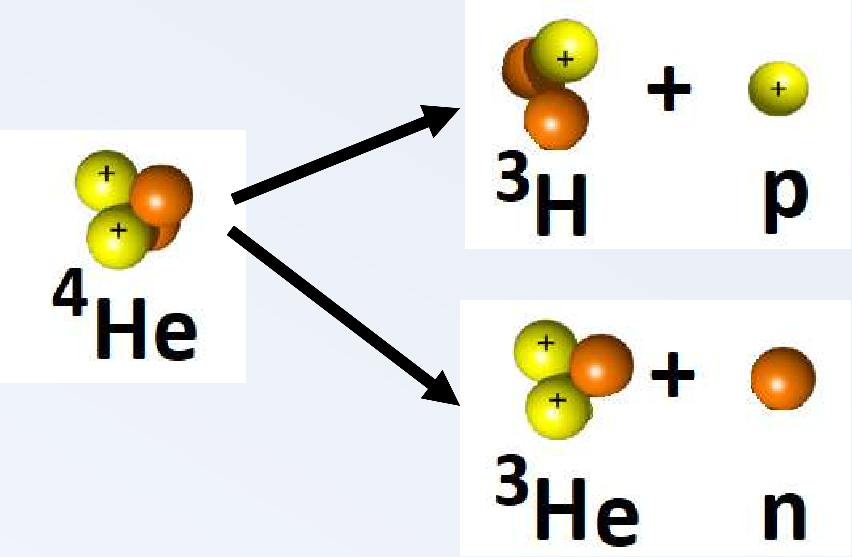
  - ➢ Recent theoretical studies
  - ➢ Existing $^{4}He(e,e')^{4}He^{*}$ and $^{4}He(^{4}He,^{4}He)^{4}He^{*}$ studies
- ❖Experimental setup
- ❖Particle identification
- ❖Results
  - ❖ Elastic scattering
  - ❖ Inelastic scattering (& simulations !)
- ❖Fano analysis
- ❖Theoretical interpretation
- ❖Summary and perspectives

The physics case



D.R. Tilley et al., Nucl. Phys. A 541, 1 (1992)



BU_{th}=19.8 MeV

BU_{th}=20.6 MeV

E_x (MeV)	J^π	T	Γ_p (MeV)	Γ_n (MeV)	Γ_d (MeV)	Γ (MeV)	Decay
g.s.	0^+	0					
20.21	0^+	0	0.50	0.00	0.00	0.50	p
21.01	0^-	0	0.64	0.20	0.00	0.84	p, n
21.84	2^-	0	1.26	0.75	0.00	2.01	p, n
23.33	2^-	1	2.64	2.37	0.00	5.01	p, n
23.64	1^-	1	3.44 [a]	2.76 [a]	0.00	6.20	p, n, (γ)
24.25	1^-	0	3.08 [a]	2.87 [a]	0.15	6.10	p, n, d
25.28	0^-	1	4.12	3.85	0.00	7.97	p, n
25.95	1^-	1	6.52 [b]	6.14 [b]	0.00	12.66	p, n, γ
27.42	2^+	0	0.25	0.23	8.21 [c]	8.69	p, n, d
28.31	1^+	0	4.72	4.66	0.51	9.89	p, n, d
28.37	1^-	0	0.07	0.08	3.77	3.92	(p, n), d
28.39	2^-	0	0.02	0.02	8.71	8.75	(p, n), d
28.64	0^-	0	0.00	0.00	4.89	4.89	d
28.67	2^+	0	0.00	0.00	3.78 [d]	3.78	d, γ
29.89	2^+	0	0.04	0.04	9.64 [e]	9.72	(p, n), d

[a] Primarily $^3P_1$. [b] Primarily $^1P_1$. [c] Primarily $^5S_2$. [d] Primarily $^1D_2$. [e] Primarily $^5D_2$.

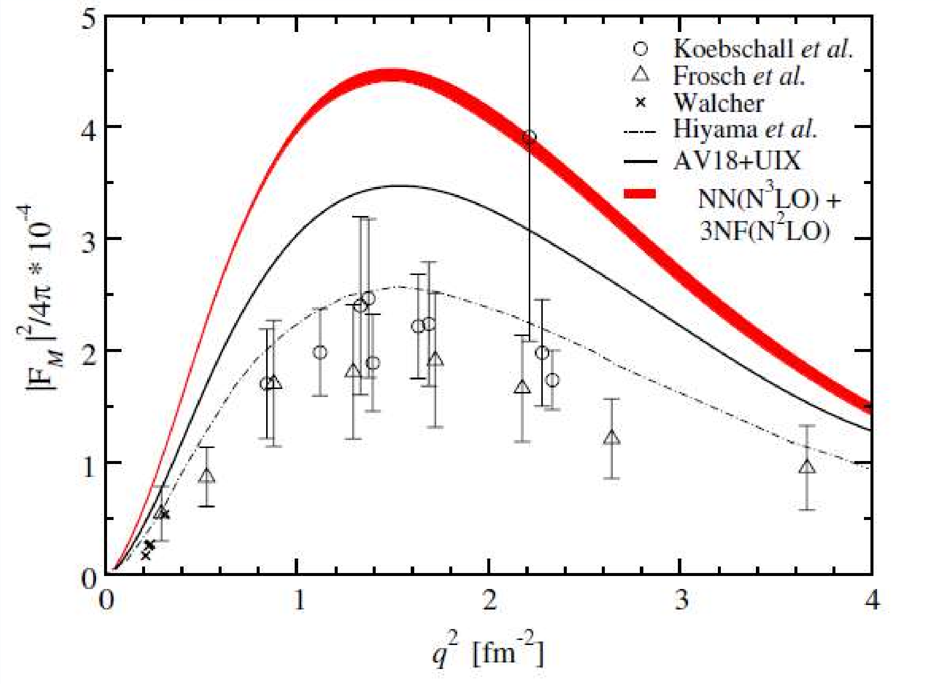
Resonance energy and width were obtained as an average of very different values

- ✓ It is important to extract in a modern measurement the position and width of the first 0^+ resonance with a better accuracy with respect to previous $^4He(^4He,^4He)^4He^*$ and $^4He(e,e')^4He^*$ data

Recent theoretical studies (1)

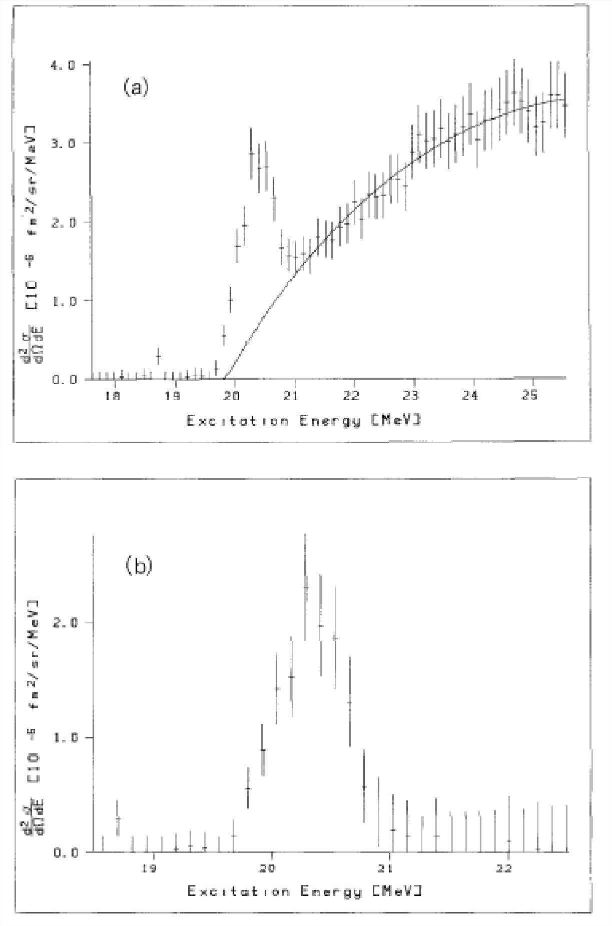
- A recent **ab-initio calculation** of the monopole transition form factor of ^{4}He with realistic nuclear forces
  - pointed to a strong dependence on the different realistic potentials used
  - a significant disagreement with respect to all existing electron scattering data was found when a method based on modern 3-body Hamiltonians from chiral perturbation theory was adopted.

S. Bacca, et al., Phys. Rev. Lett. 110, 042503 (2013)



- The puzzling inconsistency between the recent ab-initio form factor calculation and the existing data from ^{4}He(e,e')^{4}He* makes **necessary the further investigation of the subject with increased precision**.

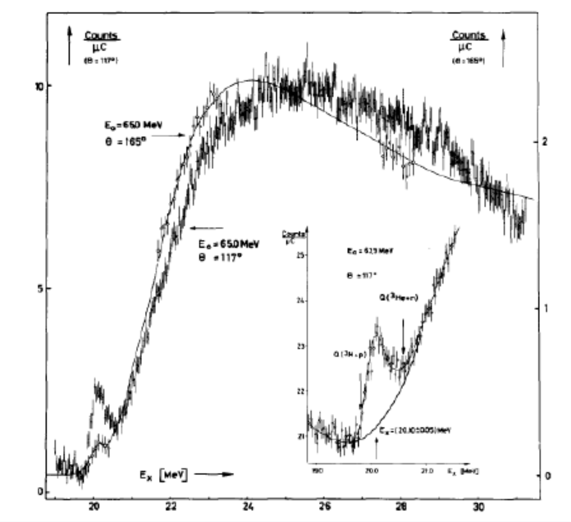
Existing $^4He(e,e')^4He^*$ experimental data



G. Kobschall et al. NPA 405, 648 (1983)

E* = 20.12 ± 0.16 MeV

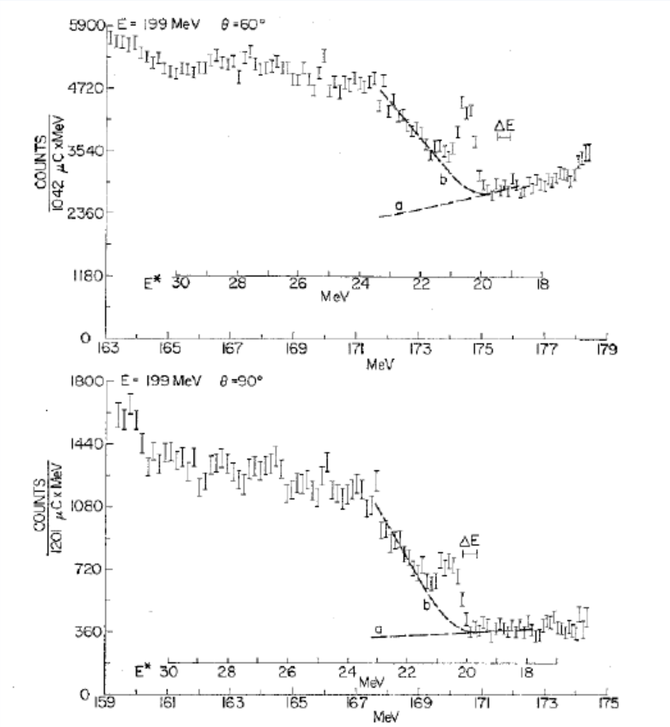
Γ = 0.24 ± 0.07 MeV



T. Walcher, Phys. Lett. B 31, 442 (1970)

E* = 20.10 ± 0.05 MeV

Γ = 0.27 ± 0.05 MeV



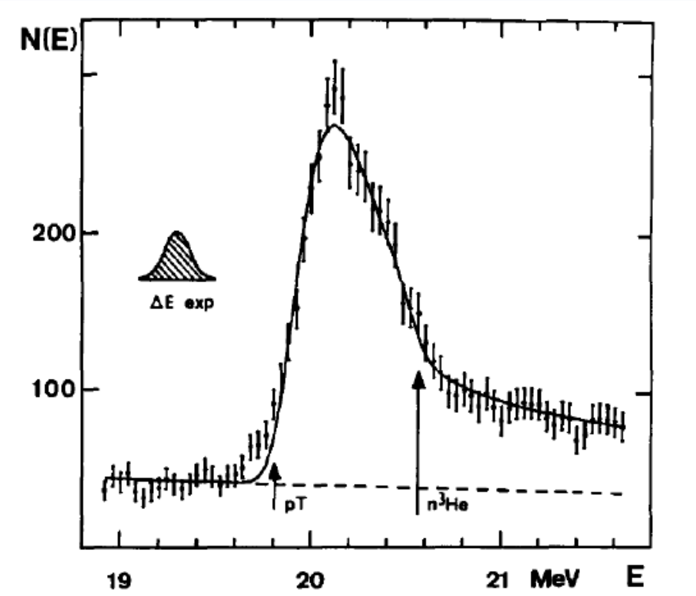
R.F. Frosch et al. NPA 110, 657 (1968)

E* = 20.29 ± 0.16 MeV

Γ = 0.39 ± 0.10 MeV

- Large background
- The reported centroids seem to agree

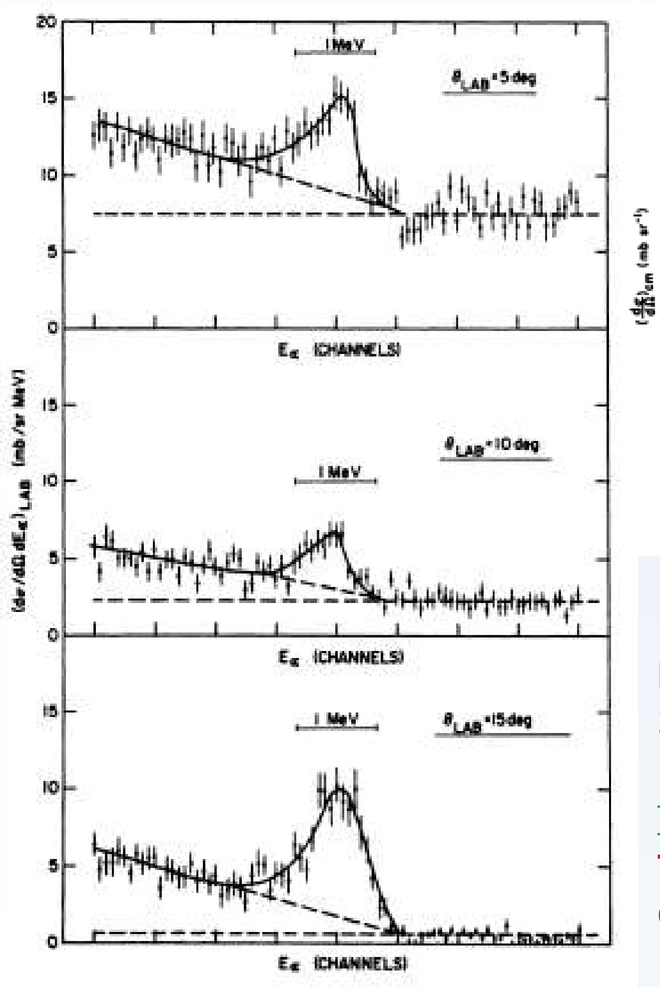
Existing $^4He(^4He,^4He)^4He^*$ experimental data

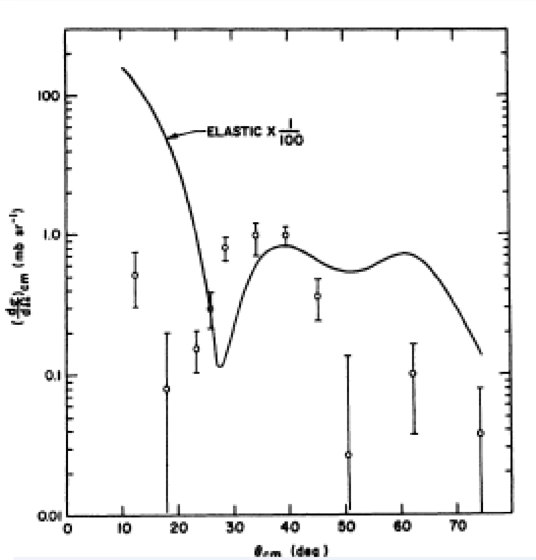


M. Baumgartner et al., Nucl. Phys. A 368, 189 (1981)

E* = 20.29 ± 0.02 MeV

Γ = 0.89 ± 0.04 MeV





E.E. Gross et al., Phys. Rev. 178, 1584 (1969)

E* = 20.28 ± 0.05 MeV

Γ = 0.41 ± 0.05 MeV

The only available angular distribution

- Small background
- Larger obtained widths with respect to (e,e’) studies

(e,e´) vs (^{4}He,^{4}He*)

^{4}He(e,e´)^{4}He*

Positive features

- Pure electro-magnetic
- Direct access to the form factor

Negative features

- Mixed isoscalar and isovector probe
- Only protons are involved
- The higher multipolarities cannot be excluded (dipole, quadrupole ...)
- Very low cross sections

^{4}He(^{4}He,^{4}He)^{4}He*

Positive features

- Purely isoscalar
- Large cross section
- Higher multipolarities easier to be unfolded

Negative features

- Involves the nuclear force
- The monopole form factor must be extracted from the measured cross section by optical model analysis

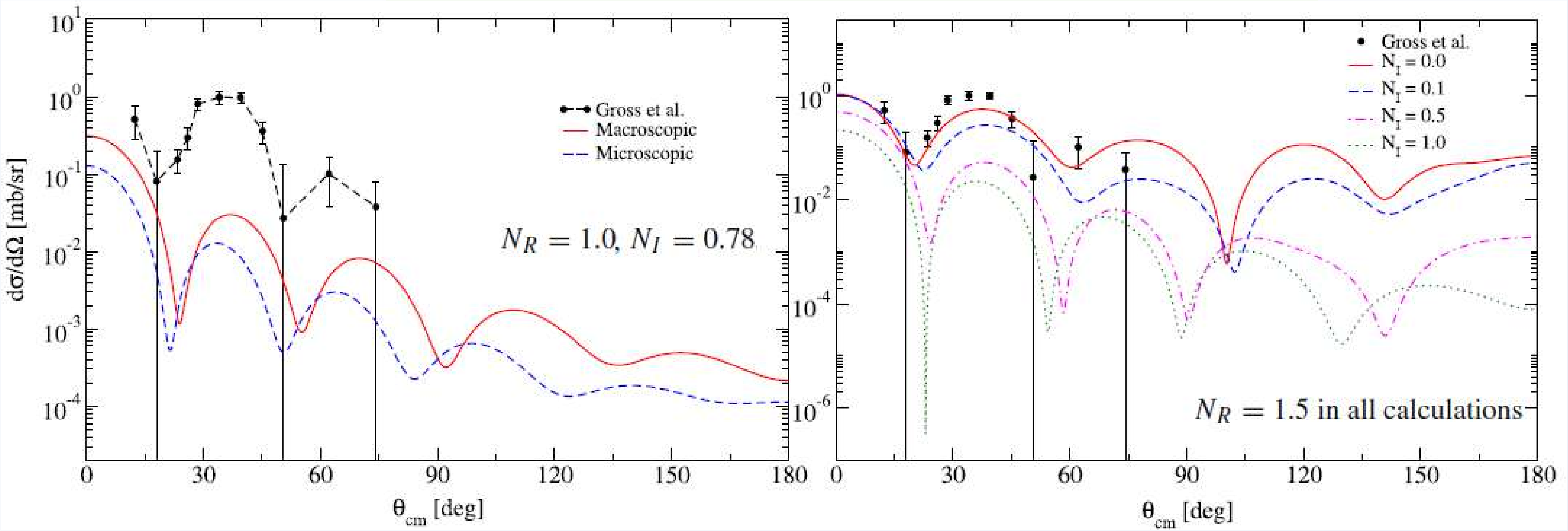
➢ **Study the first excited 0^+ state in ^{4}He with an hadron probe involving a nuclear field**

Recent theoretical studies (2)

- ❑ In a recent work by Kucuk, Karakoc and Vitturi
- ➢ the transition densities to 0^+ state were calculated and nuclear form factors were constructed by folding procedure
- ➢ cross section angular distributions were calculated for the first excited 0^+ state of ^{4}He by using both **macroscopic** and **microscopic** models

Comparison with the experimental data of Gross et al. at 64 MeV

Y. Kucuk et al., Eur. Phys. J. A 57, 37 (2021)



The proposed experiment

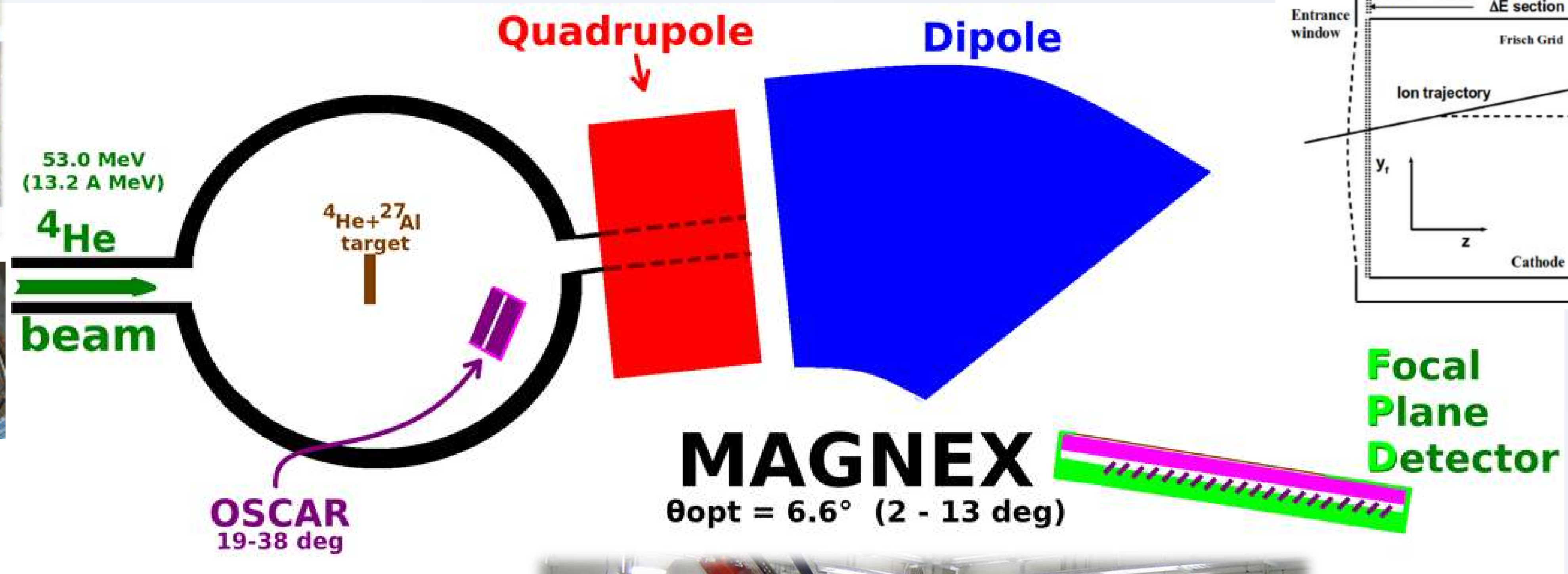
- ✓ **Elastic** & **inelastic** scattering measurements by using:
  - ➢ Superconducting cyclotron beam of ^{4}He at 53 MeV
  - ➢ ^{4}He target (implanted on a thin ^{27}Al foil)
- ✓ Measurement of the elastically scattered ^{4}He particles by the large acceptance MAGNEX spectrometer
- ✓ Measurement of the **inelastic** scattering by detected ^{4}He particles in MAGNEX **in coincidence** with one of ^{4}He* breakup fragments detected in OSCAR silicon telescope

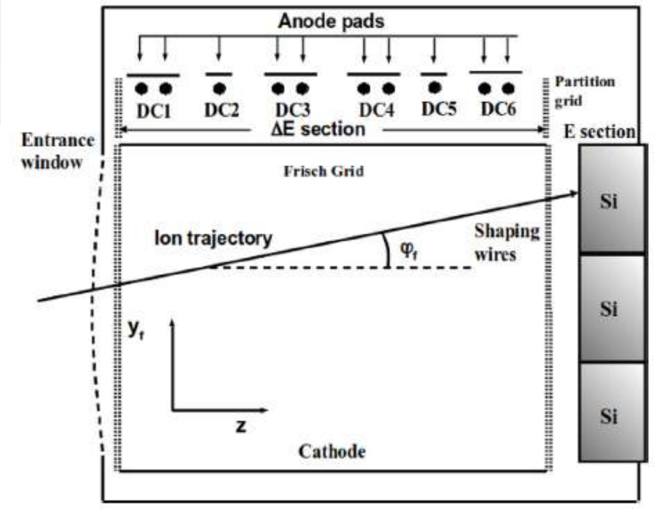
→ Goals:

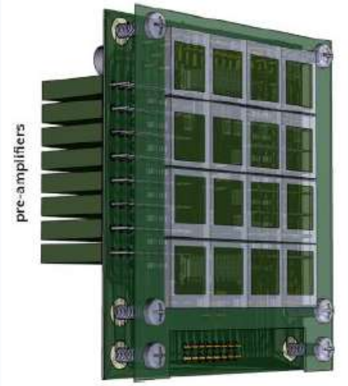
- ➢ **Clarify** the previous inconsistencies between (^{4}He,^{4}He) and (e,e‘) data
- ➢ Extract the characteristics of the first excited state (0^{+}) of ^{4}He in a modern measurement
- ➢ A **global** theoretical interpretation of all measured reactions

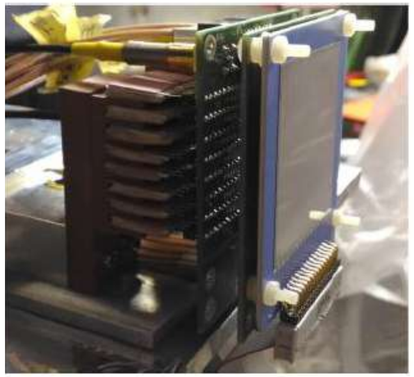
Experimental setup

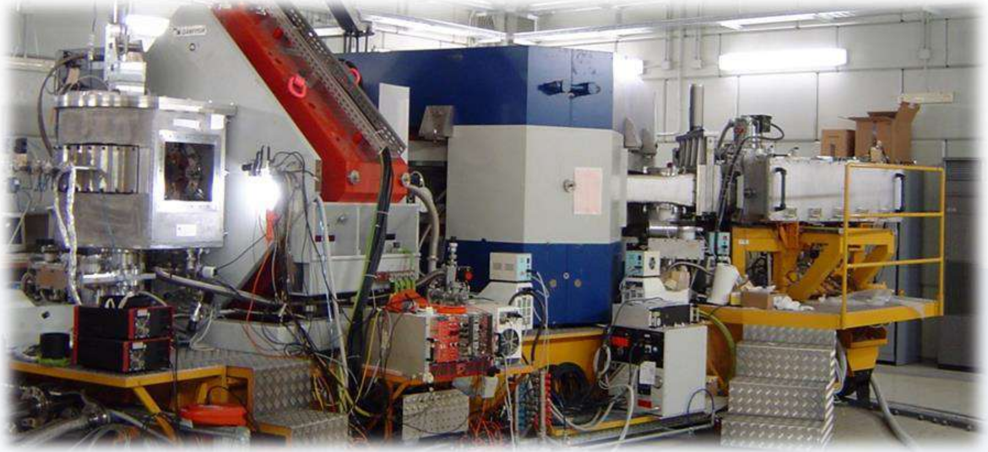
F. Cappuzzello et al., Eur. Phys. J. A 52, 167 (2016)
M. Cavallaro et al., Eur. Phys. J. A 48, 59 (2012)
D. Torresi et al., NIM A 989, 164918 (2021)





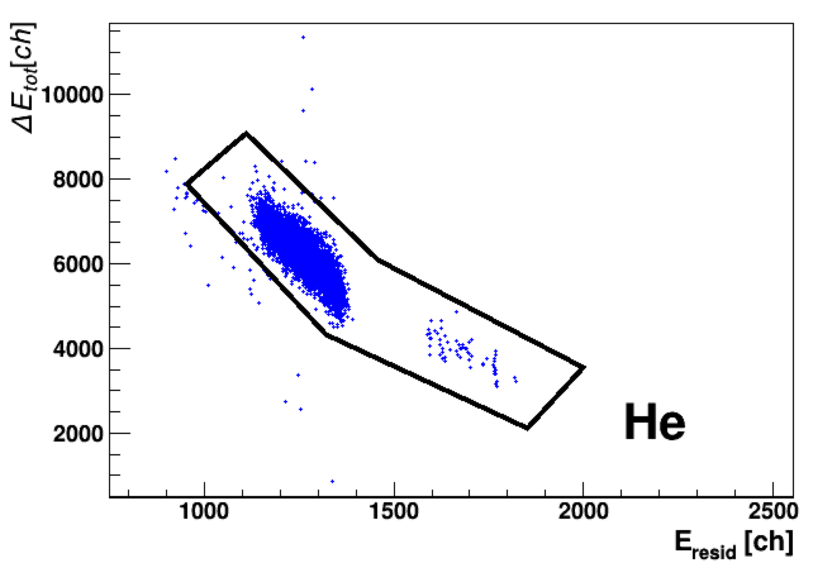


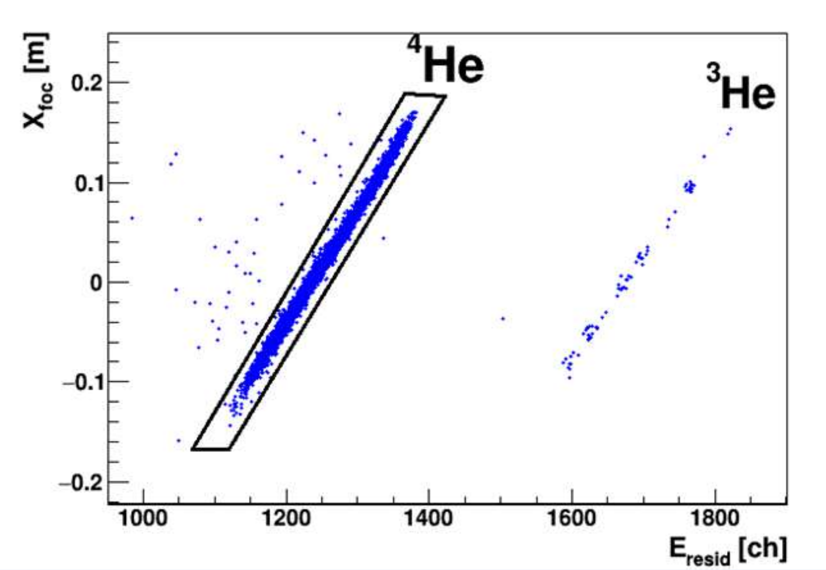




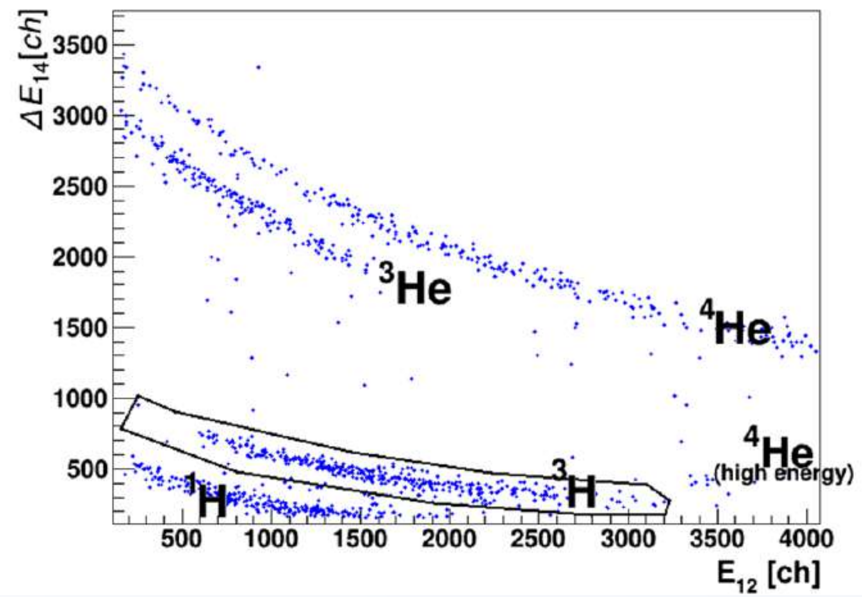
D. Dell'Aquila et al., NIM A 877, 227 (2018)

Particle Identification



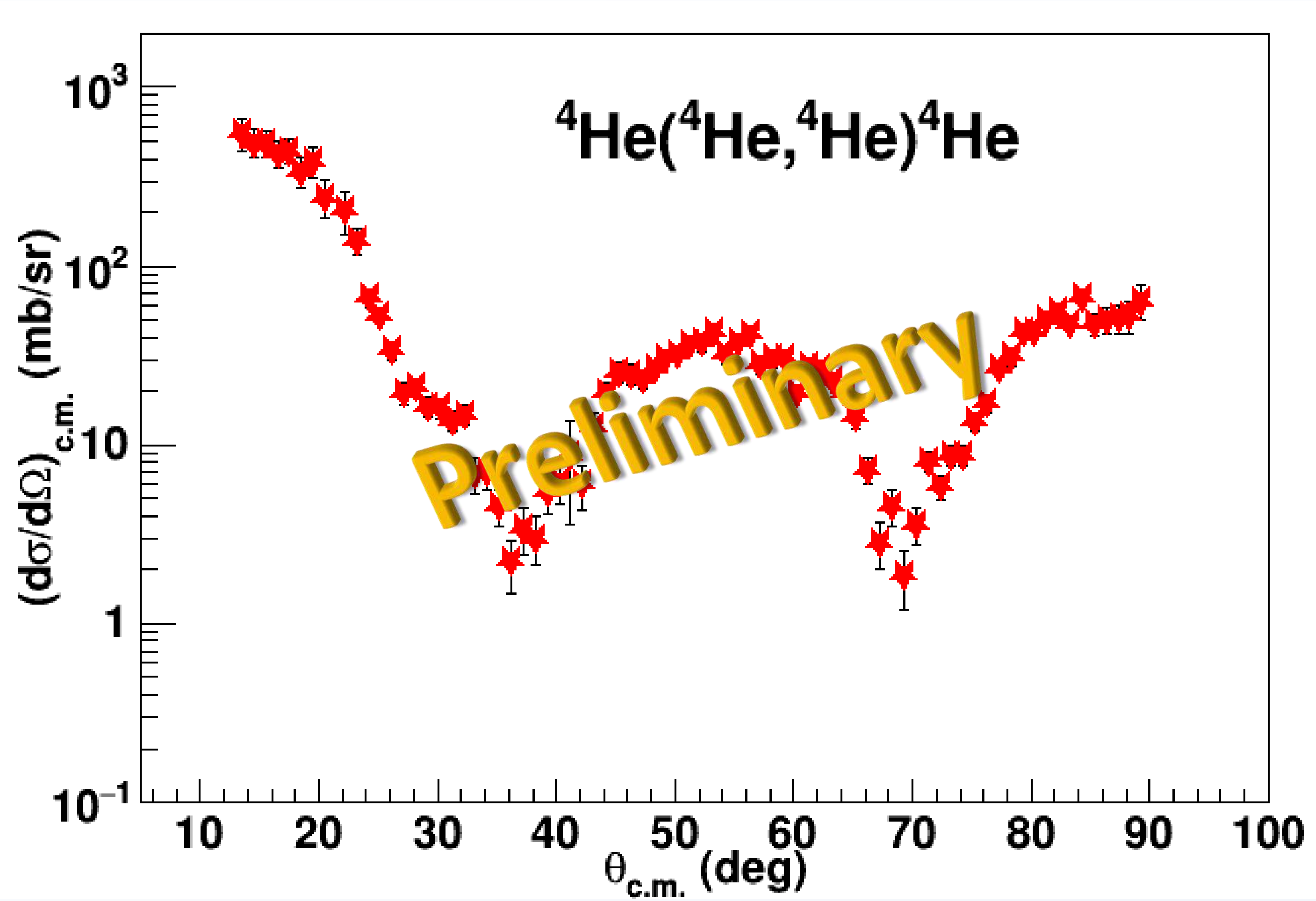


MAGNEX



OSCAR

Elastic scattering

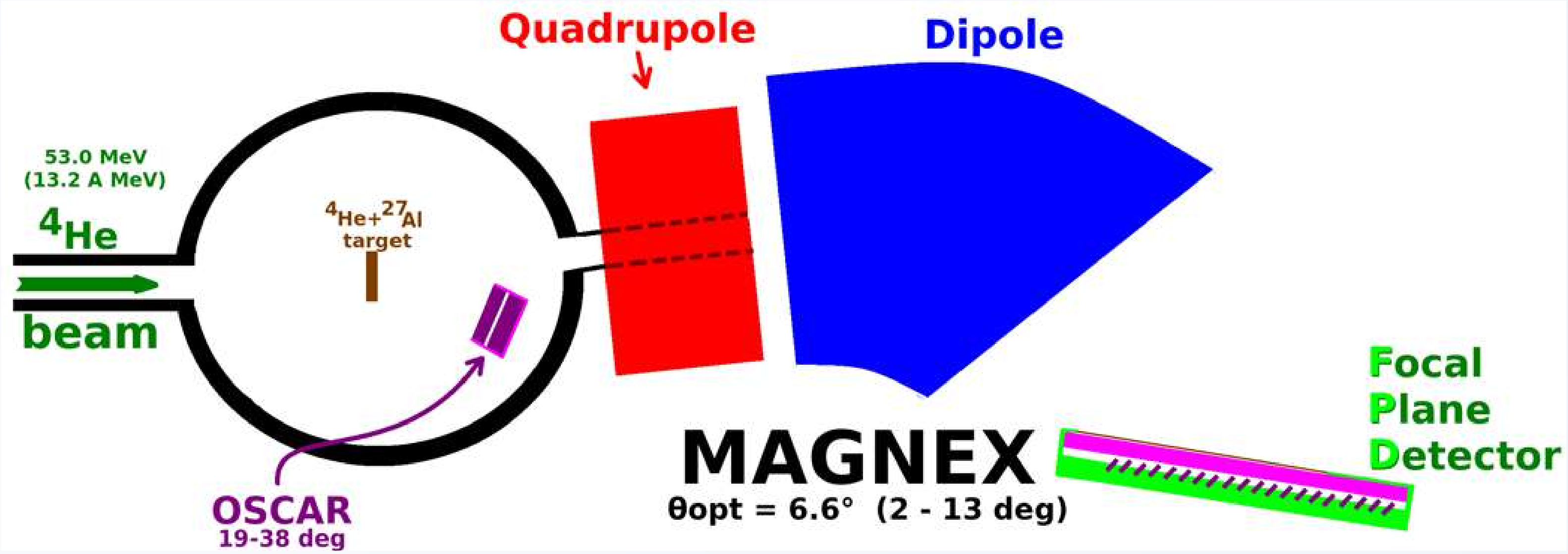


Inelastic scattering

- $^{4}He + {}^{4}He \rightarrow {}^{4}He + {}^{4}He^{*} \rightarrow {}^{4}He + {}^{3}H + {}^{1}H$
- $^{4}He + {}^{4}He \rightarrow {}^{4}He + {}^{4}He^{*} \rightarrow {}^{4}He + {}^{3}He + n$

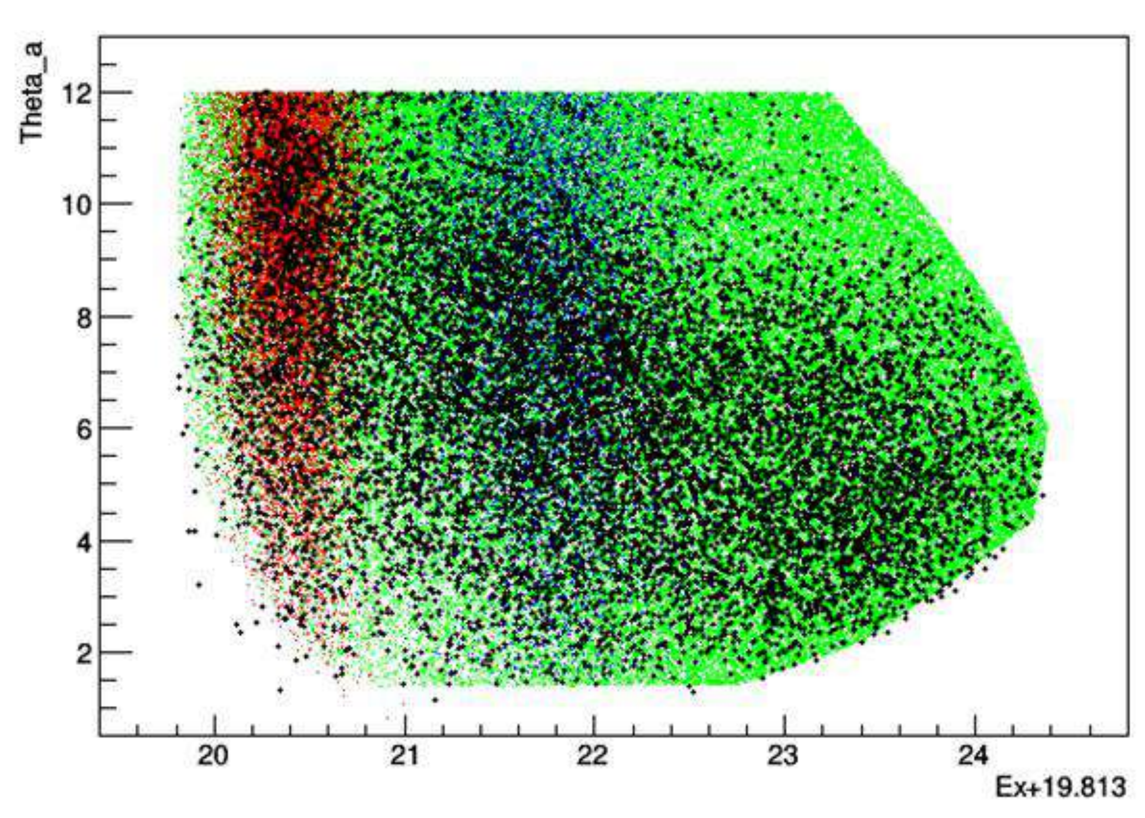
MAGNEX

OSCAR



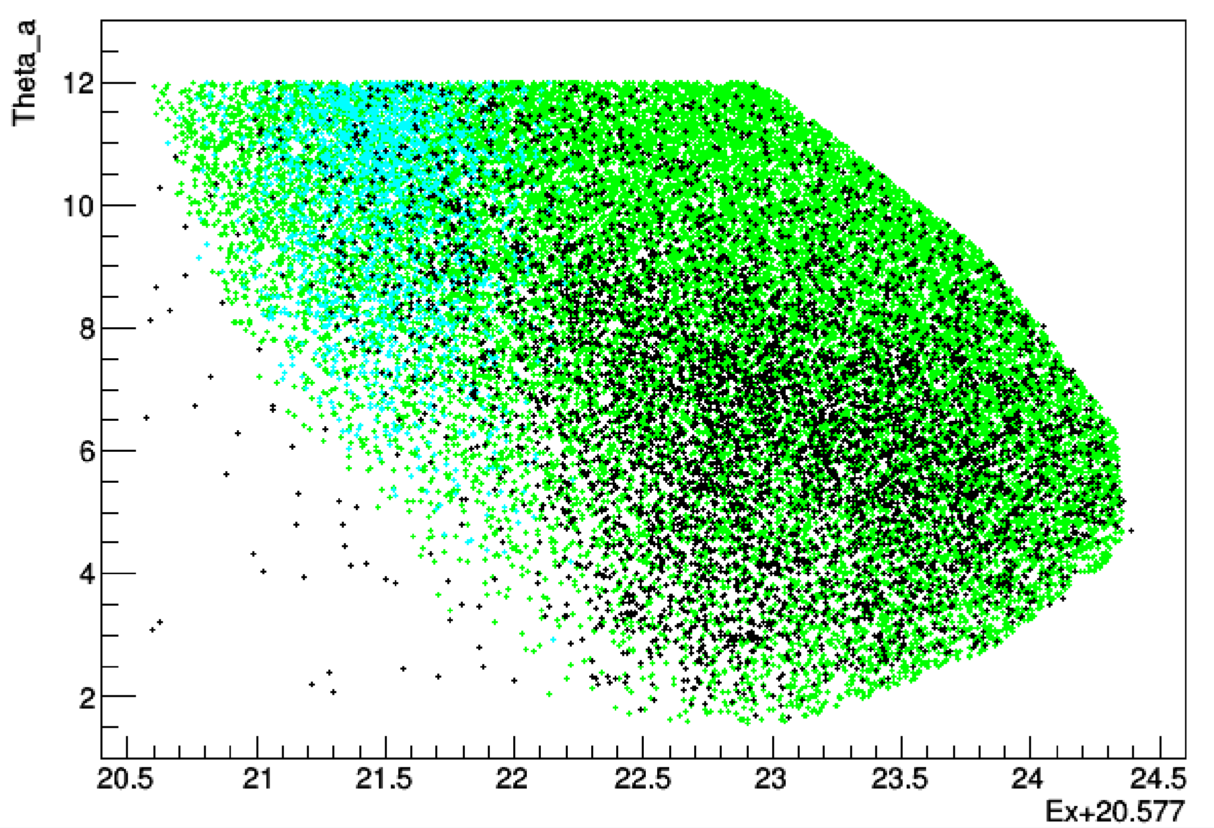
Experimental data VS simulations

$^4He + ^4He^* \rightarrow ^4He + ^3H + ^1H$



Black → **experimental** spectrum
Red → **resonant** continuum
Green → **non-resonant** continuum
Cyan blue → transfer ($^4He+^4He \rightarrow ^3H+^5Li \rightarrow ^4He+^3H+^1H$)

$^4He + ^4He^* \rightarrow ^4He + ^3He + n$

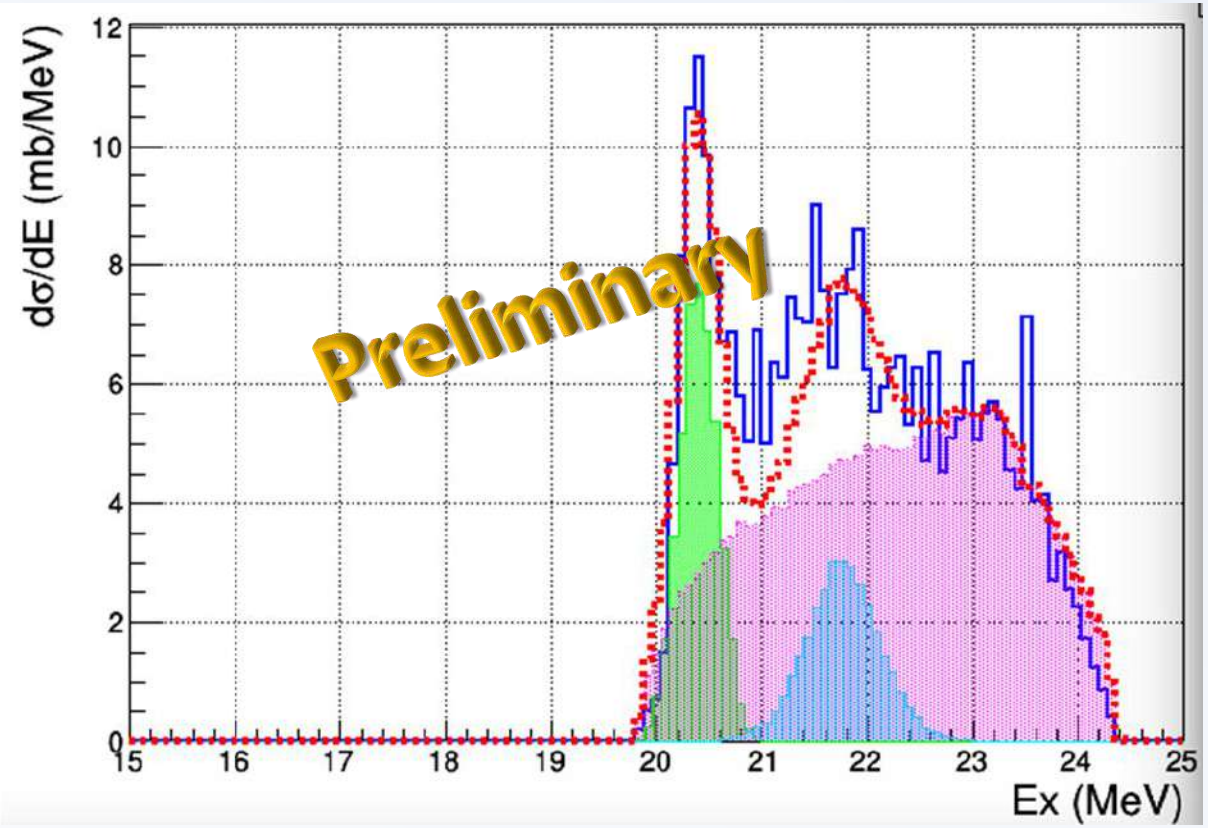


Black → **experimental** spectrum
Red → **resonant** continuum
Green → **non-resonant** continuum
Cyan blue → transfer ($^4He+^4He \rightarrow ^3He+^5He \rightarrow ^4He+^3He+n$)

- **MULTIP algorithm *[O. Sgouros et al., EPJA 53, 165 (2017)]***

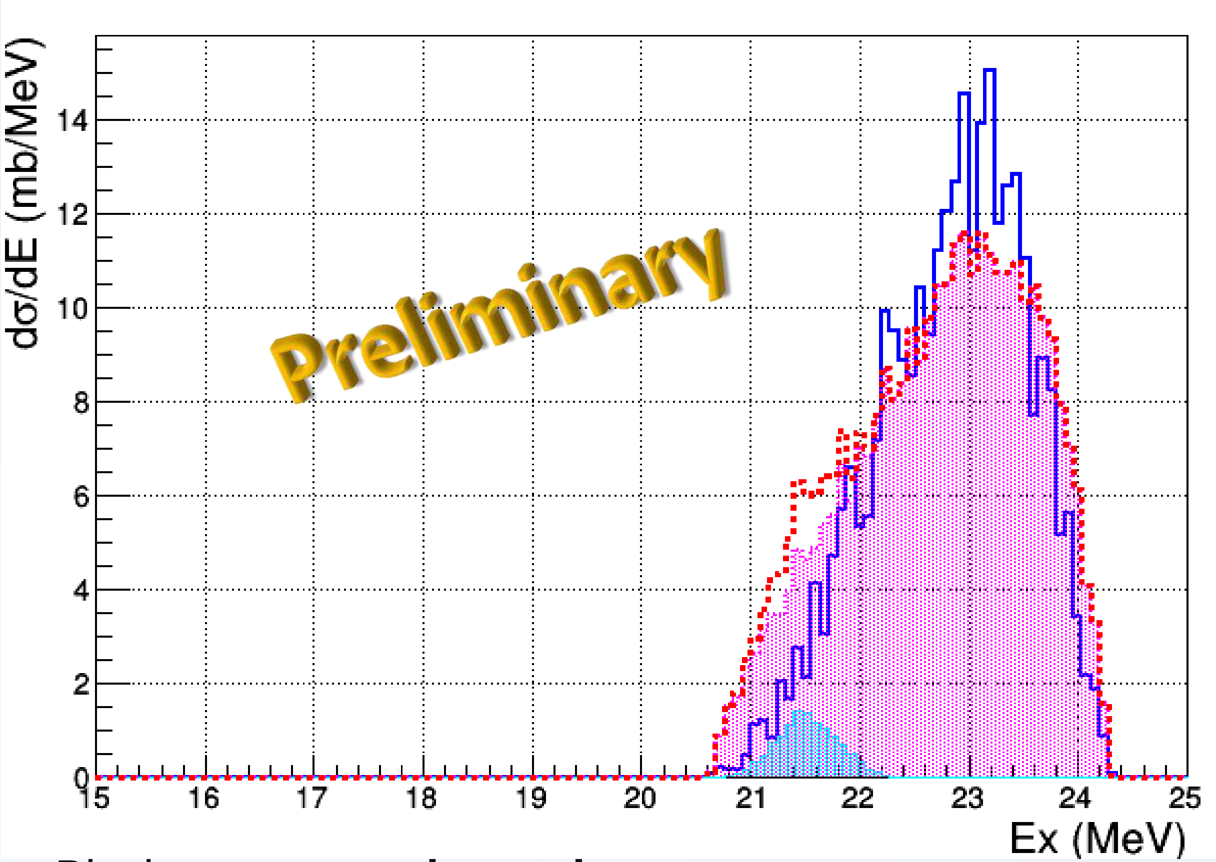
Experimental data VS simulations

$^{4}He + ^{4}He^{*} \rightarrow ^{4}He + ^{3}H + ^{1}H$



Black → **experimental** spectrum
Light Green → **resonant** continuum
Magenta → **non-resonant** continuum
Cyan blue → **transfer** ($^{4}He+^{4}He \rightarrow ^{3}H+^{5}Li \rightarrow ^{4}He+^{3}H+^{1}H$)
Red dashed line → **total simulated** spectrum

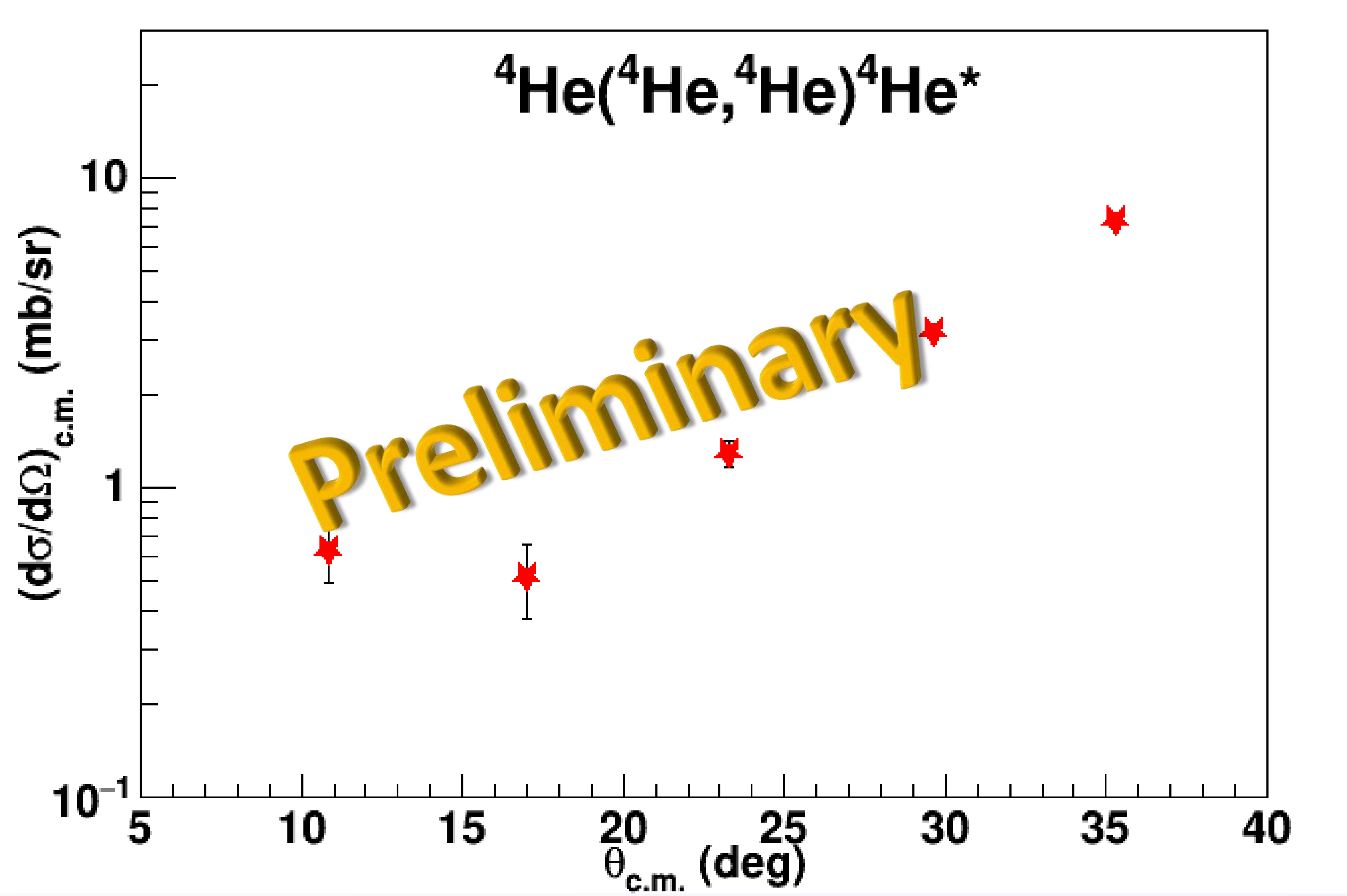
$^{4}He + ^{4}He^{*} \rightarrow ^{4}He + ^{3}He + n$



Black → **experimental** spectrum
Magenta → **non-resonant** continuum
Cyan blue → **transfer** ($^{4}He+^{4}He \rightarrow ^{3}He+^{5}He \rightarrow ^{4}He+^{3}He+n$)
Red dashed line → **total simulated** spectrum

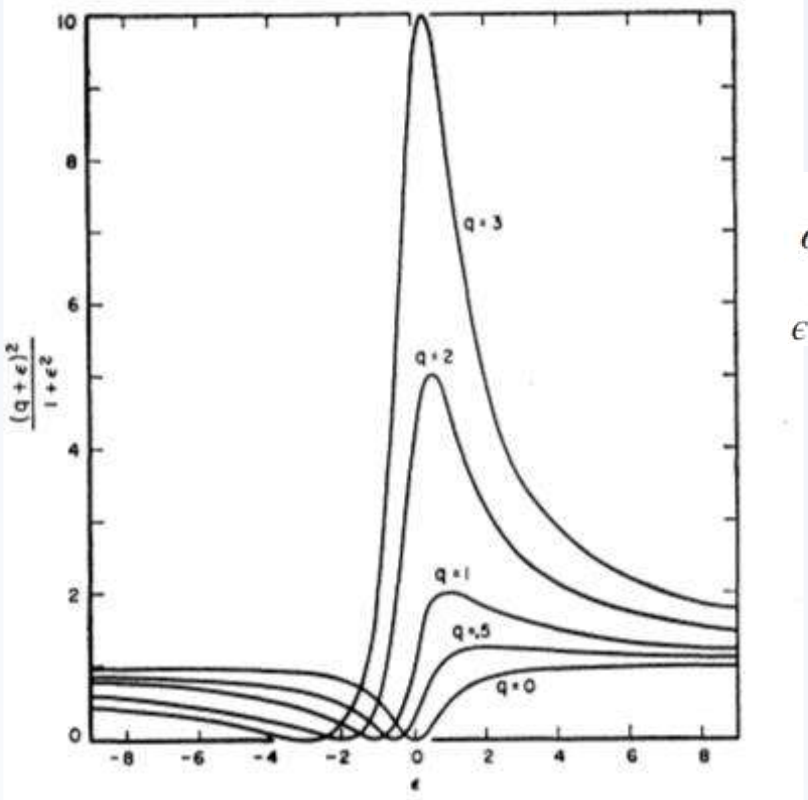
- **MULTIP algorithm *[O. Sgouros et al., EPJA 53, 165 (2017)]***

Angular distribution for the 1st exc. state of ^{4}He (0$^+$)



Fano analysis

U. Fano, Phys. Rev. 124, 1866 (1961)
C. Ott et al., Science 340, 716 (2013)
M.F. Limonov et al., Nature Photonics 11, 543 (2017)
M. Cavallaro et al., Phys. Rev. Lett. 118, 012701 (2017)



Natural line shapes for different values of q. (Reverse scale of abscissas for negative q.)

$$\sigma = \sigma_{\mathrm{cont}} \frac{|q+\epsilon|^2}{1+\epsilon^2}$$

$$\epsilon = 2(E - E_r)/\Gamma_r$$

U. Fano, Phys. Rev. 124, 1866 (1961)

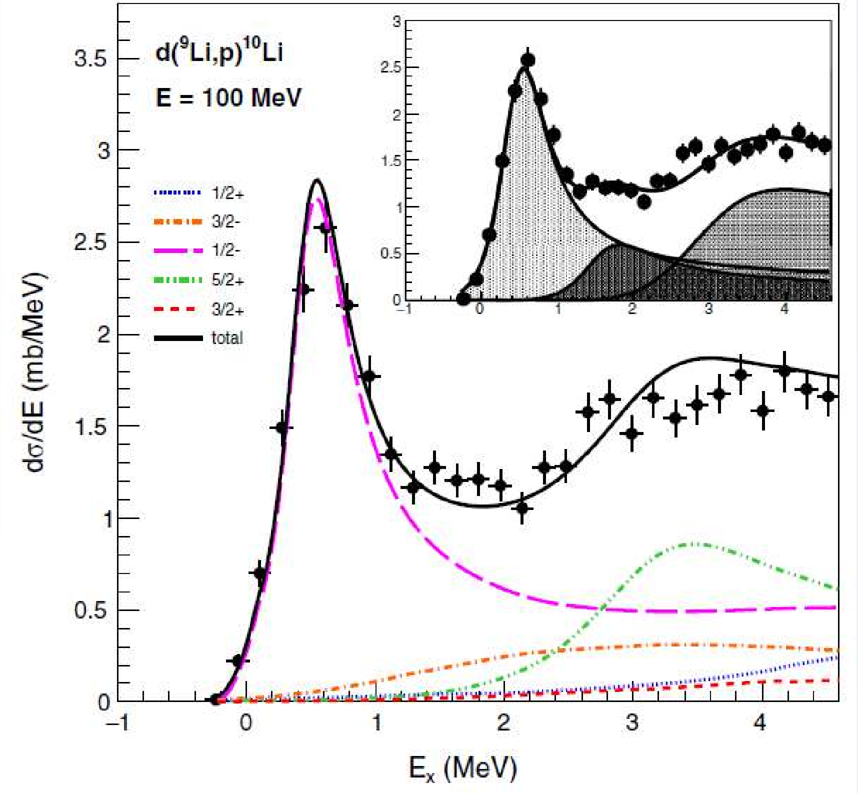


FIG. 1. ^{10}Li energy spectrum for the $d(^9\mathrm{Li}, p)^{10}\mathrm{Li}$ reaction at 100 MeV incident energy and $\theta_{CM} = [5.5°, 16.5°]$. The curves

M. Cavallaro et al., Phys. Rev. Lett. 118, 012701 (2017)

Fano analysis for the $^4He\ 0^+$ resonance

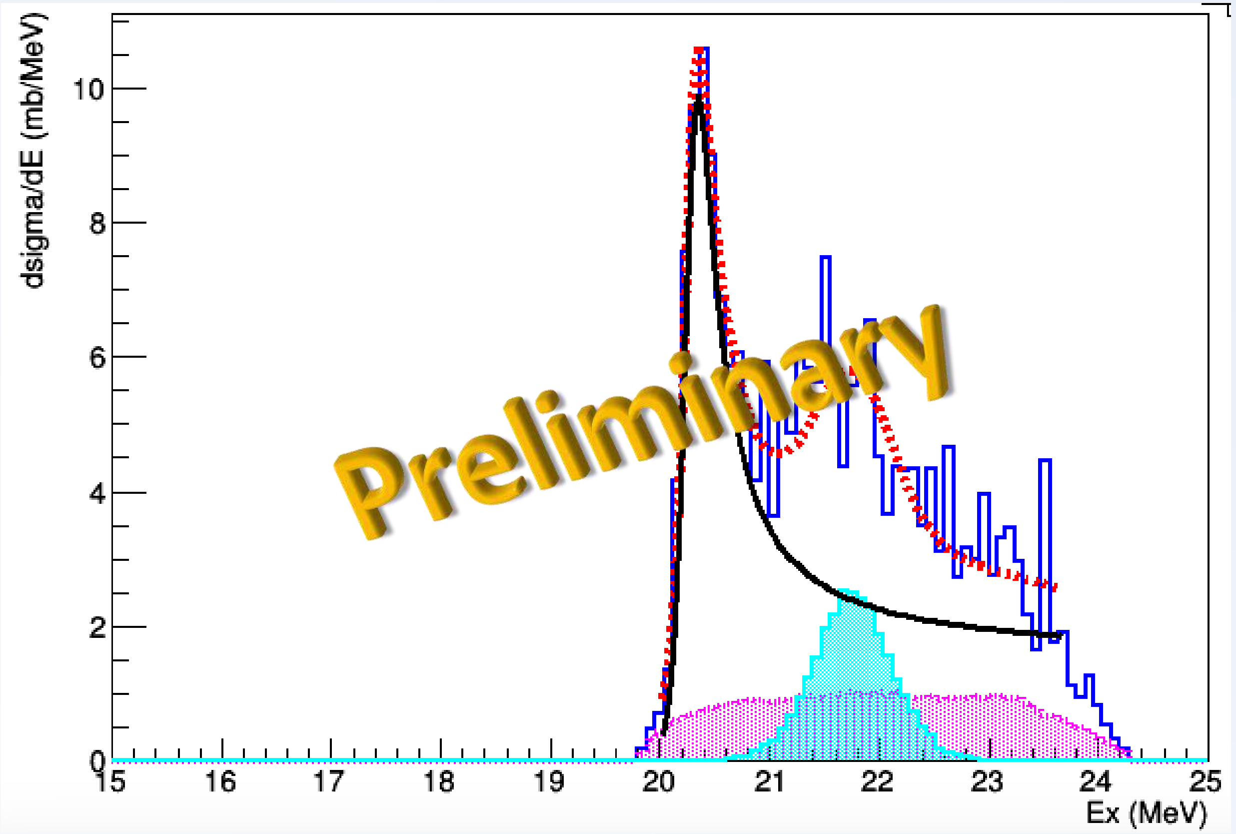
$$\sigma = \sigma_{\rm cont} \frac{|q+\epsilon|^2}{1+\epsilon^2}$$

$$\epsilon = 2(E - E_r)/\Gamma_r$$

dσ/dE spectrum **(6.5-12.0 deg)**
Fit with **6 free parameters:**
4 Fano parameters
2 parameters for the pure non-resonant continuum and transfer, respectively

Obtained Fano parameters:

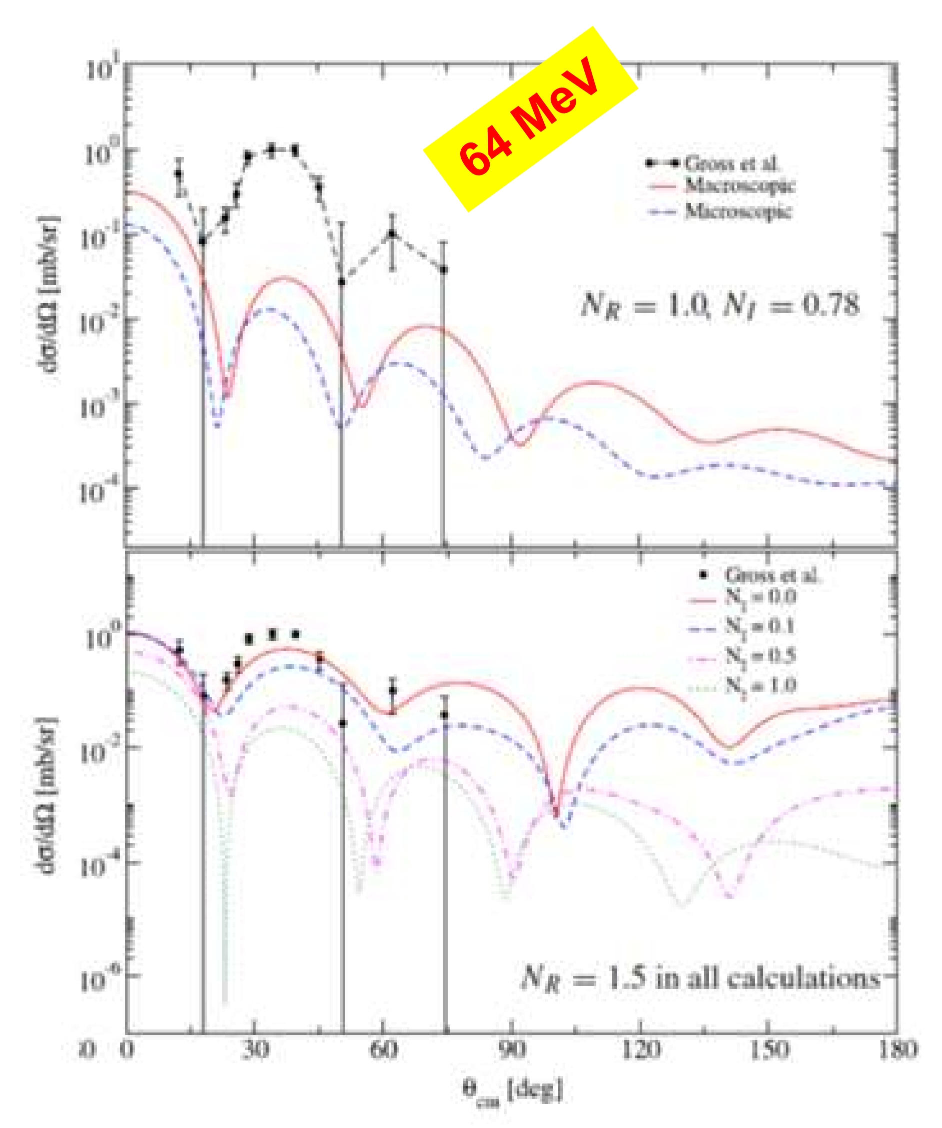
σ_{cont}	**=**	**1.49 ± 0.88**
q	**=**	**2.37 ± 0.86**
E_r	**=**	**20.27 ± 0.06**
Γ_r	**=**	**0.35 ± 0.11**



Theoretical interpretation

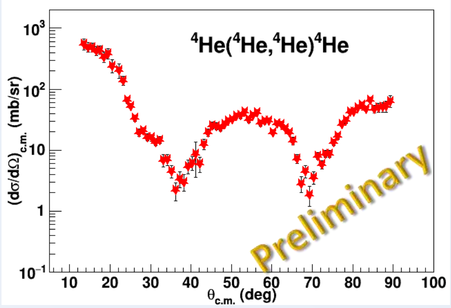
Following the prescription of Kucuk, Karakoc and Vitturi with microscopic and macroscopic models

Y. Kucuk et al., Eur. Phys. J. A 57, 37 (2021)

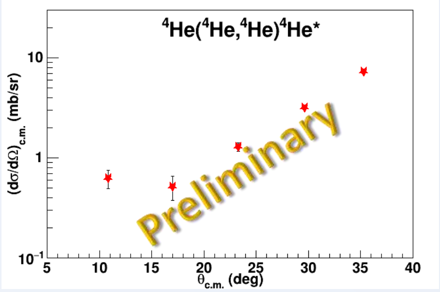


Summary and perspectives

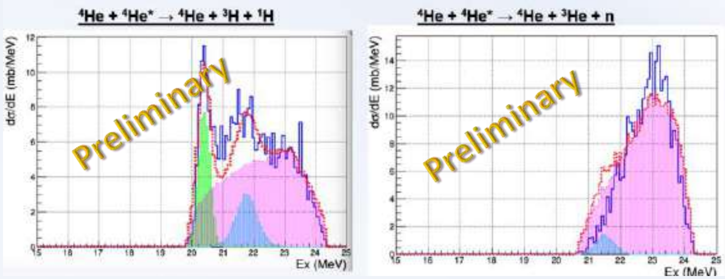
- ✓**Elastic scattering** measurements for the ^{4}He + ^{4}He system were performed at the beam energy of 53 MeV in a wide angular range with the MAGNEX spectrometer.



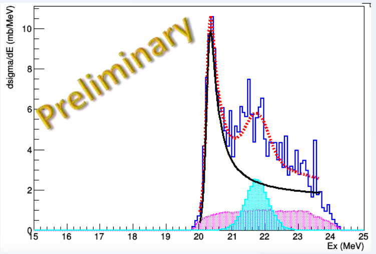
- ✓**Inelastic scattering** measurements were performed for the same system by measuring the ^{4}He particles in MAGNEX **in coincidence** with the ^{3}H (^{3}He) particles coming from the ^{4}He* breakup in the OSCAR telescope.



- ✓Monte Carlo kinematical simulations were performed for both the resonant (inelastic to 0^{+} excited state of ^{4}He) and non – resonant breakup and seem to describe very well the experimental data.



- ✓An analysis based on Fano function was performed for the first excited state (0^{+}) region of ^{4}He and the Fano parameters were determined.



- ✓The theoretical interpretation of the data is in progress

Collaborators

V. Soukeras, F. Cappuzzello, M. Cavallaro, D. Carbone, A. Hacisalihoglu, M. Fisichella, C. Agodi, H.-W. Becker, G. A. Brischetto, S. Calabrese, C. Ciampi, M. Cicerchia, M. Cinausero, I. Ciraldo, M. D' Andrea, D. Dell' Aquila, S. Firat, C. Frosin, M. Hilcker, M. Karakoç, Y. Kucuk, L. La Fauci, H. Lenske, I. Lombardo, T. Marchi, O. Sgouros, A. Spatafora, D. Torresi, M. Vigilante, A. Vitturi, A. Yildirim

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- Akdeniz University, Antalya, Turkey
- Department of Physics, University of Giessen, Germany
- INFN – Sezione di Napoli and Università degli Studi di Napoli "Federico II", Napoli, Italy
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Thank you very much for your attention