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THE XL RSEF PHYSICS BIENNIAL

20-24 JULIO 2026
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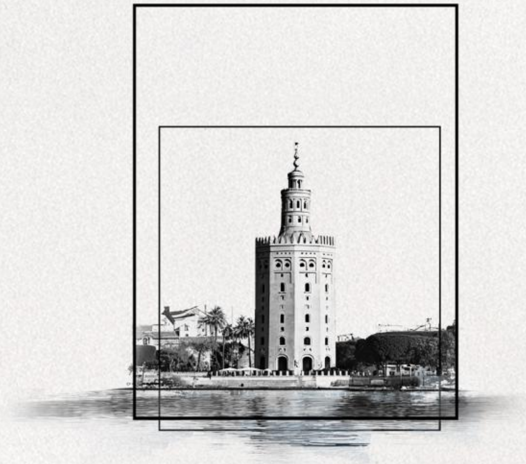

RSEF XL BIENAL SEVILLA 2026

Real Sociedad Española de Física

Escuela Técnica Superior de Ingeniería, Universidad de Sevilla

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A NOVEL OPTICAL MODEL PROTOCOL FOR NUCLEAR REACTION ANALYSES AT NEAR-BARRIER ENERGIES

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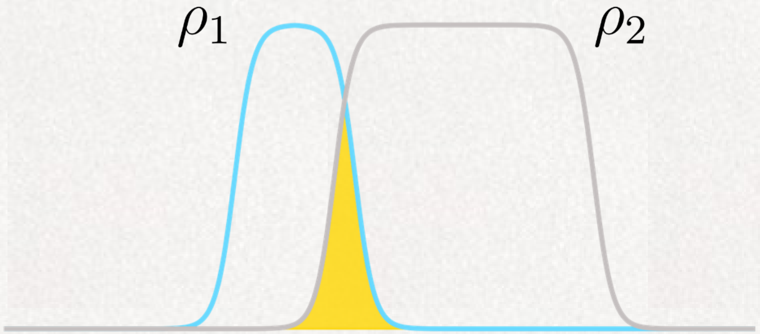
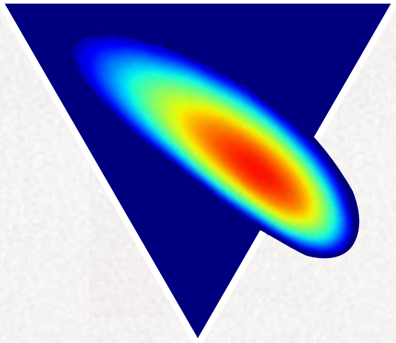
$$V(R) = U_0 \, e^{-4v^2/c^2} \iint \rho_1(\mathbf{r_1}) \, \rho_2(\mathbf{r_2}) \, e^{-(r_{12}/a)^2} \, \mathrm{d}\mathbf{r_1} \mathrm{d}\mathbf{r_2}$$





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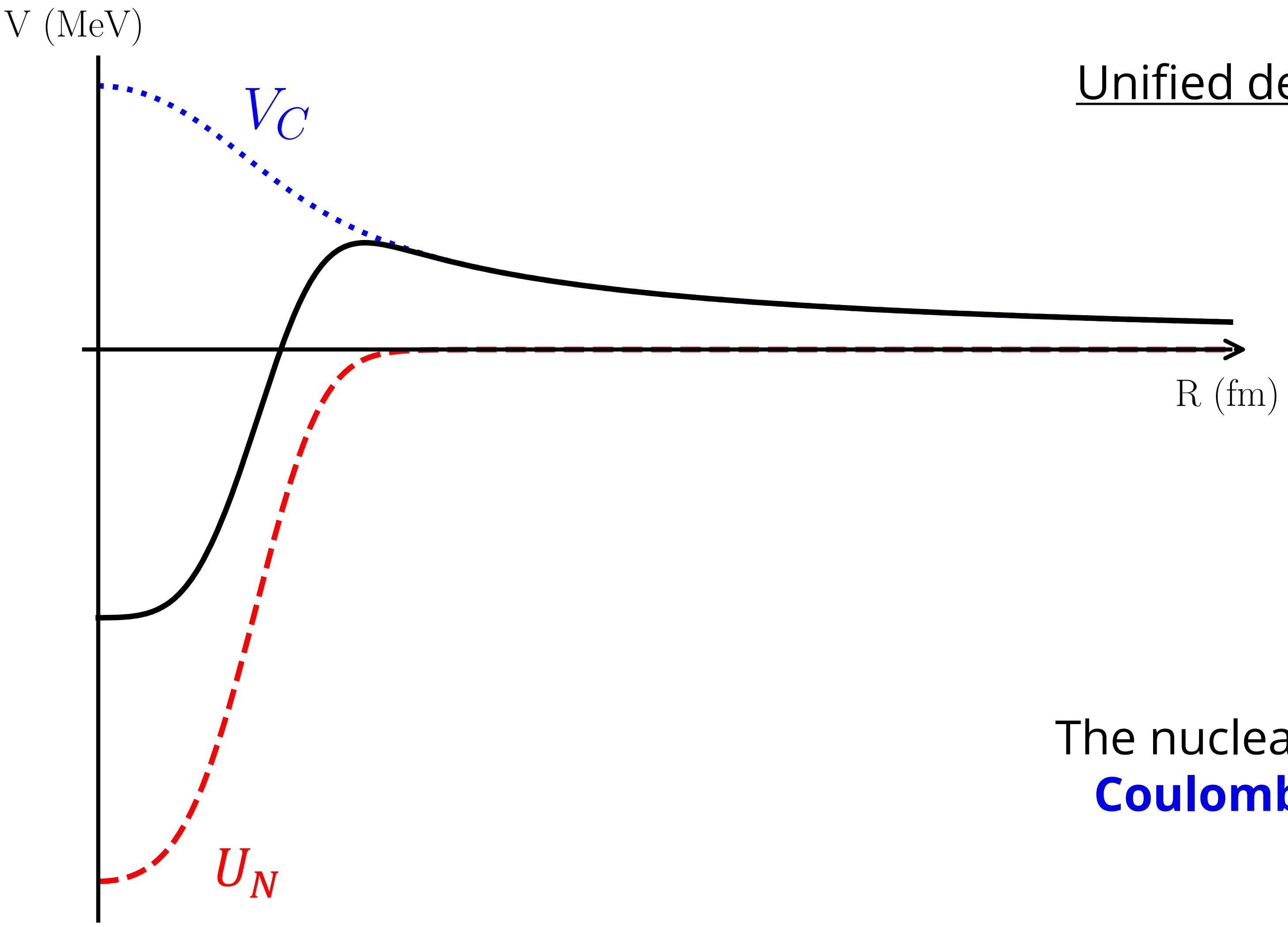
- Motivations
- The São Paulo Optical Model Protocol (SP-OMP)
- What can we learn from the SP-OMP
- Application to X + ^{64}Zn reactions
- New measurements of ^{12,13}C + ^{64}Zn

Motivations



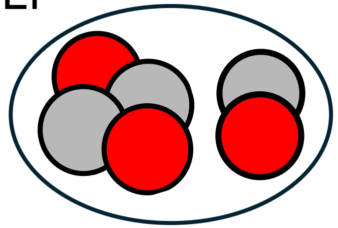
Unified description of the nuclear interaction

$$V_C + U_N \;\; ??$$

The nuclear potential must include the **Coulomb** and **nuclear** interactions

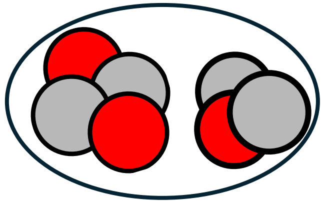
Motivations

^{6}Li



α + d

^{7}Li



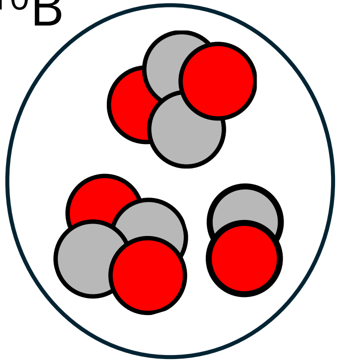
α + t

Structure of matter and mechanisms of nuclear reactions

Cluster structures

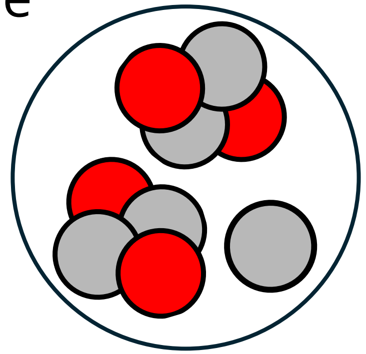
How does nuclear structure affect nuclear reaction dynamics?

^{10}B

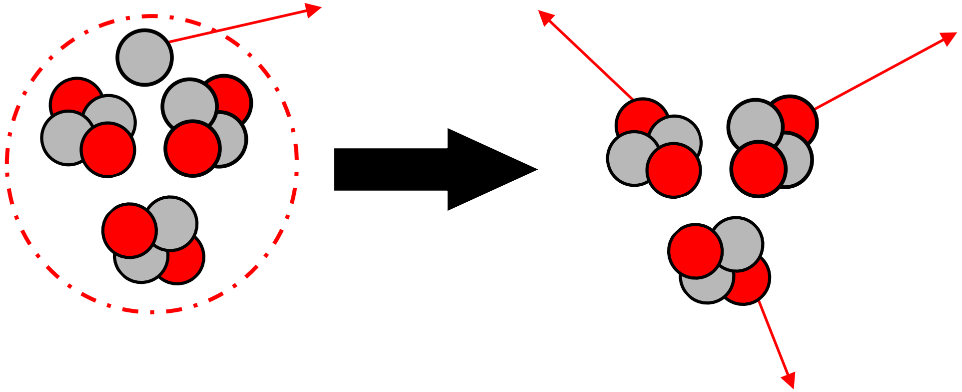


^{6}Li + α

^{9}Be



α + α + n



The São Paulo Optical Model Protocol

In the **Optical Model formalism** the nuclear potential is **complex**

$$V_C + U_N$$

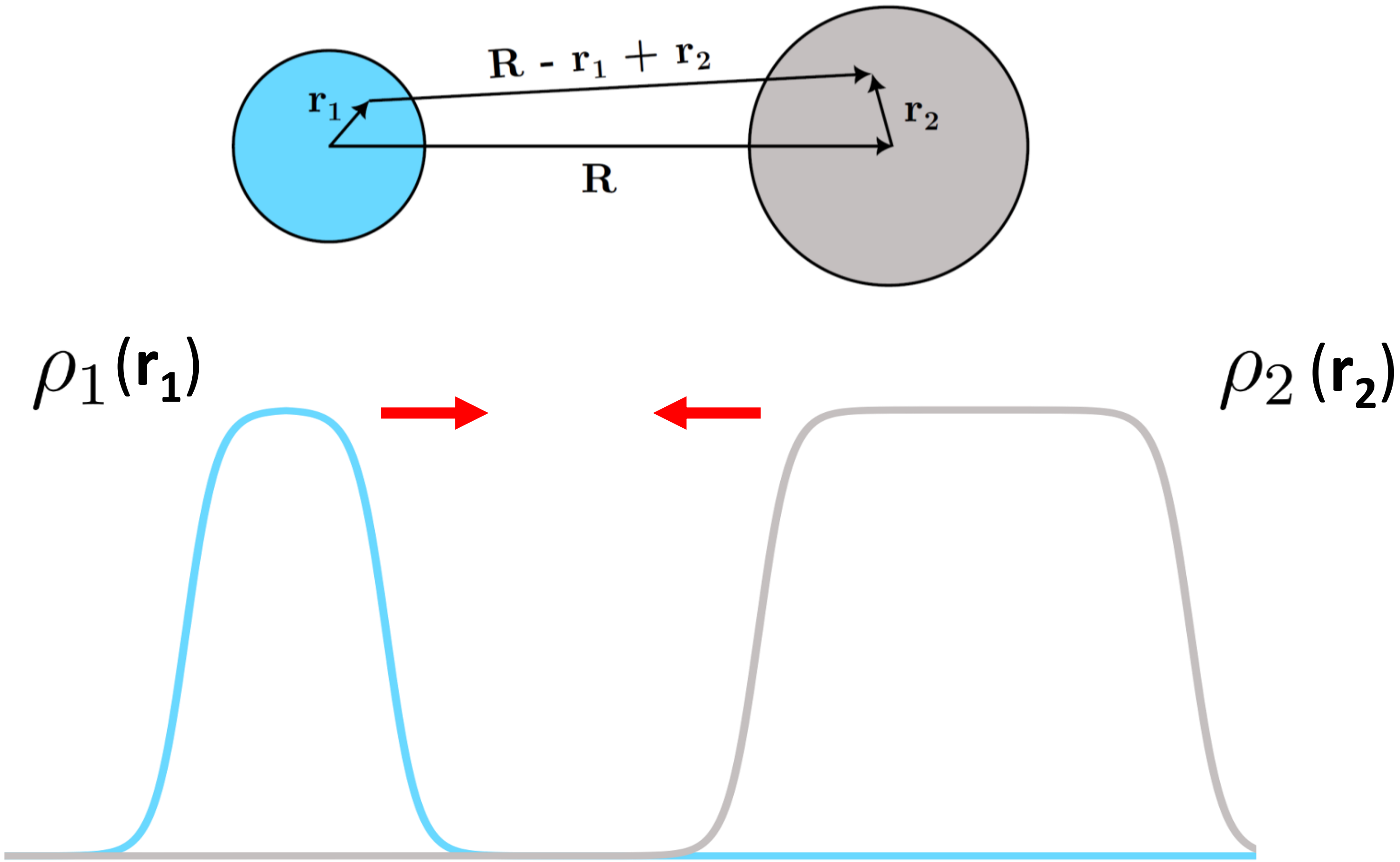
$$U_N(R) = V(R) + iW(R)$$

The **imaginary part** accounts for the **non-elastic processes**

(absorption from the elastic flux)

The **real part** models the **nuclear interaction** itself

The São Paulo Optical Model Protocol



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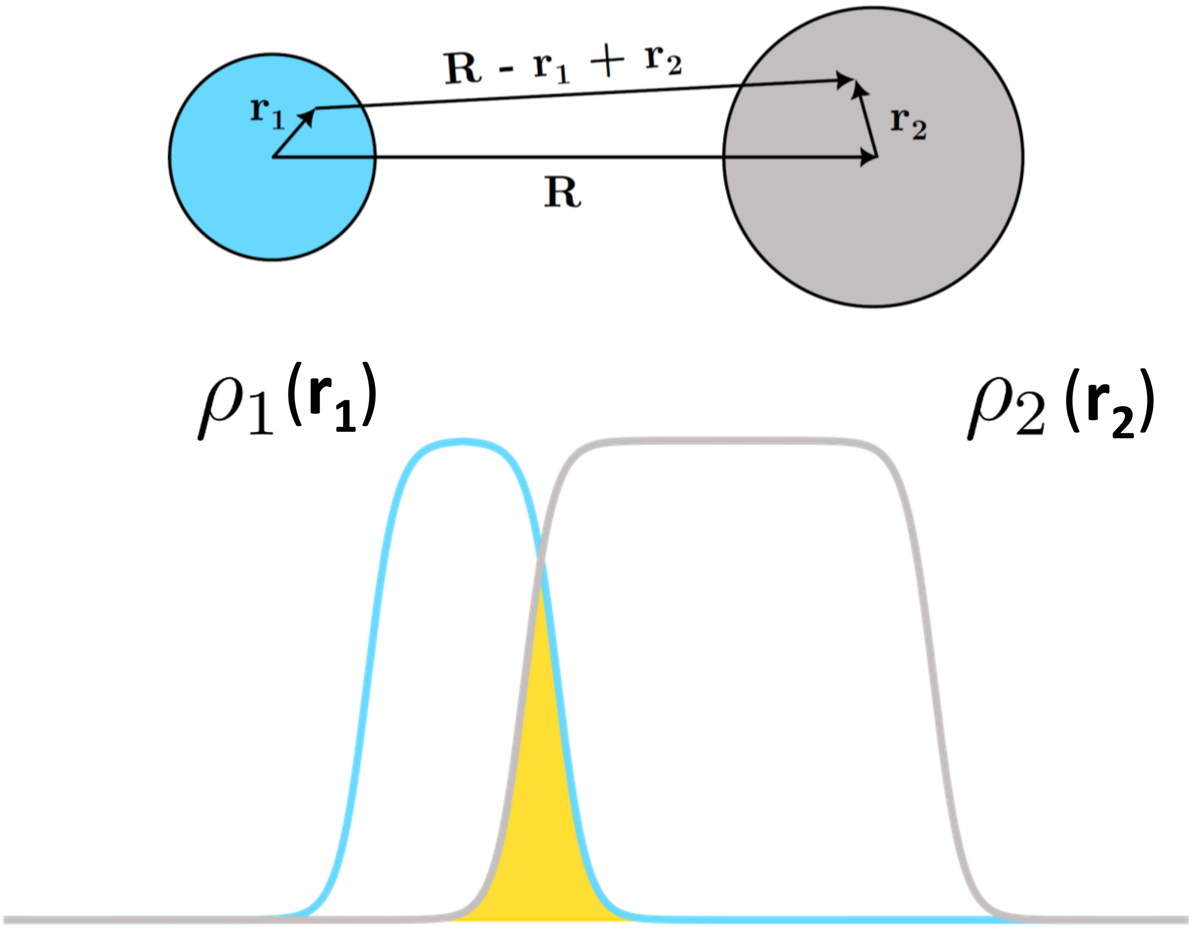

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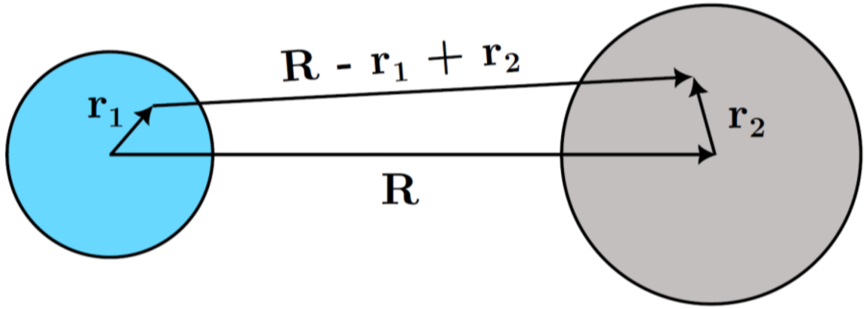


$$V(R) = \iint \underbrace{\rho_1(\mathbf{r_1})\,\rho_2(\mathbf{r_2})}\,\underbrace{\nu(\mathbf{R} - \mathbf{r_1} + \mathbf{r_2})}\,\mathrm{d}\mathbf{r_1}\mathrm{d}\mathbf{r_2}$$

matter densities

effective nucleon-nucleon interaction

The São Paulo Potential 2 (SPP2)

$$V(R) = U_0\, e^{-4v^2/c^2} \iint \rho_1(\mathbf{r_1})\, \rho_2(\mathbf{r_2})\, e^{-(r_{12}/a)^2}\, \mathrm{d}\mathbf{r_1} \mathrm{d}\mathbf{r_2}$$

$U_0 = -735.813$ MeV

$a = 0.50$ fm

Theoretical distributions (Dirac-Hartree-Bogoliuvob)

Experimental distributions (electron scattering experiments)

No FREE parameters!

B. V. Carlson et al., ***Phys. Rev. C 62, 054310 (2000)***

L. C. Chamon et al., ***Comput. Phys. Commun. 267, 108061 (2021)***

The SP-OMP

(São Paulo Optical Model Protocol)

consists in

applying → **4 OM variants**

- ✓ OM1
- ✓ OM2
- ✓ OM3
- ✓ OM4

studying → **the behavior of the nuclear potential**

- ✓ Variation with energy
- ✓ Sensitivity to data
- ✓ Coupling reaction channels

The São Paulo Optical Model Protocol (SP-OMP)

OM1

$$U_N(R) = V_{\text{SPP2}}(R) + iW(R)$$

This **internal potential simulates the fusion process** and does not include other peripheral reactions

The **real term** uses the **SPP2** parameterization

The **imaginary term** uses the **WS** parameterization

$$W(R) = \frac{W_0}{1 + \exp(\frac{R - R_0}{a})}$$

$$\begin{cases} W_0 = -100 \text{ MeV} \\ R_0 = r_0(A_1^{1/3} + A_2^{1/3}) \\ r_0 = 1.06 \text{ fm} \\ a = 0.25 \text{ fm} \end{cases}$$

OM1 has **no free parameters**

OM2

$$U_N(R) = N_r\, V_{\text{SPP2}} + i N_i\, V_{\text{SPP2}}$$

This **superficial potential** **simulates peripheral reactions**

Both **real** and **imaginary** parts use the **SPP2** parameterization

OM2 has **no free parameters**

The **standard** parameters:

$N_r = 1$

$N_i = 0.78$

The São Paulo Optical Model Protocol (SP-OMP)

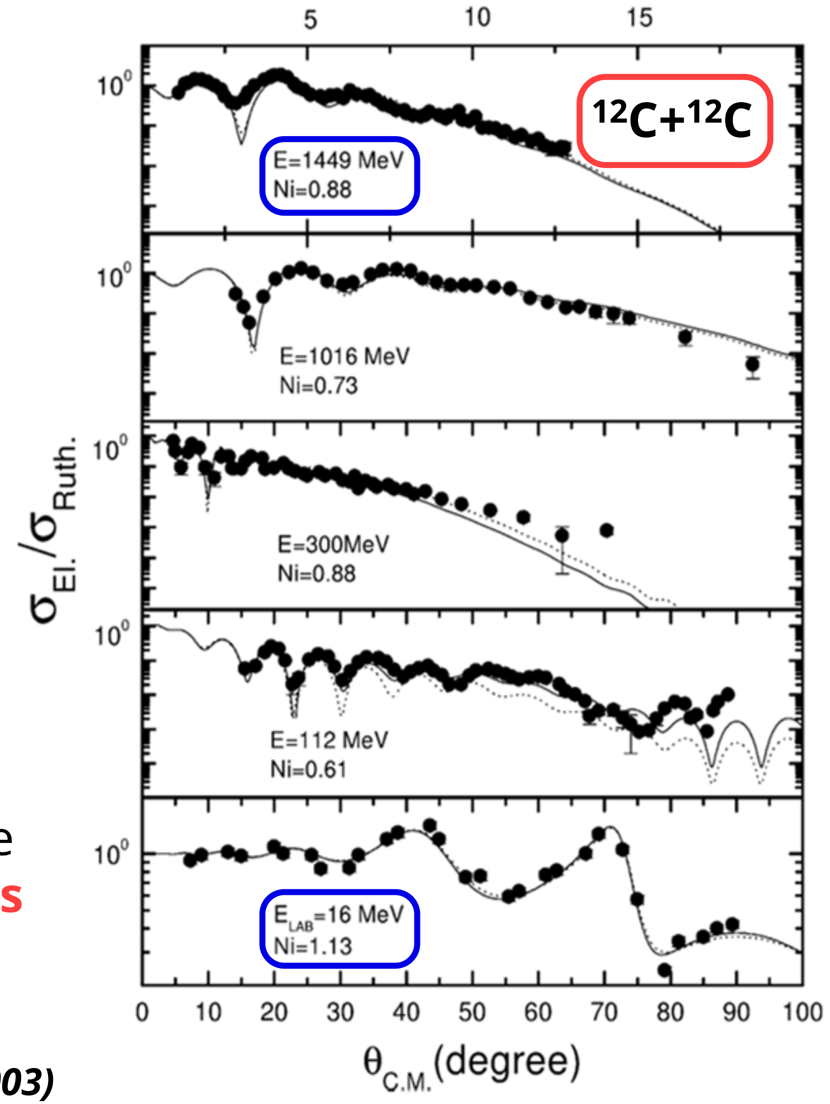
OM2

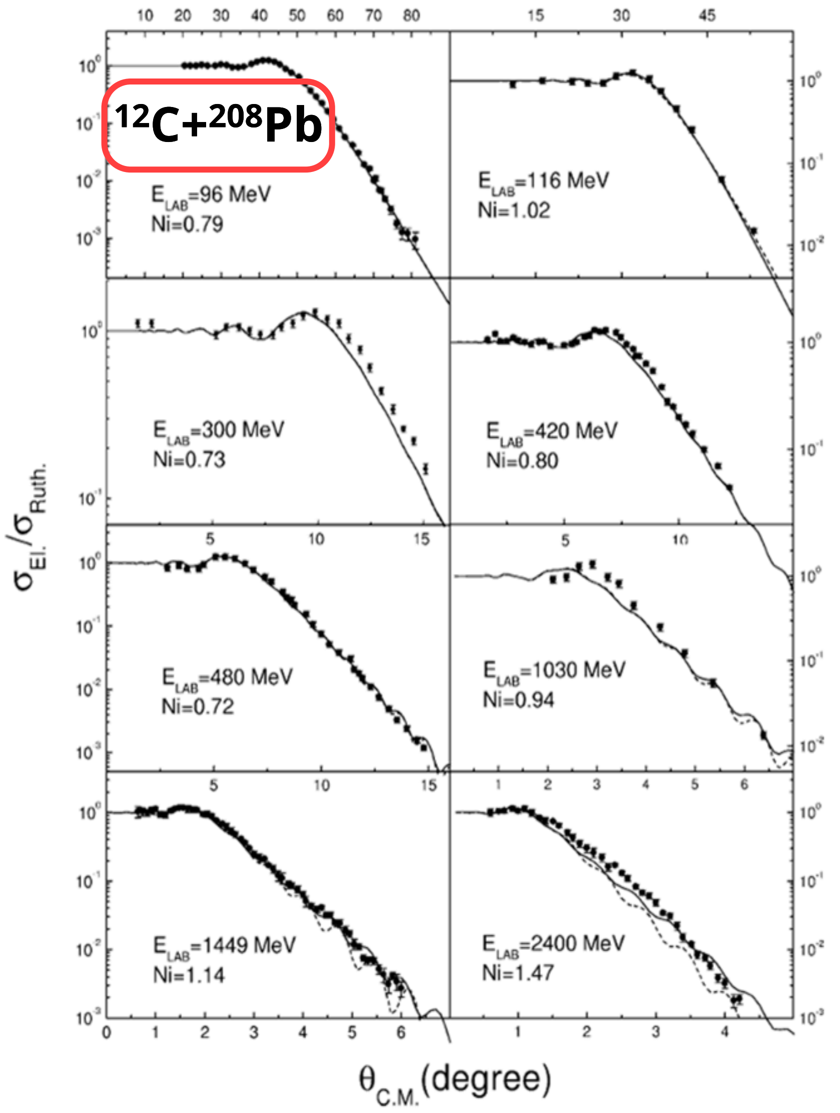
The **standard** parameters:

$N_r = 1$

$N_i = 0.78$

Good description in a wide range of **energies** and **reduced masses**





M. A. G. Alvarez et al. ***Nucl. Phys. A 723, 93 (2003)***

The São Paulo Optical Model Protocol (SP-OMP)

OM3

$$U_N(R) = N_r\, V_{\text{SPP2}} + i N_i\, V_{\text{SPP2}}$$

Both **real** and **imaginary** parts use the **SPP2** parameterization

The **imaginary strength** is allowed to vary in order to **fit** the data

Simulates **opening/closing** reaction channels

OM3 is a **one-parameter fit**

The São Paulo Optical Model Protocol (SP-OMP)

OM4

$$U_N(R) = N_r V_{\mathrm{SPP2}} + i N_i V_{\mathrm{SPP2}}$$

Both **real** and **imaginary** parts use the **SPP2** parameterization

The **real and imaginary strengths** are allowed to vary in order to **fit** the data

Simulates **opening/closing** reaction channels and **polarization effects**

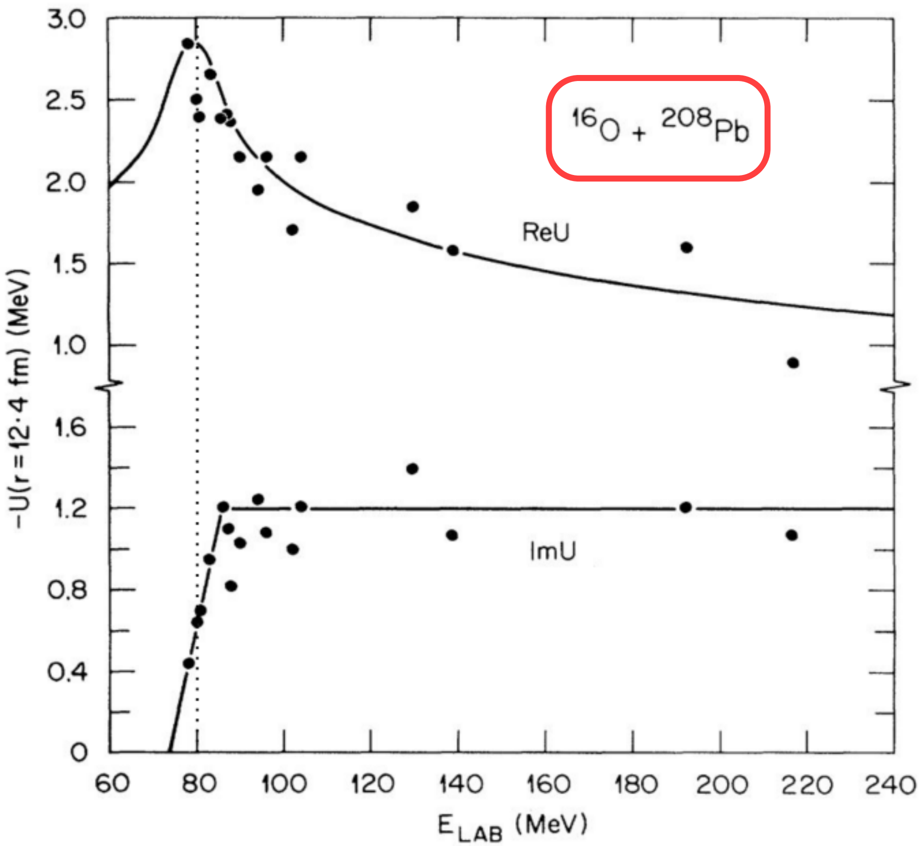
OM4 is a **two-parameter fit**

The São Paulo Optical Model Protocol (SP-OMP)

The dispersion relation

OM4 allows us to study the
relationship between the **real and imaginary strengths**

M. A. Nagarajan et al., ***Phys. Rev. Lett. 54, 1136 (1985)***



$$U_N(R) = N_r\, V_{\mathrm{SPP2}} + i N_i\, V_{\mathrm{SPP2}}$$

Real strength increases below the barrier

Imaginary strength vanishes below the barrier

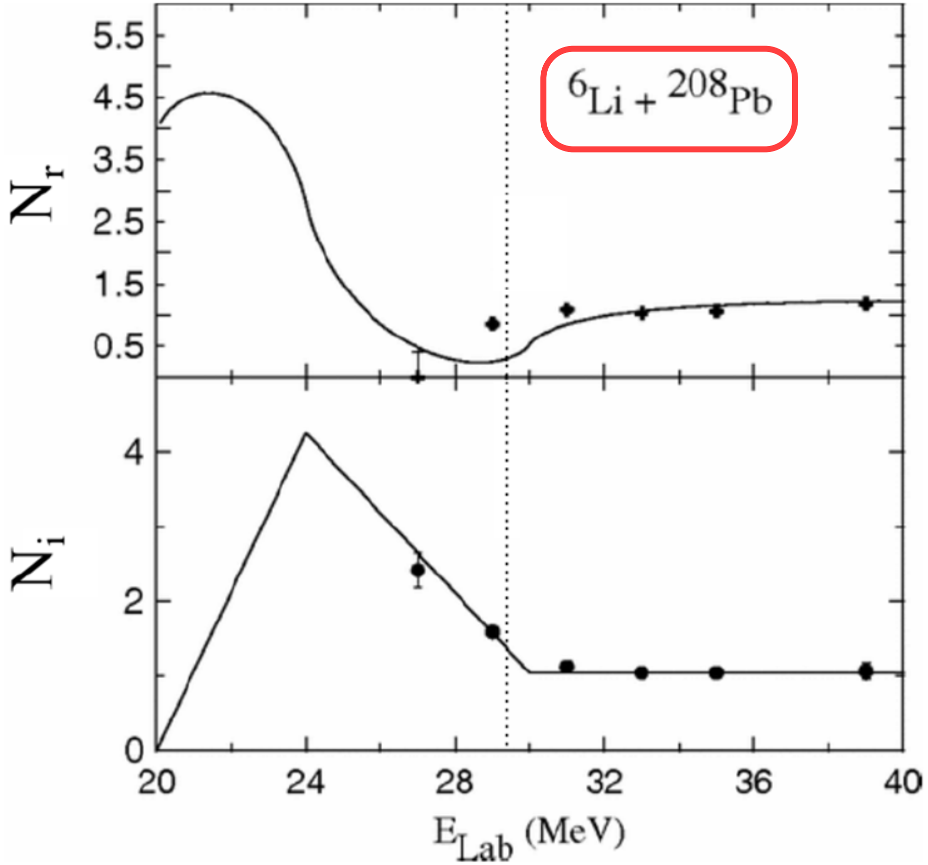
Threshold anomaly

The São Paulo Optical Model Protocol (SP-OMP)

The dispersion relation

OM4 allows us to study the
relationship between the **real and imaginary strengths**

M. S. Hussein et al., ***Phys. Rev. C 76, 019902 (2007)***



$$U_N(R) = N_r\,V_{\mathrm{SPP2}} + i N_i\,V_{\mathrm{SPP2}}$$

Real strength decreases

Breakup threshold anomaly

Significant imaginary strength below the barrier

Application to He, Li, Be, B, C projectiles at near-barrier energies

Application to ^{4,6}**He**, ^{6,7}**Li**, ^{8}**B**, ^{9,10,11}**Be** on a ^{64}Zn target

Data from:

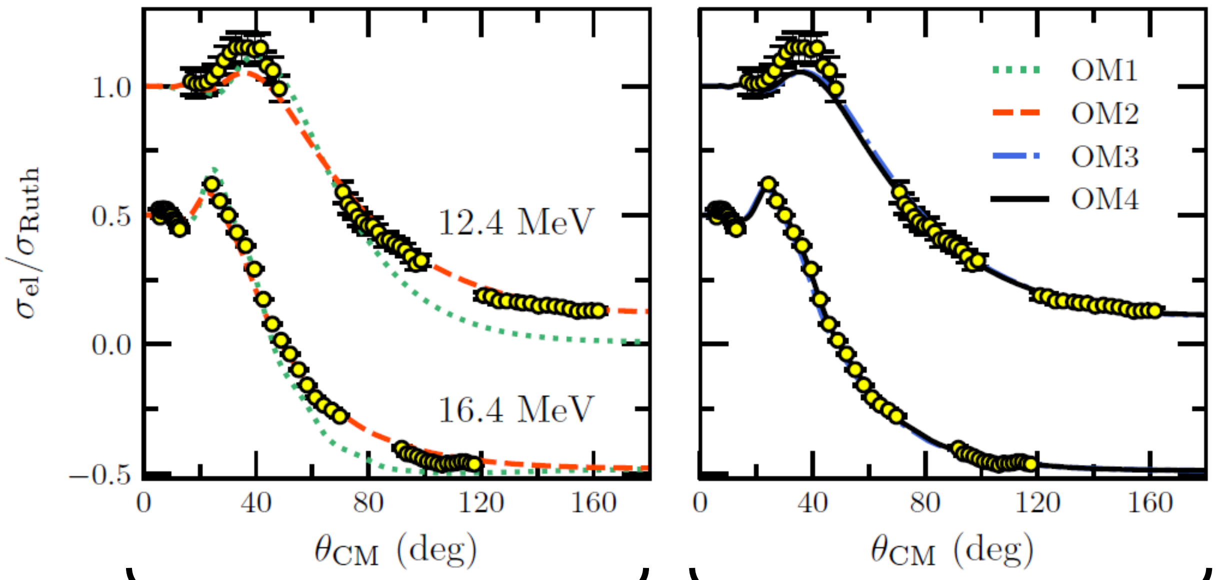
- A. Di Pietro *et al.*, **Phys. Rev. C 69, 044613 (2004)**
- M. Zadro *et al.*, **Phys. Rev. C 80, 064610 (2009)**
- A. Di Pietro *et al.*, **Phys. Rev. C 85, 054607 (2012)**
- J. P. Fernández-García *et al.*, **Phys. Rev. C 92, 054602 (2015)**
- J. P. Fernández-García *et al.*, **Phys. Rev. C 99, 054605 (2019)**
- R. Spartà *et al.*, **Phys. Lett. B 820, 136477 (2021)**

All calculations are performed using **FRESCO** and the **SPP2**

We study the **OP strengths** as a function of the **projectile** and the **bombarding energy**

Application to ^{4,6}He, ^{6,7}Li, ^{8}B, ^{9,10,11}Be on a ^{64}Zn target

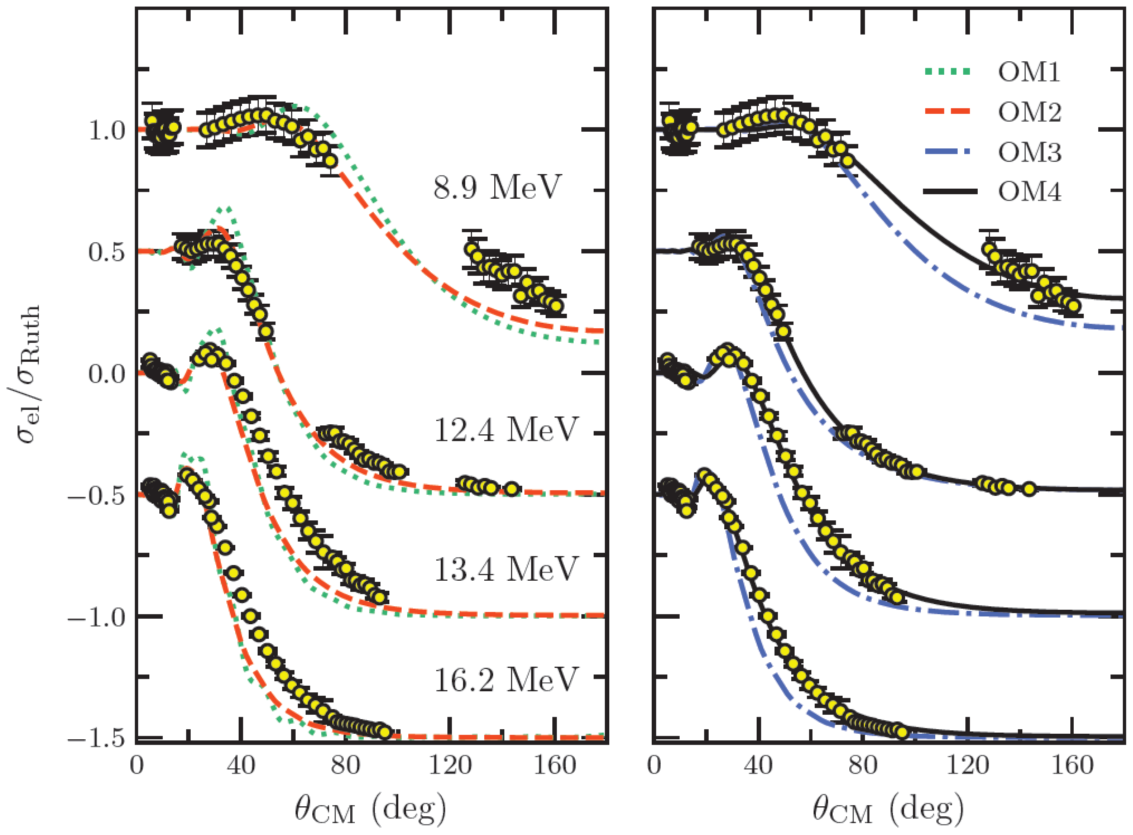
^{4}He + ^{64}Zn

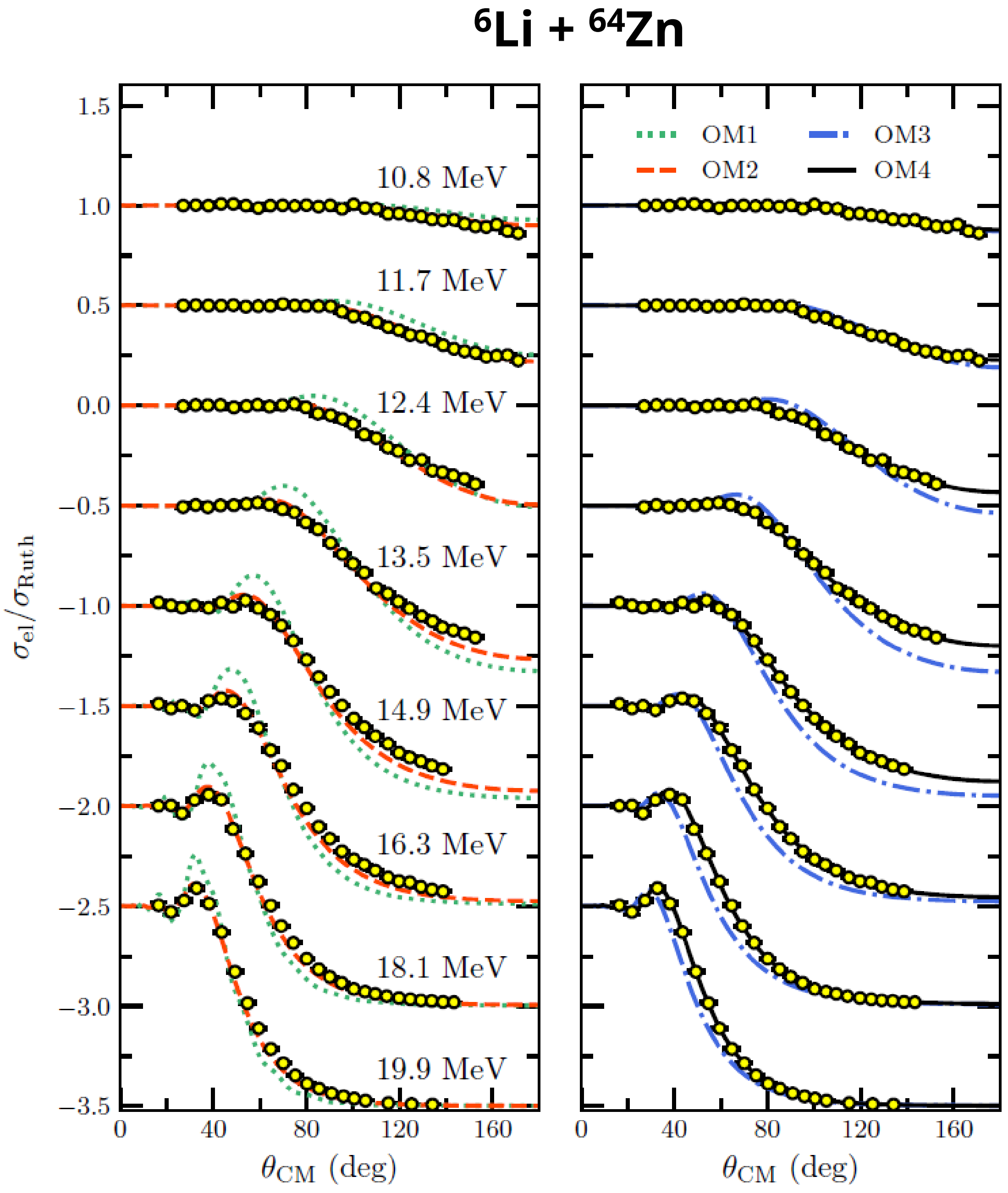


OM1 and OM2:
Parameter free

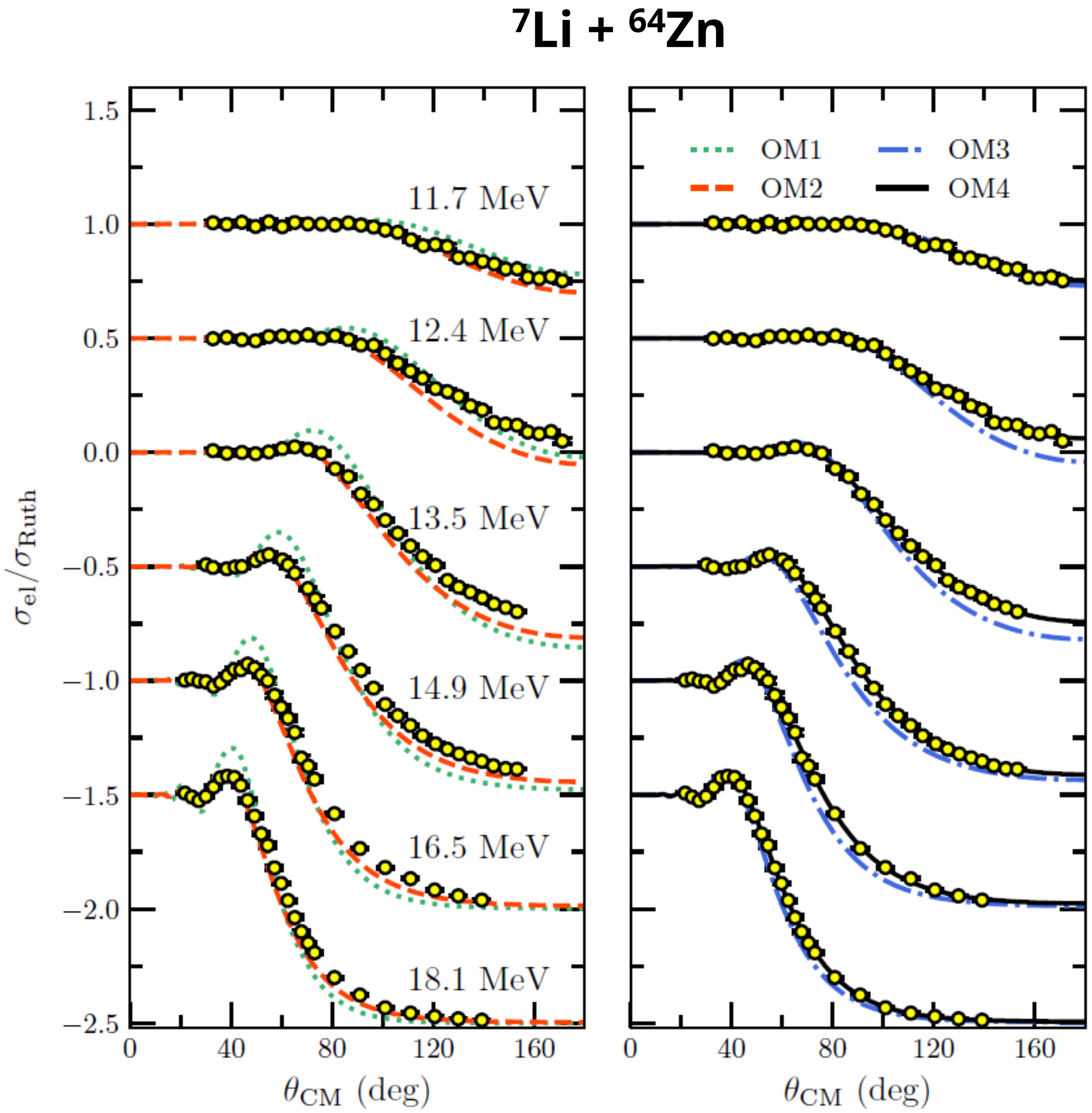
OM3 and OM4:
Parameter fit

^{6}He + ^{64}Zn



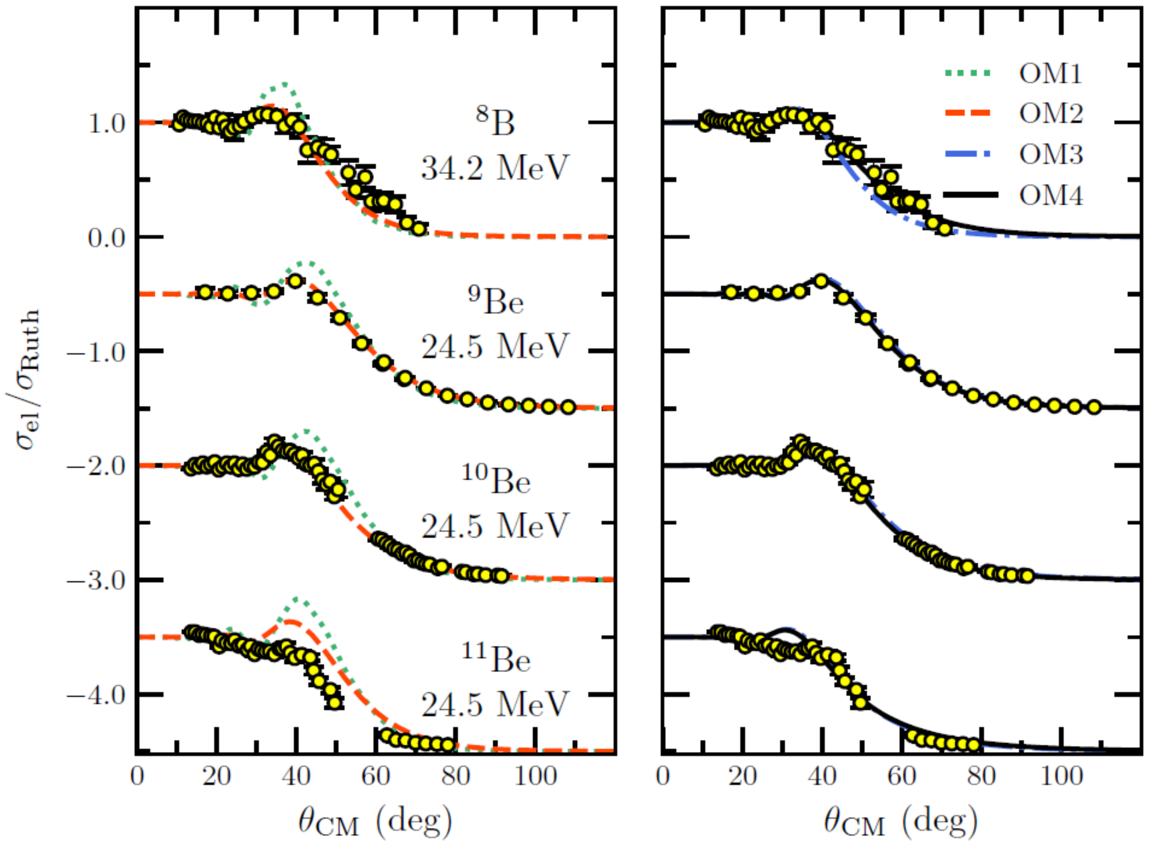


$^{6}Li + ^{64}Zn$
$\sigma_{el}/\sigma_{Ruth}$
10.8 MeV
11.7 MeV
12.4 MeV
13.5 MeV
14.9 MeV
16.3 MeV
18.1 MeV
19.9 MeV
OM1
OM2
OM3
OM4
θ_{CM} (deg)



$^{7}Li + ^{64}Zn$
$\sigma_{el}/\sigma_{Ruth}$
11.7 MeV
12.4 MeV
13.5 MeV
14.9 MeV
16.5 MeV
18.1 MeV
OM1
OM2
OM3
OM4
θ_{CM} (deg)

^{8}B, $^{9,10,11}Be$ + ^{64}Zn

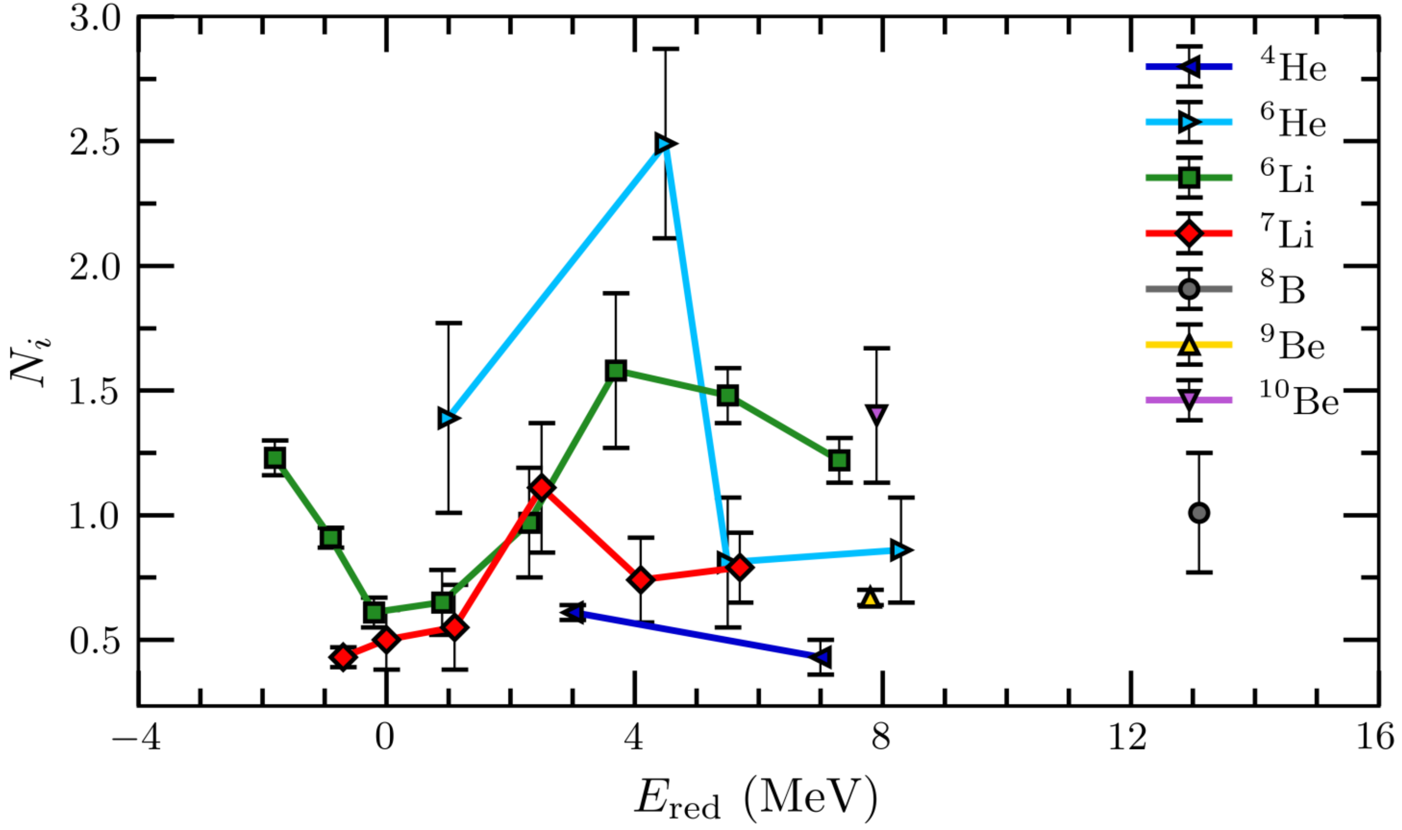


OM3 and OM4 systematically provides the **best results**

Projectile	V_B	E_{CM}	χ^2_{red} OM1	χ^2_{red} OM2	χ^2_{red} OM3	χ^2_{red} OM4
^{4}He	9.4	12.42	38	1.44	0.86	0.78
		16.37	334	104	68	34
^{6}He	7.9	8.9	4.21	2.34	2.11	0.24
		12.4	30	11	3.50	0.39
		13.4	130	98	98	66
		16.2	585	381	380	196
^{6}Li	12.6	10.77	25	3.88	1.29	1.29
		11.69	97	3.69	2.38	0.69
		12.43	44	8.25	6.22	0.92
		13.54	99	53	51	1.05
		14.92	213	101	97	1.15
		16.30	341	134	83	2.10
		18.14	581	162	42	2.34
		19.98	317	75	29	1.19
^{7}Li	12.4	11.69	16	7.73	2.30	0.78
		12.43	24	74	56	1.24
		13.54	129	88	82	0.84
		14.92	439	168	154	0.72
		16.46	109	47	47	1.06
		18.14	144	50	50	0.68
^{8}B	21.1	34.22	6.79	2.17	2.08	0.96
^{9}Be	16.7	24.50	484	9.17	5.42	3.59
^{10}Be	16.6	24.50	48	13	11	8.52
^{11}Be	16.2	24.50	82	47	30	30

What can we learn from OM3?

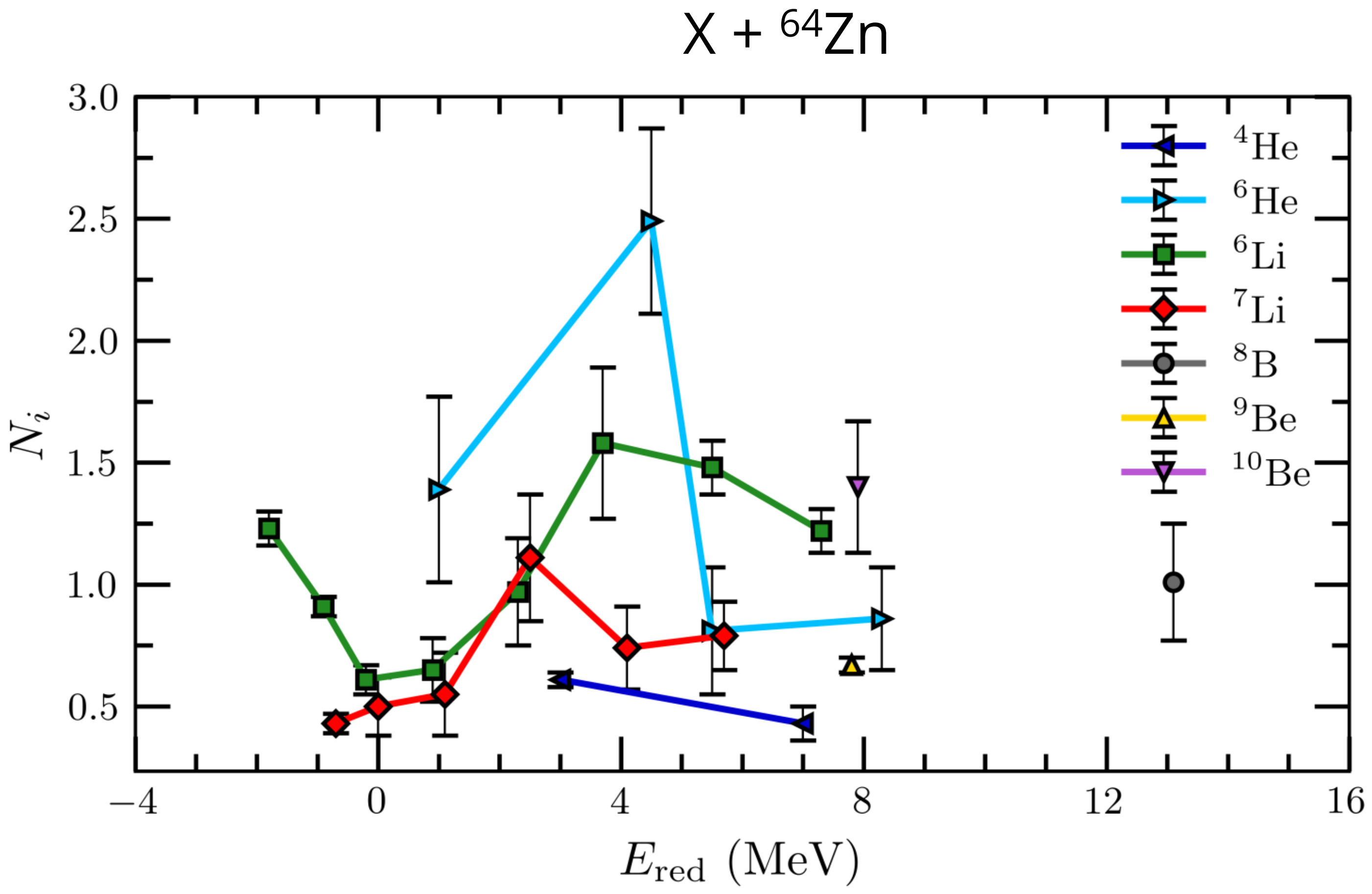
X + ^{64}Zn



$$E_{\text{red}} = E_{\text{CM}} - V_{\text{B}}$$

Imaginary strength as a function of the **energy** and **projectile**

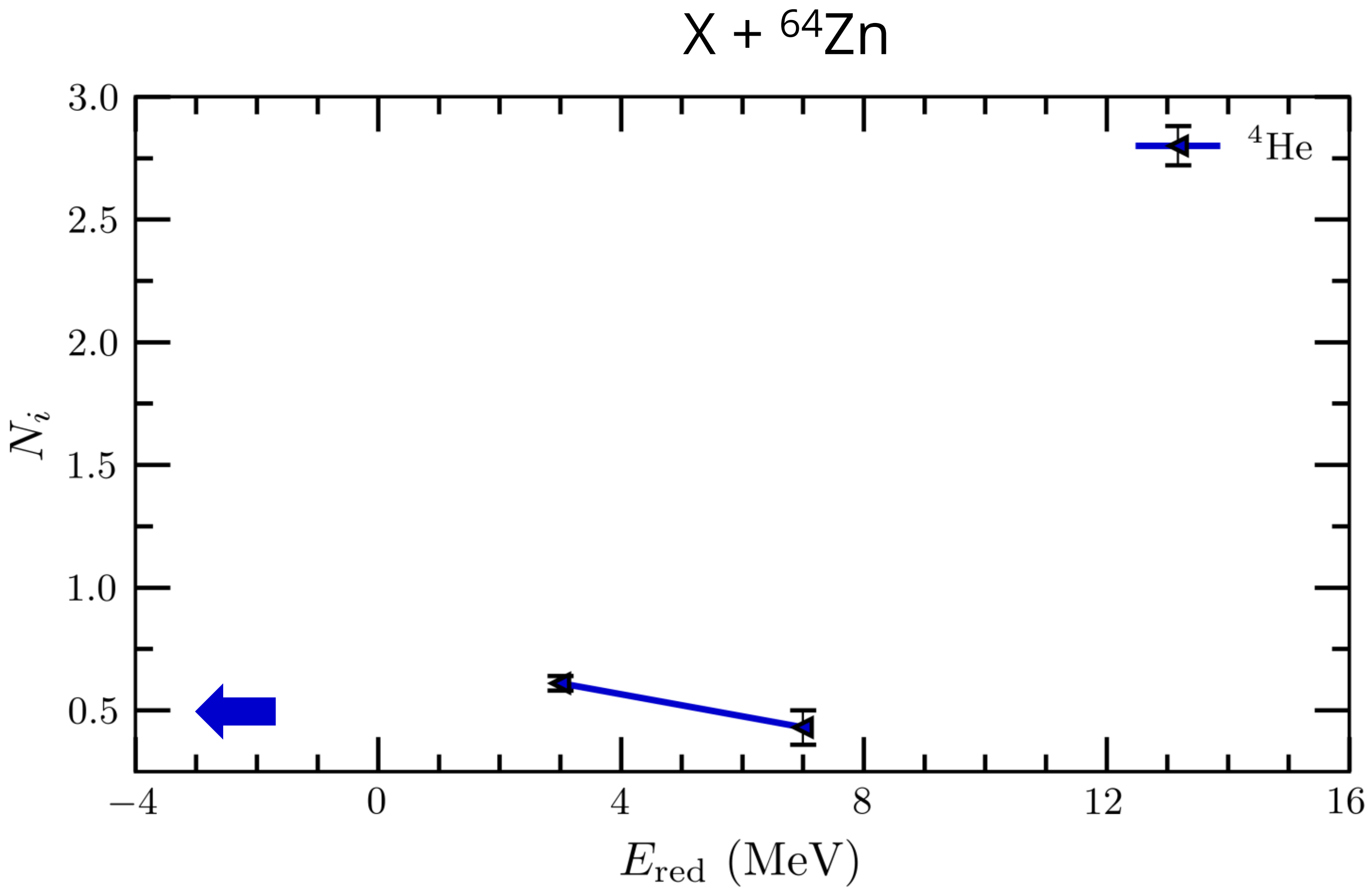
What can we learn from OM3?



The N_i values are ordered according to the **projectile binding energy**

Nucleus	Cluster	Q_{bu} (MeV)
^{4}He	-	-19.813
^{10}Be	^{9}Be + n	-6.812
^{7}Li	a + t	-2.468
^{9}Be	a + a + n	-1.665
^{6}Li	a + d	-1.474
^{6}He	a + n + n	-0.975
^{8}B	^{7}Be + p	-0.136

What can we learn from OM3?



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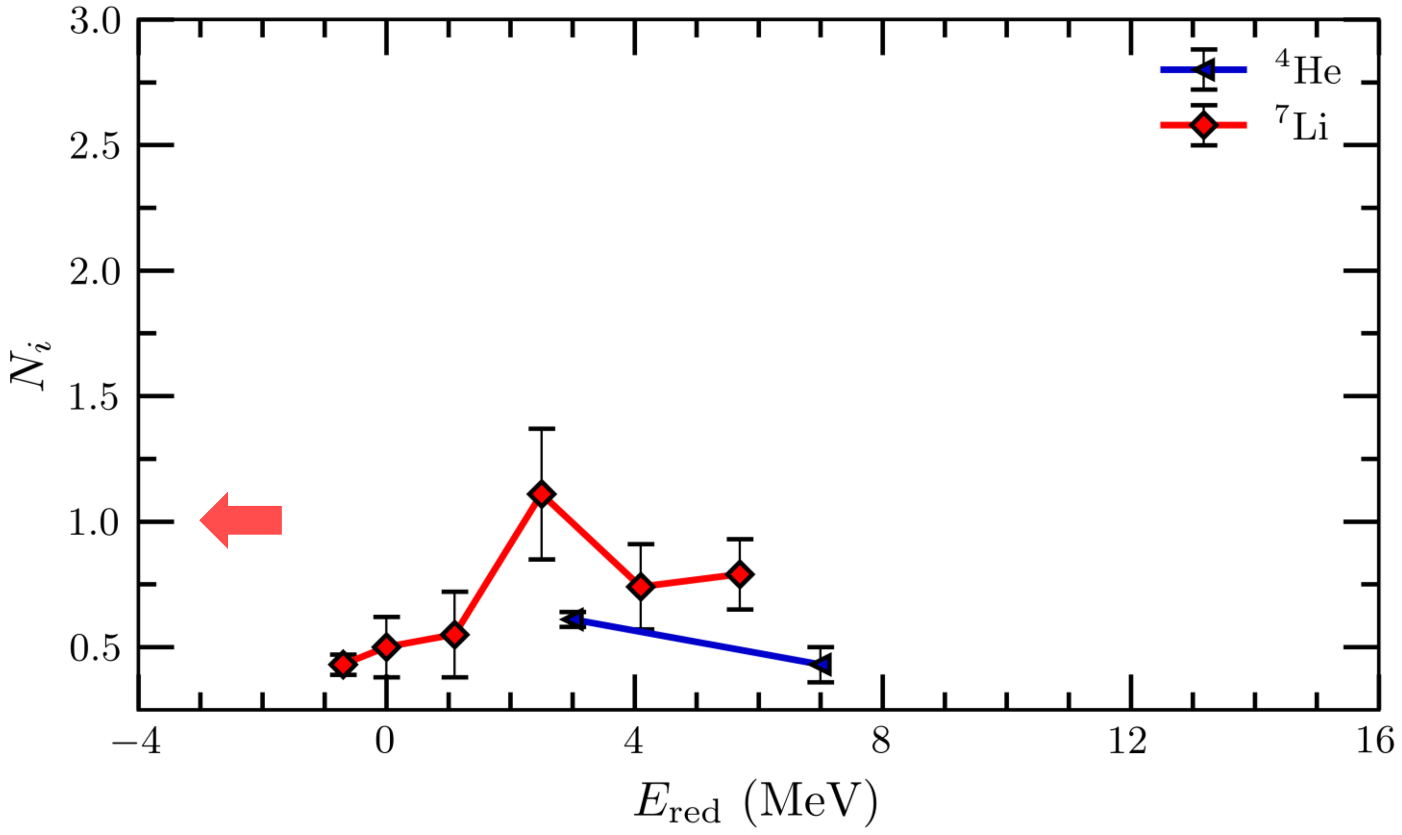
X + ^{64}Zn



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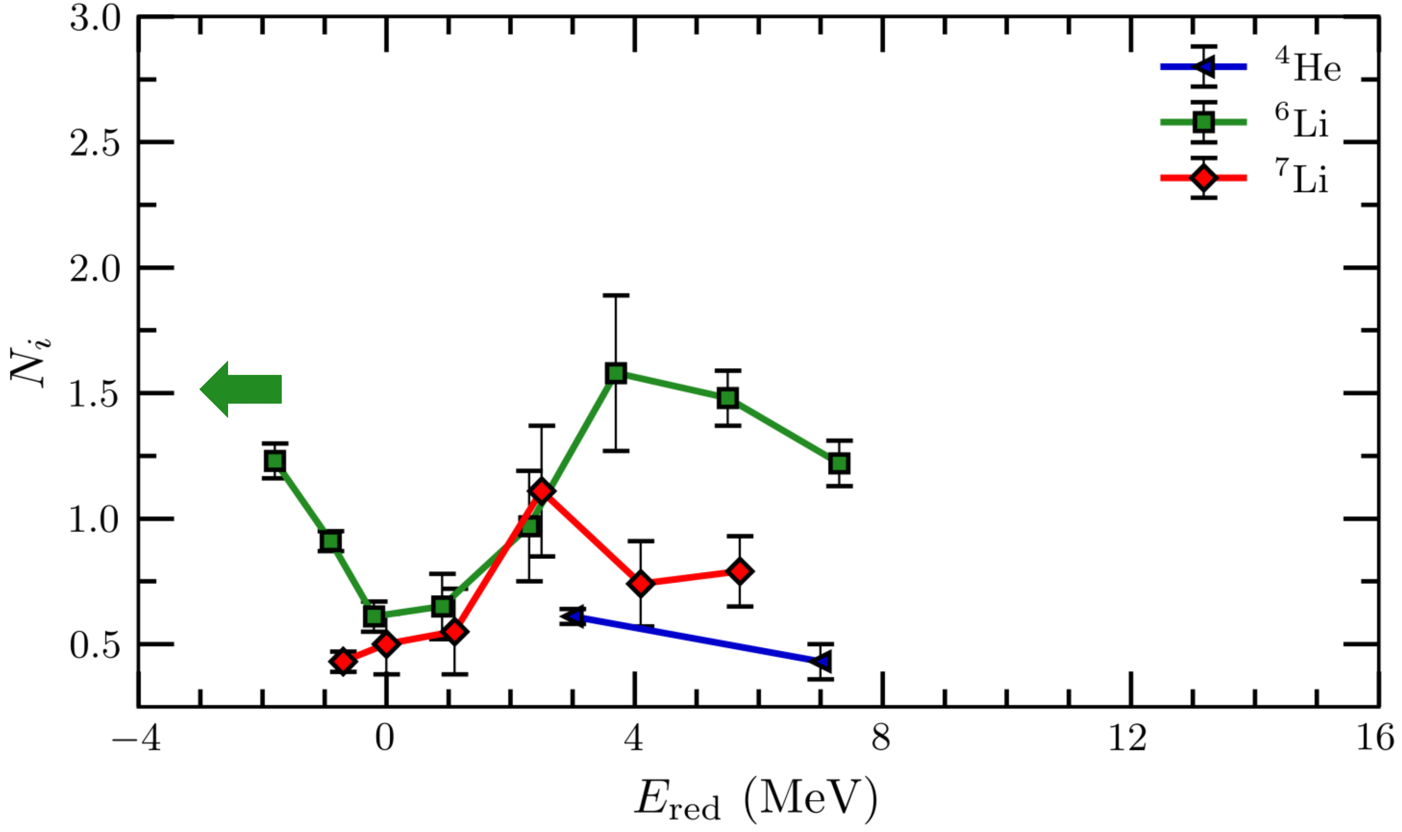

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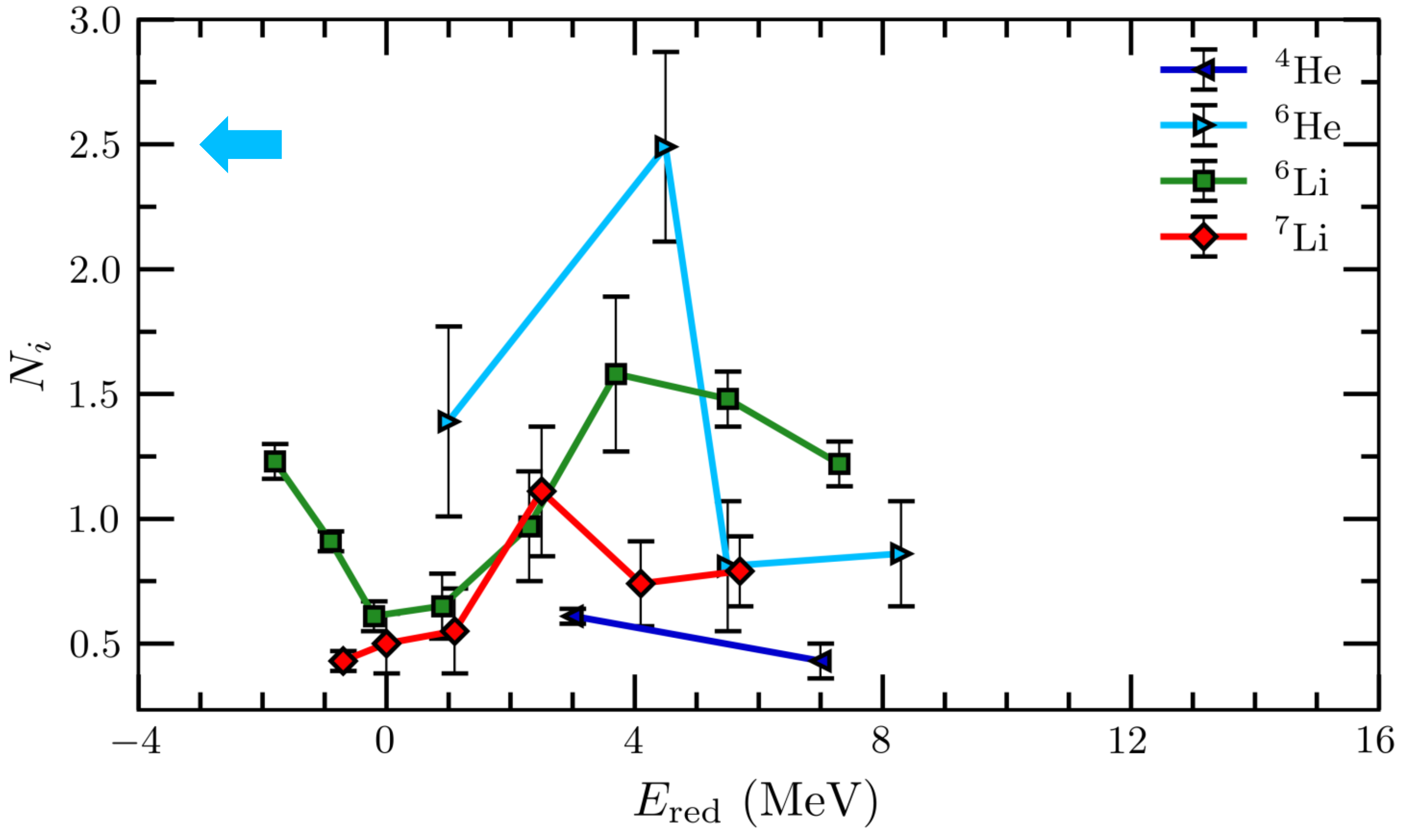

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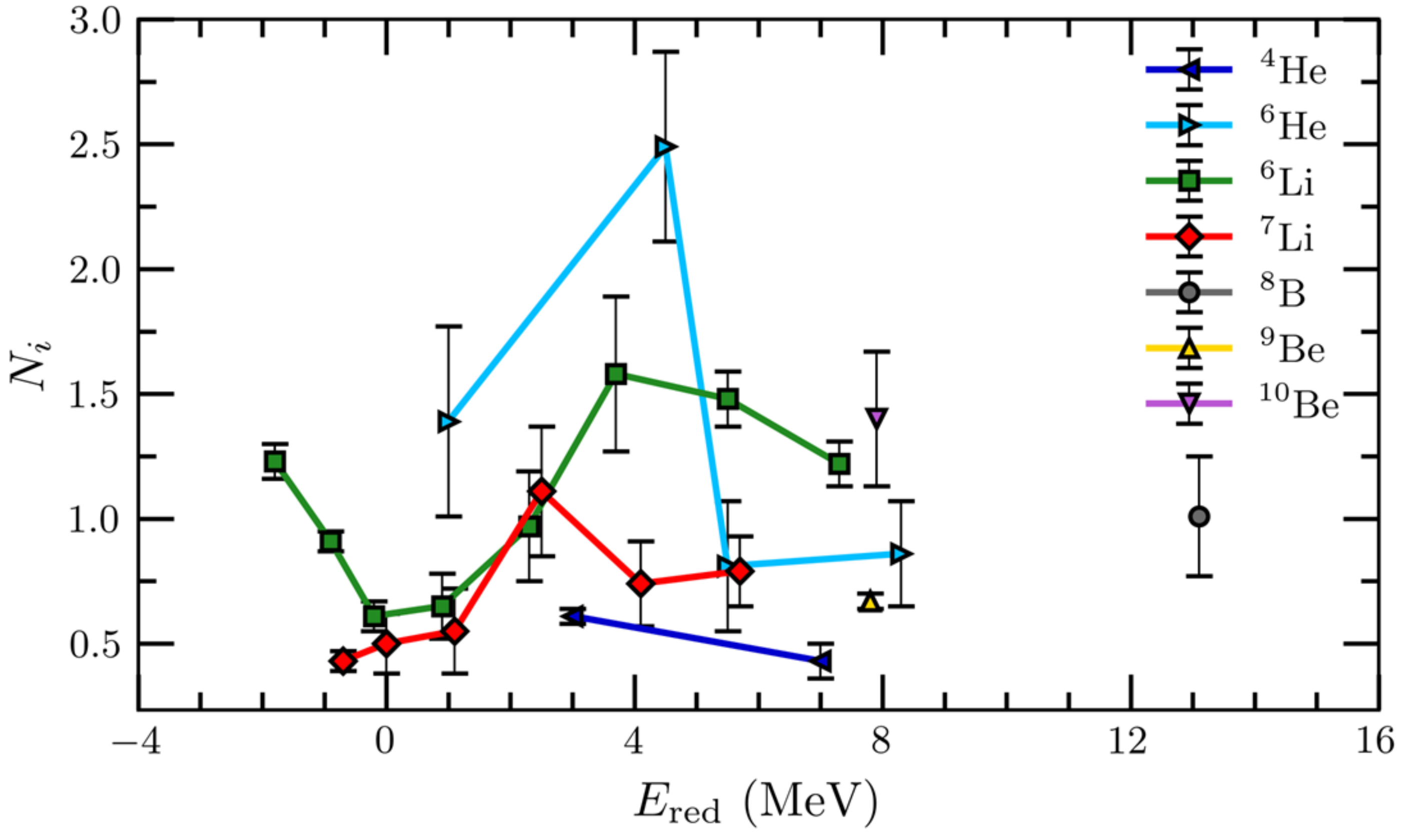
What can we learn from OM3?

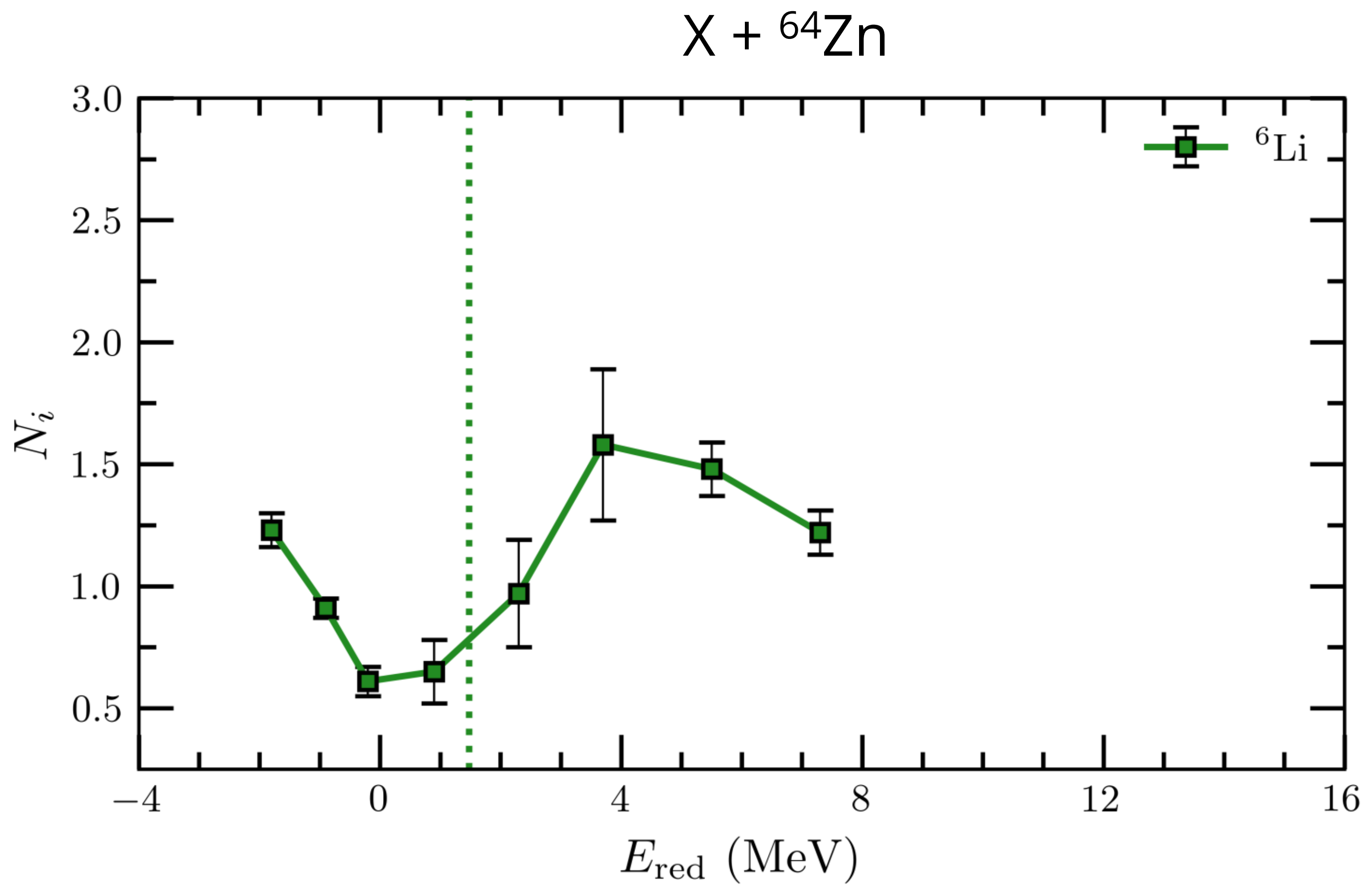
X + ^{64}Zn



The N_i values are ordered according to the **projectile binding energy**

Reaction dynamics strongly correlates to **projectile structure** for **cluster-structured nuclei**

What can we learn from OM3?



$$E_b^{\text{op}} \geq V_B + |Q_{\text{bu}}|$$

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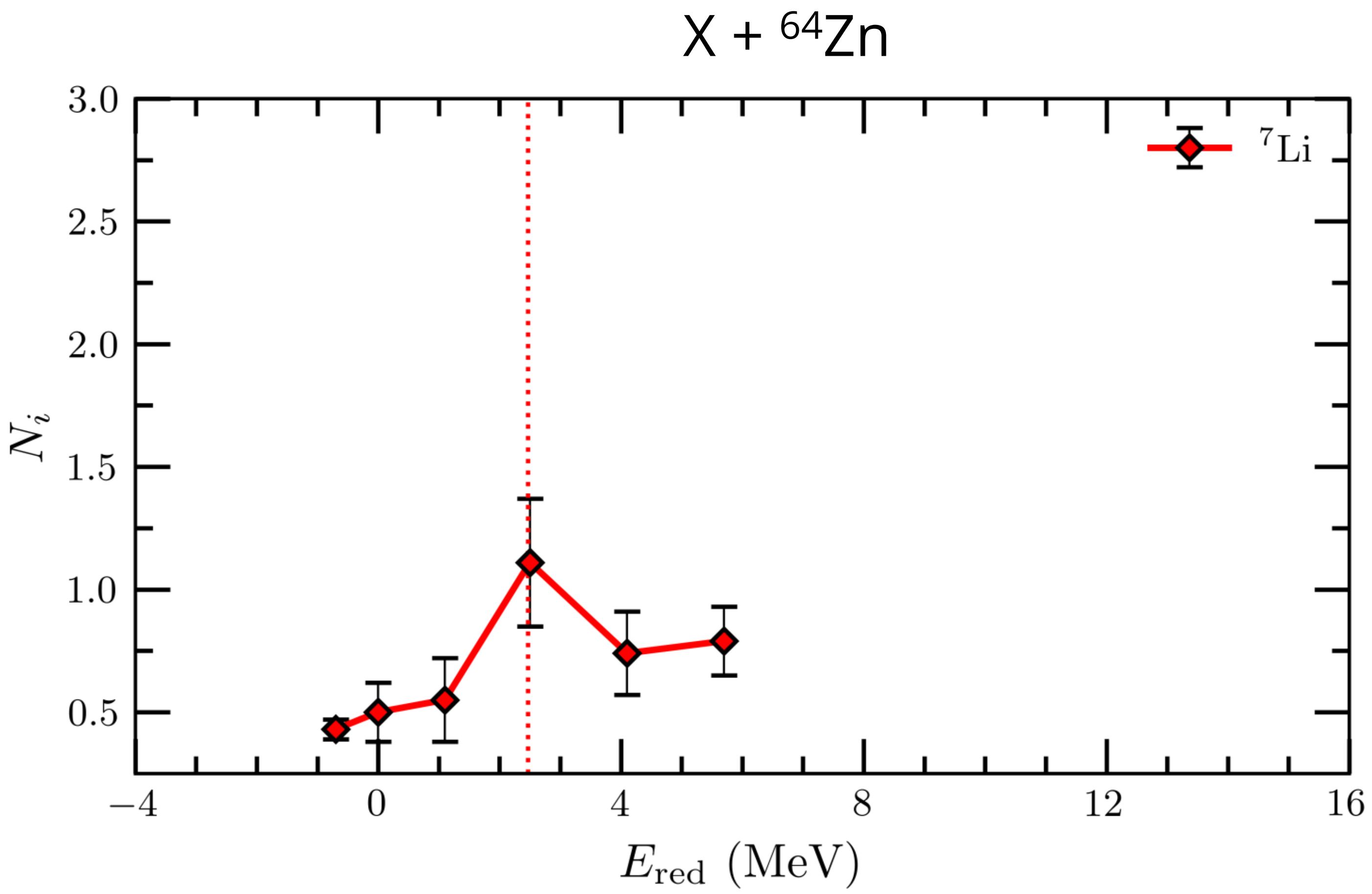
The **imaginary strength** presents a **peak structure** at above-barrier energies which correlates with $\mathbf{Q_{bu}}$

What can we learn from OM3?



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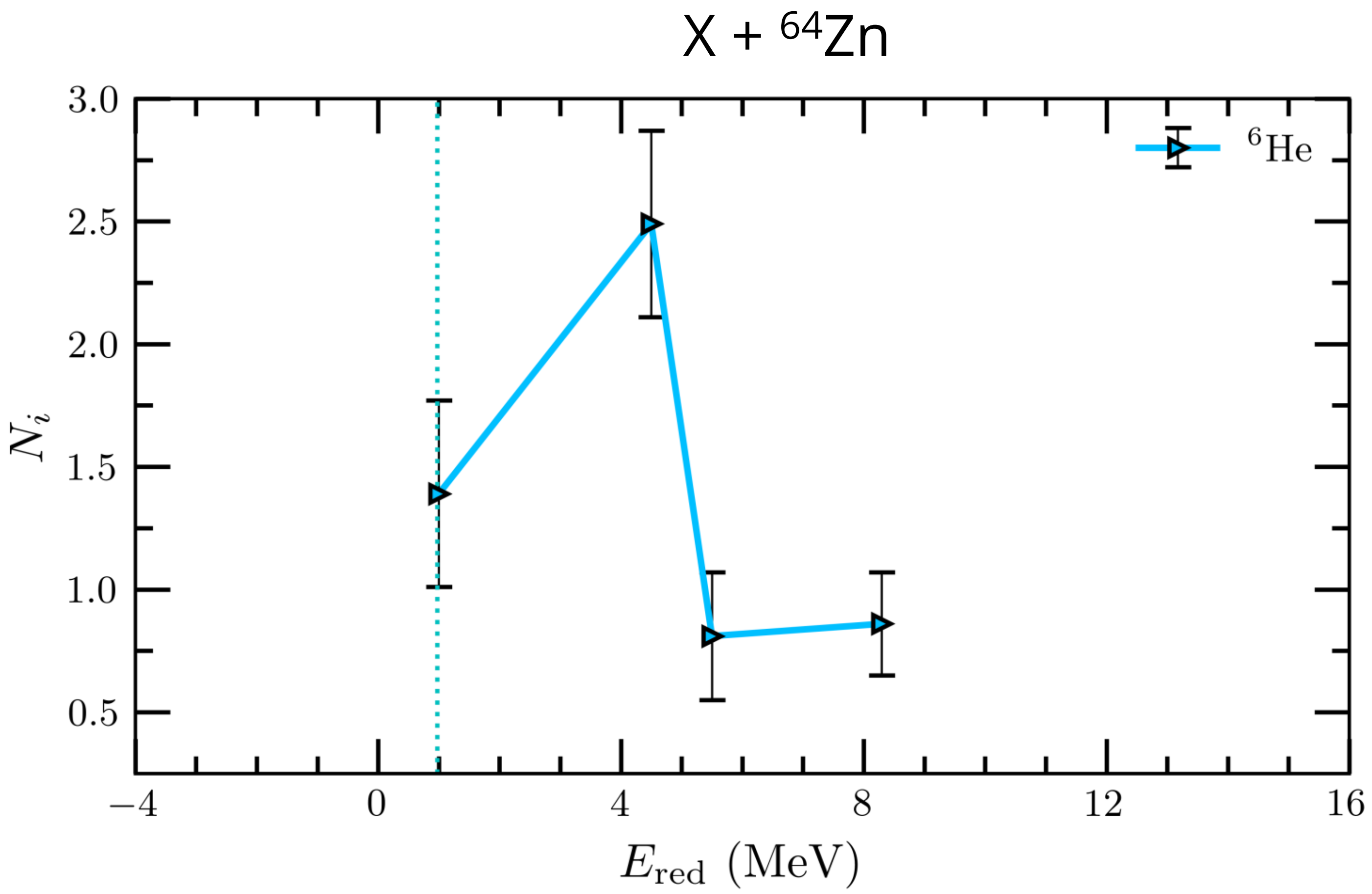

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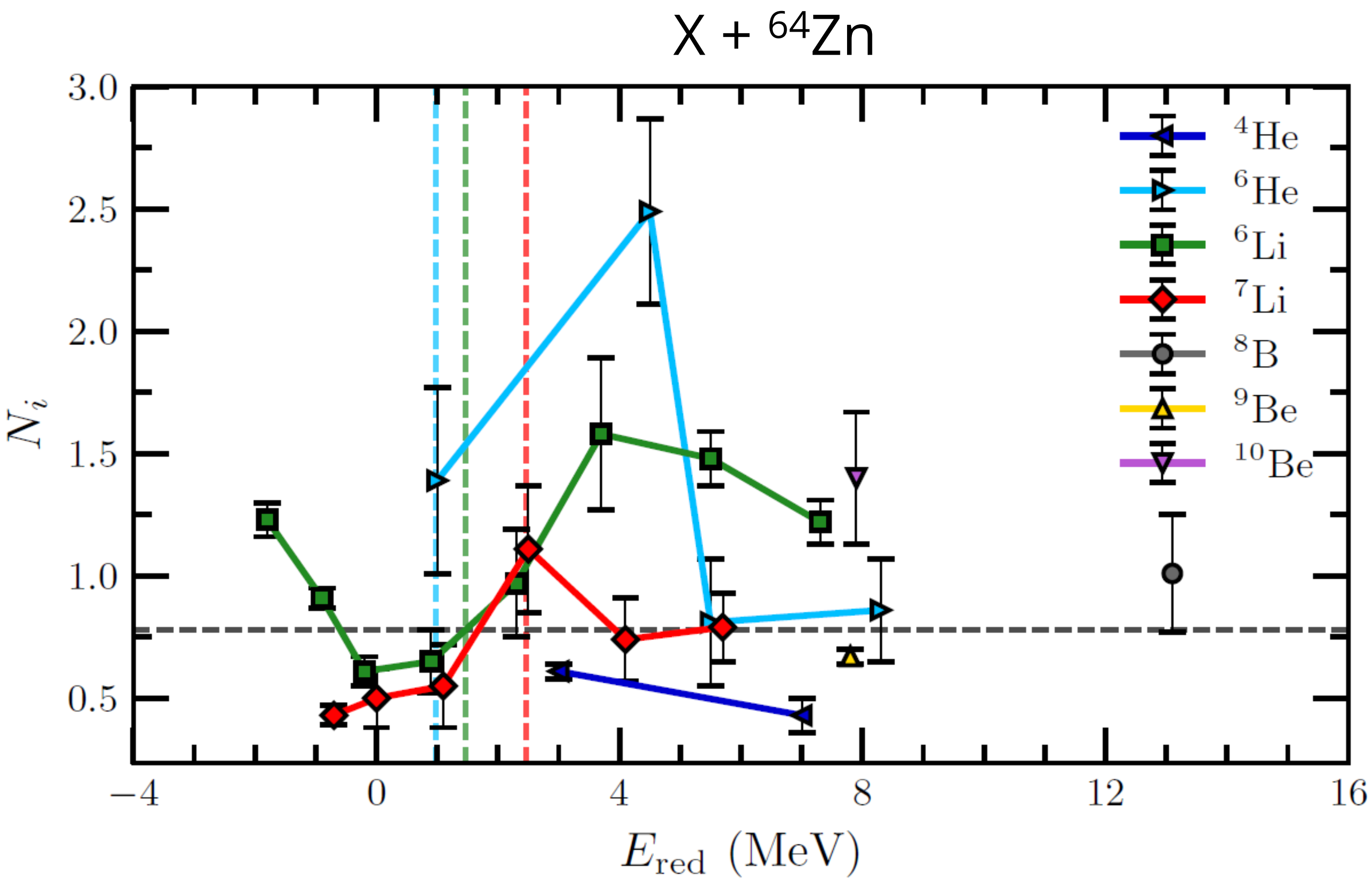

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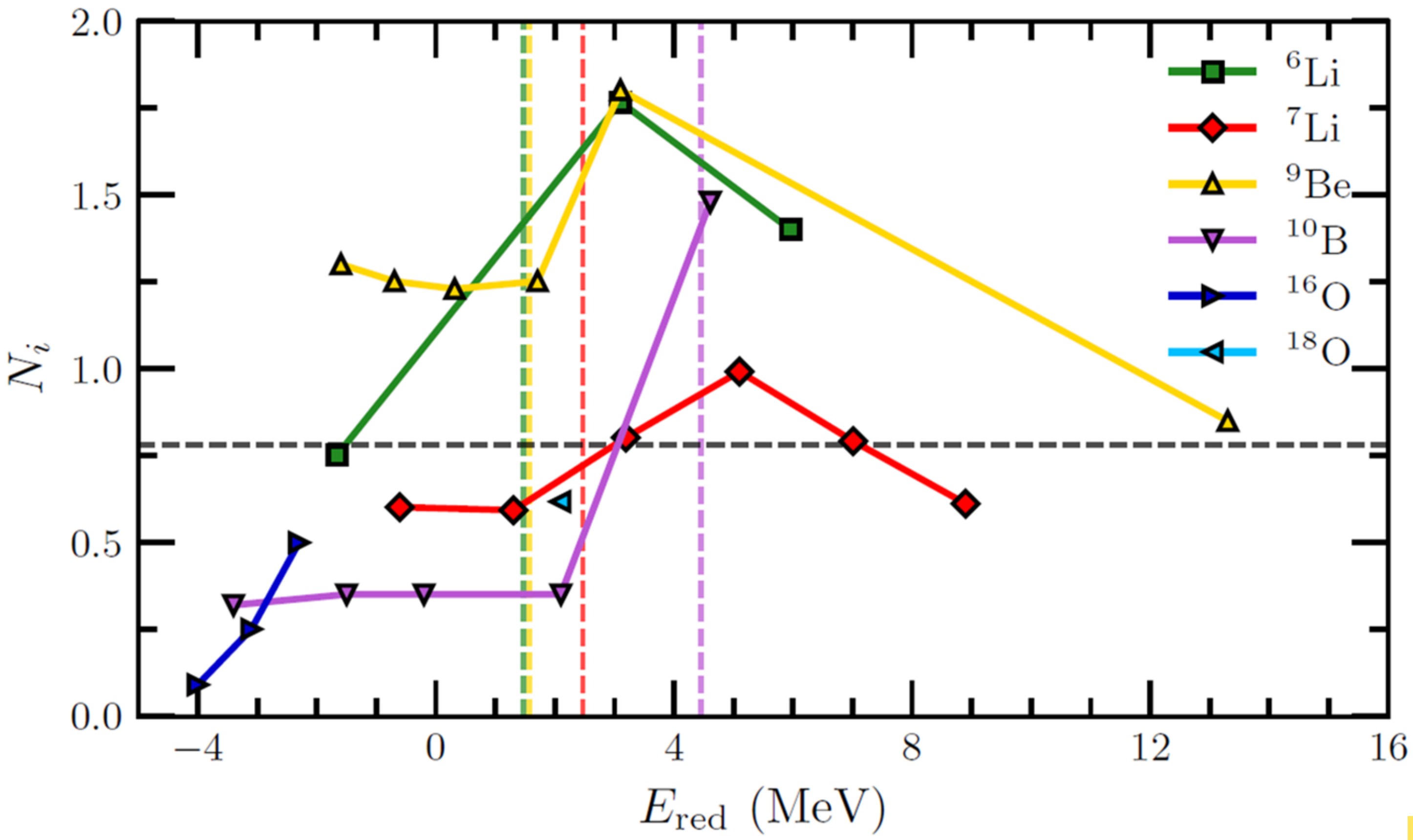
The **imaginary strength** presents a **peak structure** at above-barrier energies which correlates with $\mathbf{Q_{bu}}$

What can we learn from OM3?

X + ^{120}Sn



M. A. G. Alvarez et al. ***Phys. Rev. C 100, 064602 (2019)***

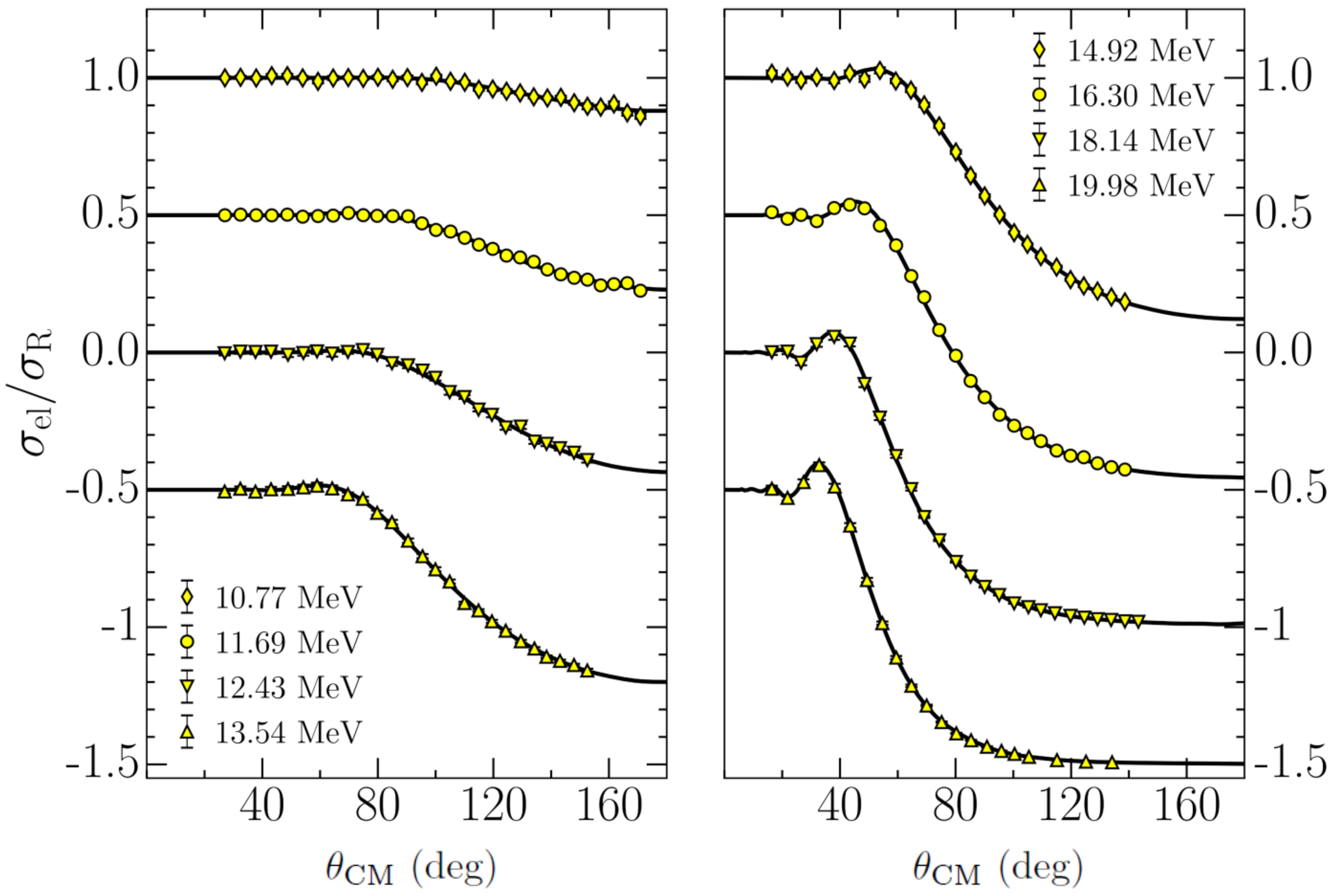
Nucleus	Cluster	Q_{bu} (MeV)
^{16}O	a + a + a + a	-7.162
^{10}B	^{9}Be + n	-6.812
^{7}Li	a + t	-2.468
^{9}Be	a + a + n	-1.665
^{6}Li	a + d	-1.474

$$E_b^{\mathrm{op}} \geq V_B + |Q_{\mathrm{bu}}|$$

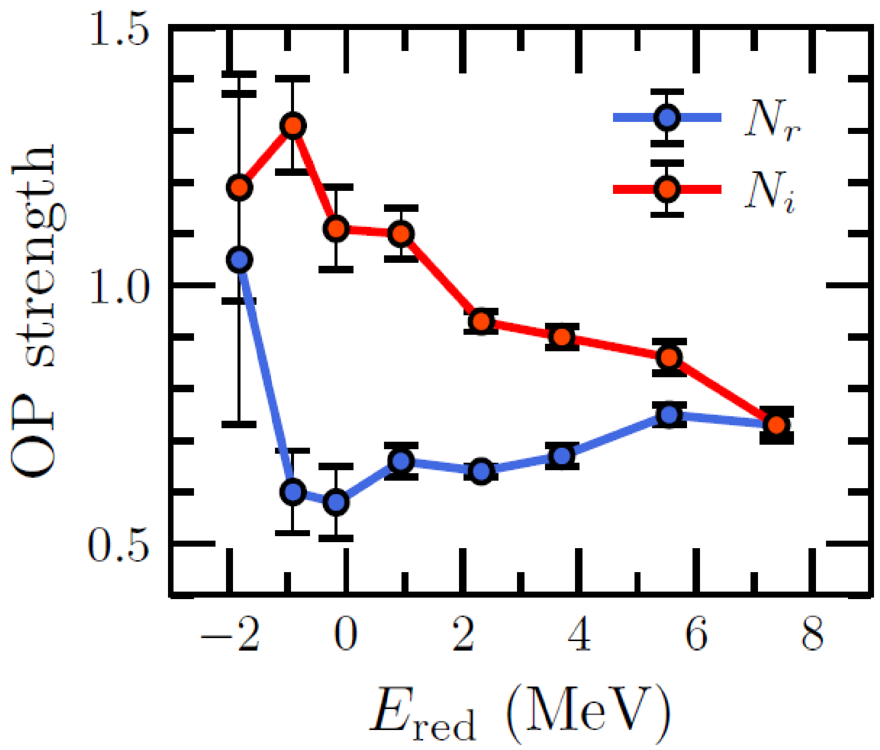
This **systematic result** was previously observed on a heavier target (^{120}Sn)

What can we learn from OM4?

$^{6}Li + ^{64}Zn$



$$U_N(R) = N_r V_{SPP2} + i N_i V_{SPP2}$$

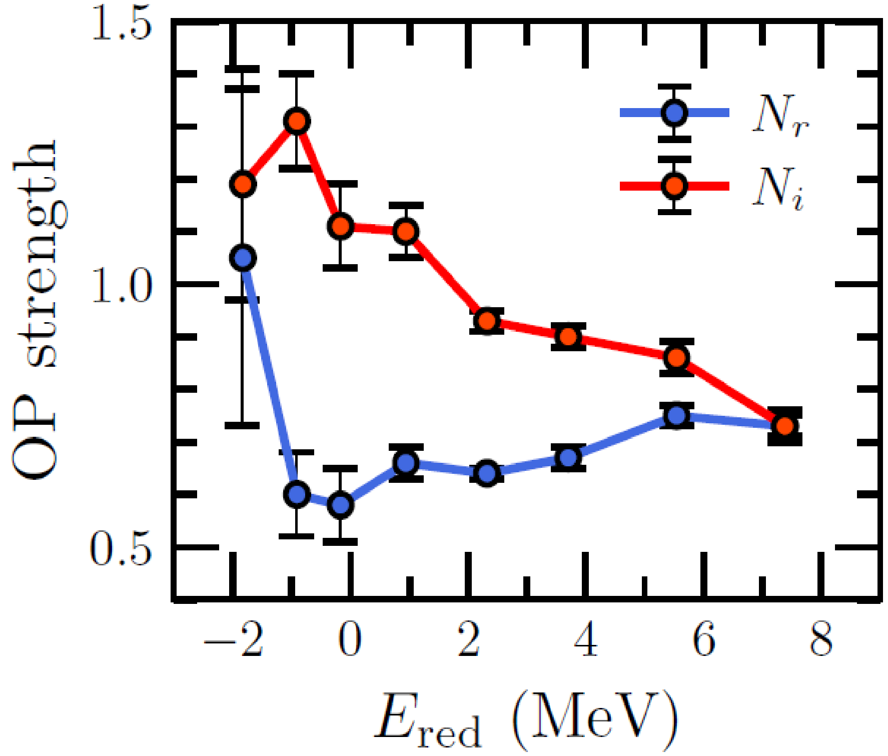


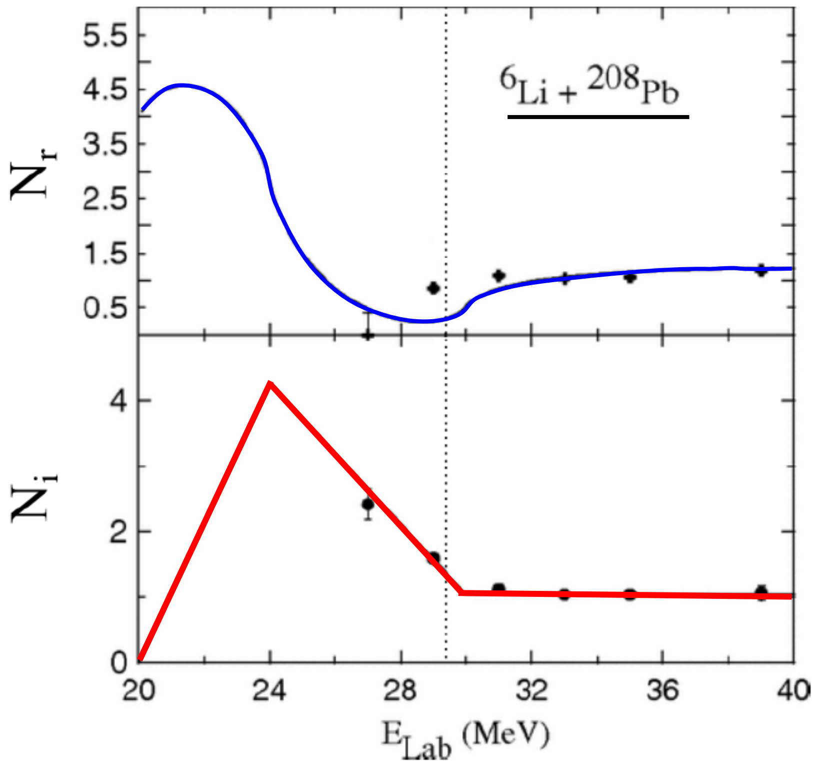
χ^2_{red} values from 0.69 to 2.34

Dispersion relation

What can we learn from OM4?

^{6}Li + ^{64}Zn

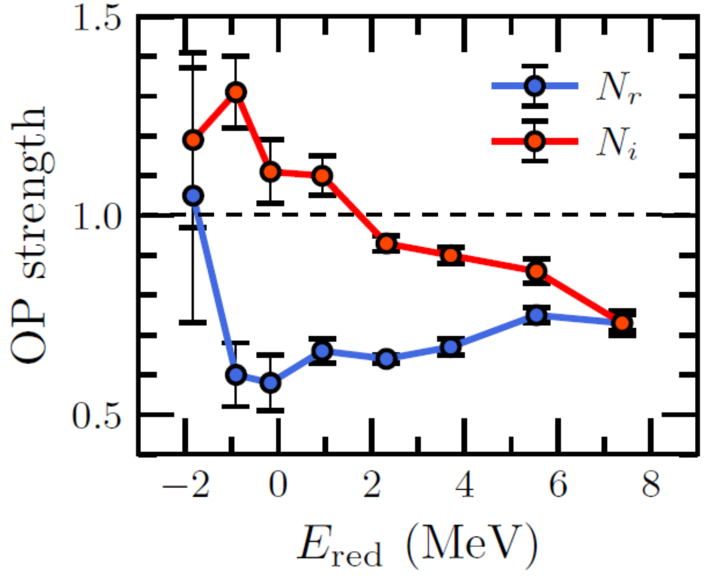




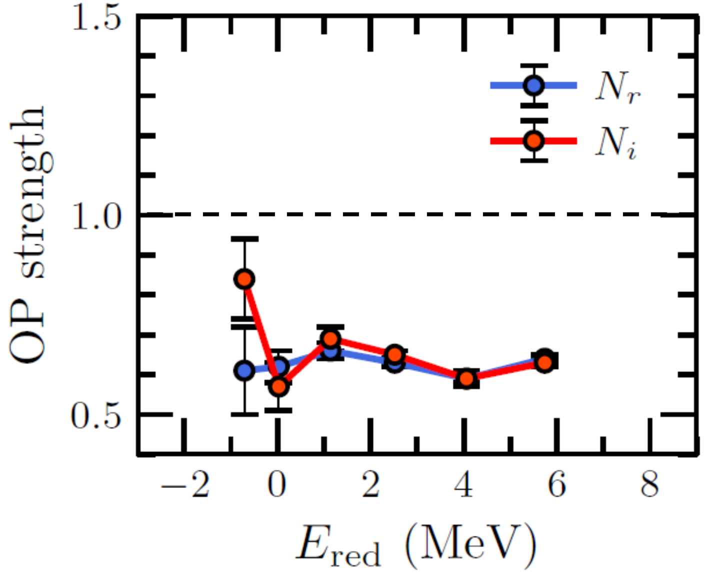
Breakup Threshold Anomaly

What can we learn from OM4?

^{6}Li + ^{64}Zn



^{7}Li + ^{64}Zn

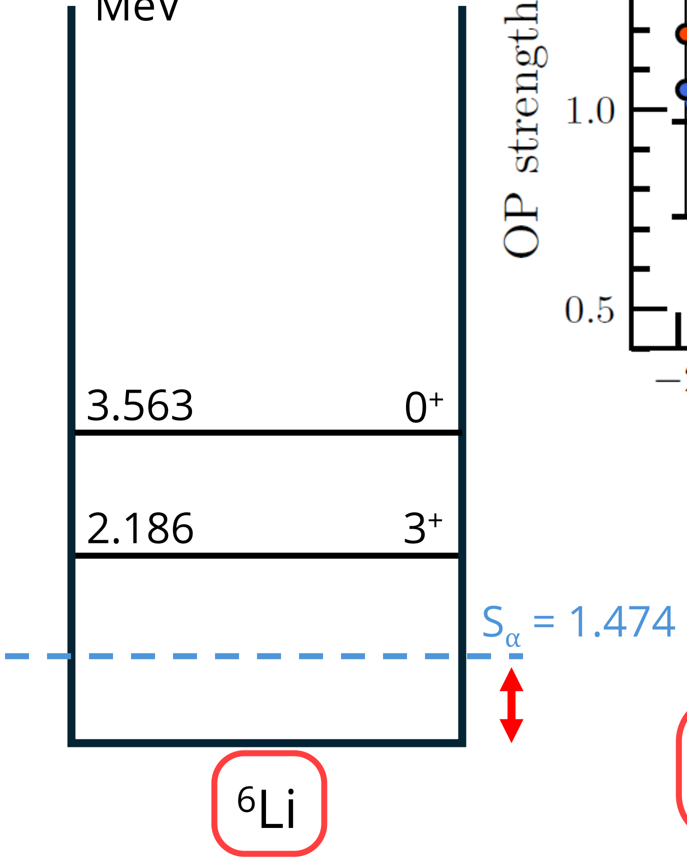


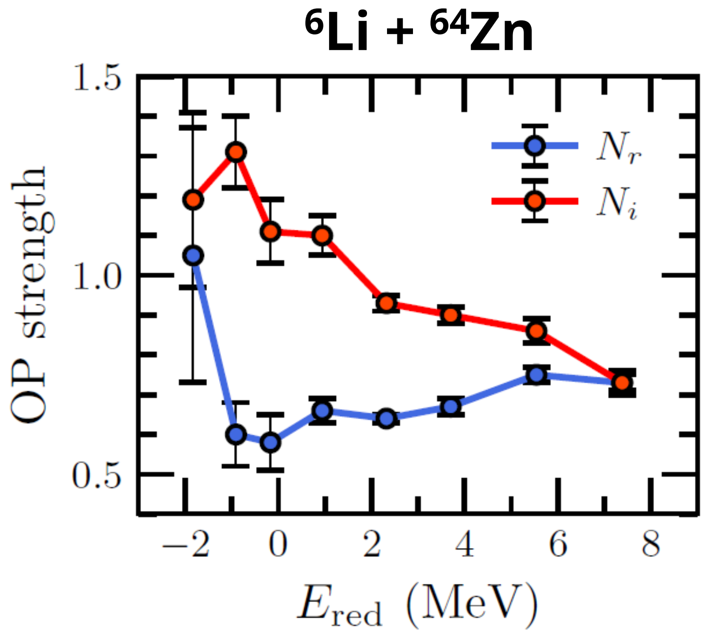
TA, BTA, or other ?

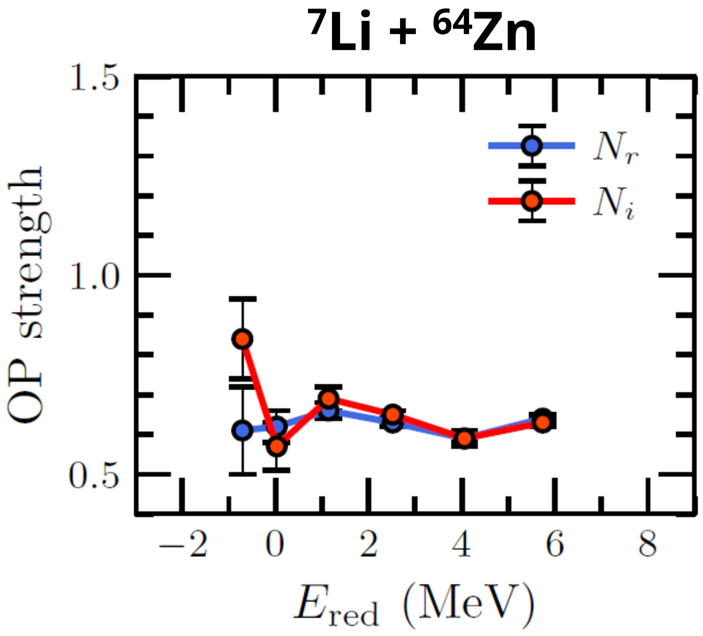
BTA is more pronounced for **^{6}Li**

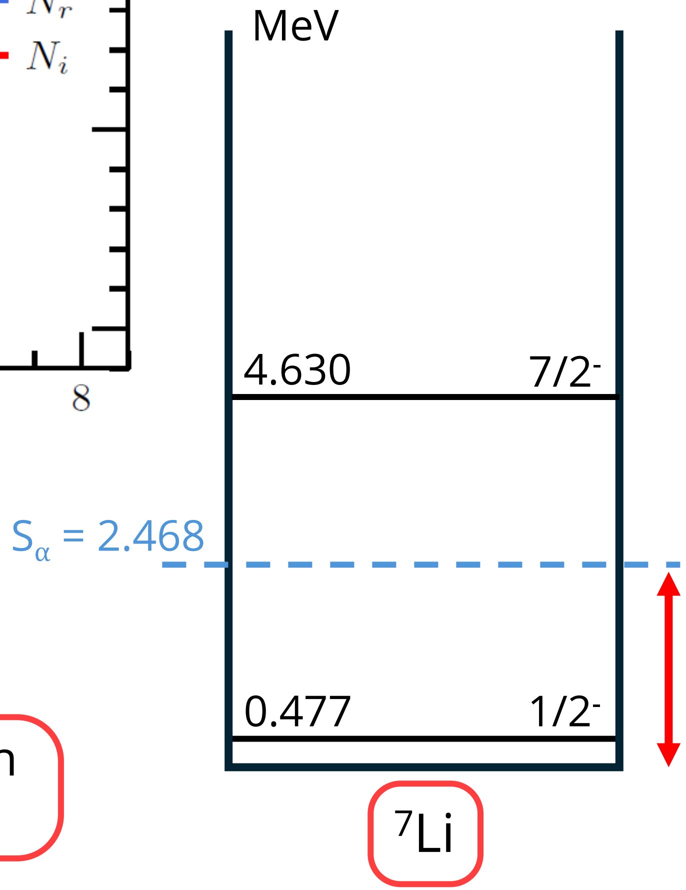
- Lower binding energy
- No excited states below breakup threshold

What can we learn from OM4?



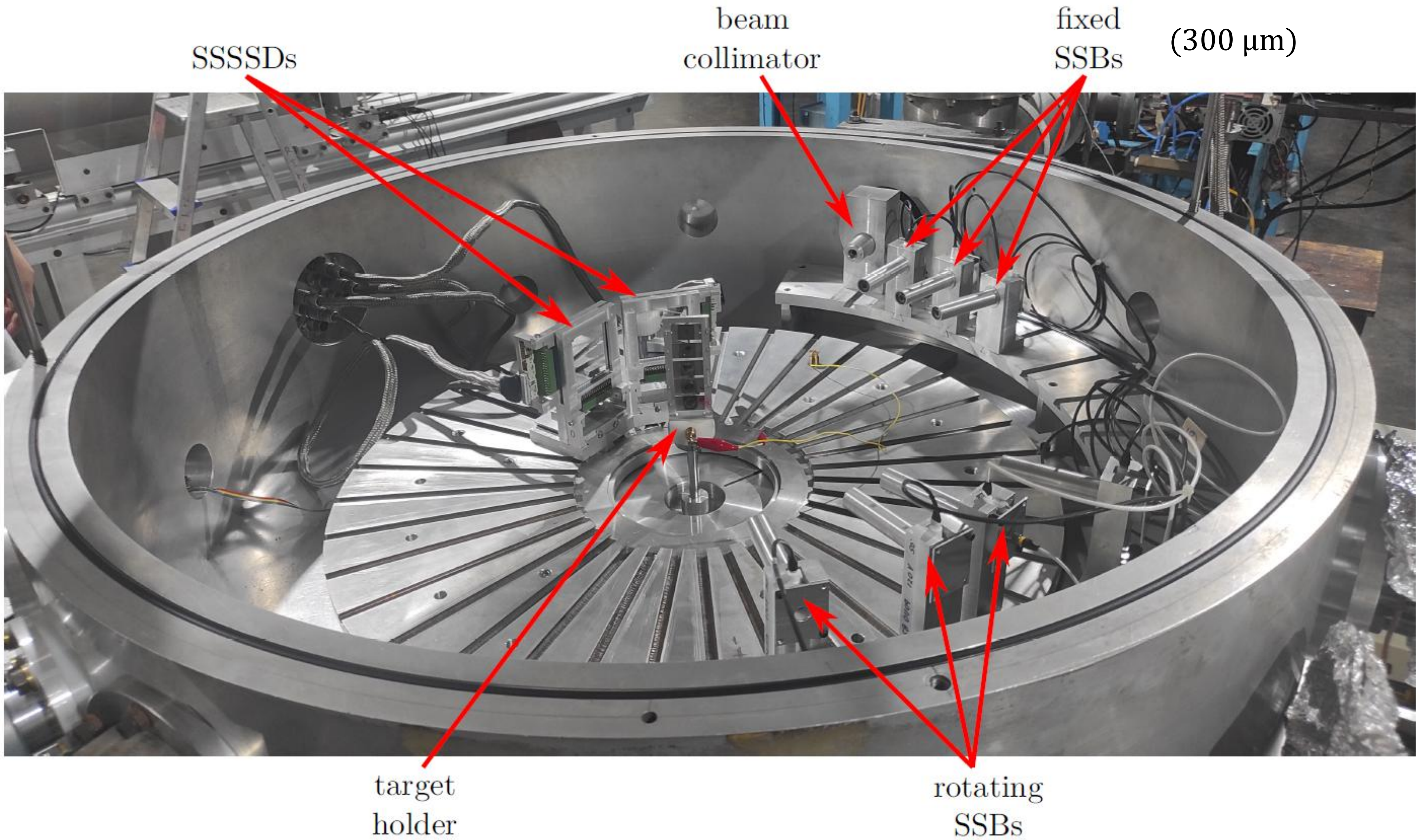




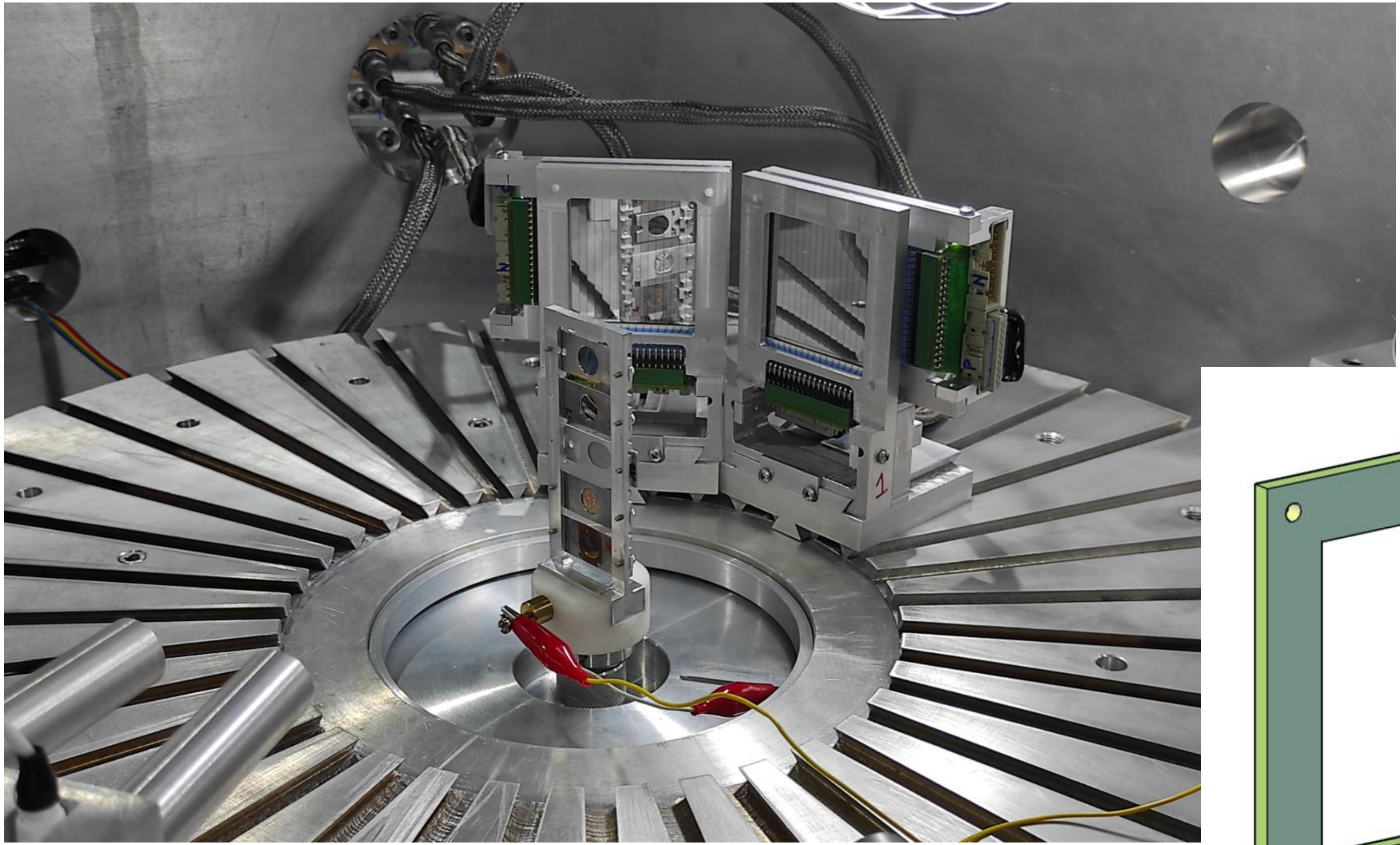


Significant variations in the nuclear potential with **projectile** and **bombarding energy**

$^{12,13}C + ^{64}Zn$ measurements



Detection system



Single Sided Silicon Strip Detectors

16 strips
50 mm x 50 mm

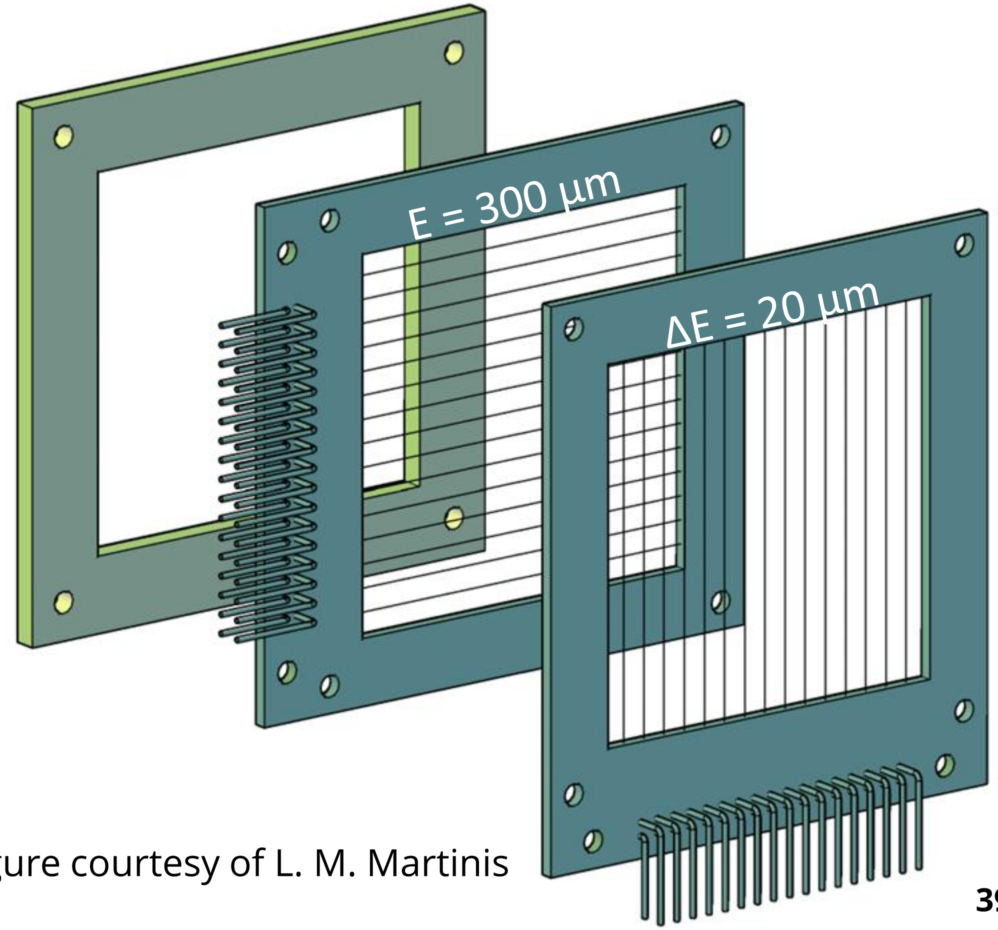


Figure courtesy of L. M. Martinis

Silicon **T**elescopes **A**rray for **R**eactions
(STAR)

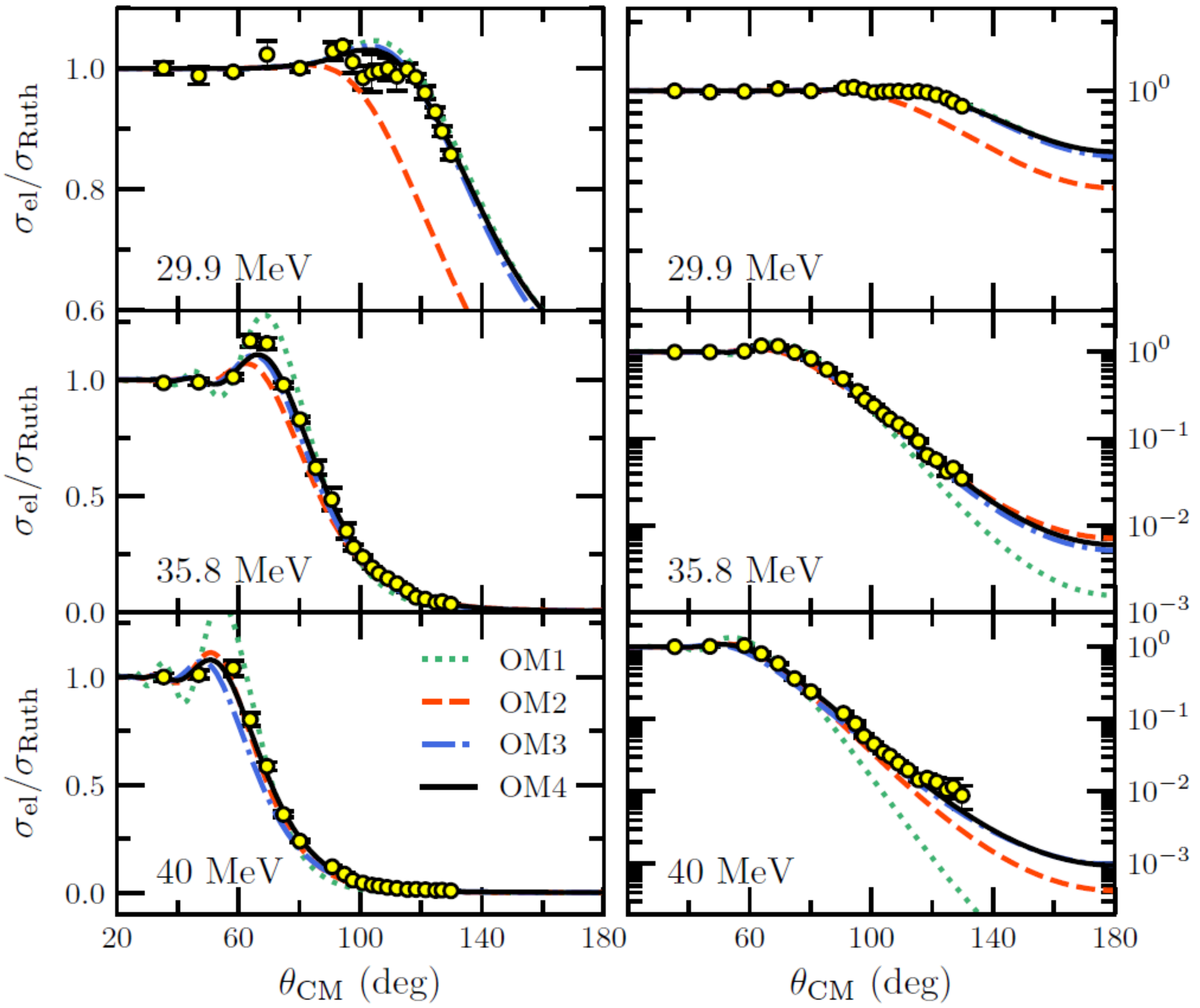
1. Elastic scattering: ^{12}C + ^{64}Zn

29.9 MeV	N_r	N_i	χ^2_{red}
OM1	1	–	4.6
OM2	1	0.78	213
OM3	1	0.05 ± 0.01	2.1
OM4	0.95 ± 0.08	0.07 ± 0.03	2.0

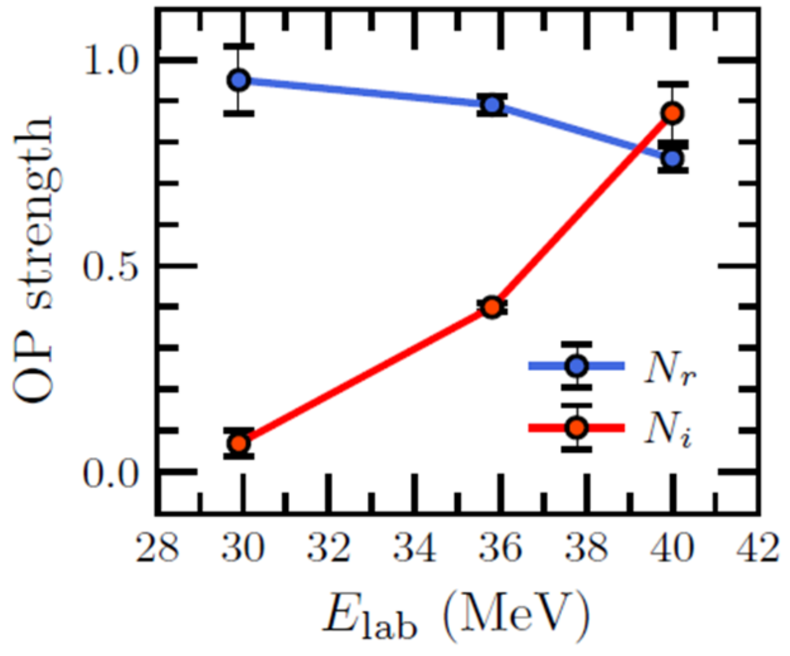
35.8 MeV	N_r	N_i	χ^2_{red}
OM1	1	–	67
OM2	1	0.78	22
OM3	1	0.48 ± 0.08	15
OM4	0.89 ± 0.02	0.40 ± 0.01	2.7

40 MeV	N_r	N_i	χ^2_{red}
OM1	1	–	110
OM2	1	0.78	26
OM3	1	1.48 ± 0.25	15
OM4	0.76 ± 0.03	0.87 ± 0.07	2.4

Strong rise in the **imaginary strength**

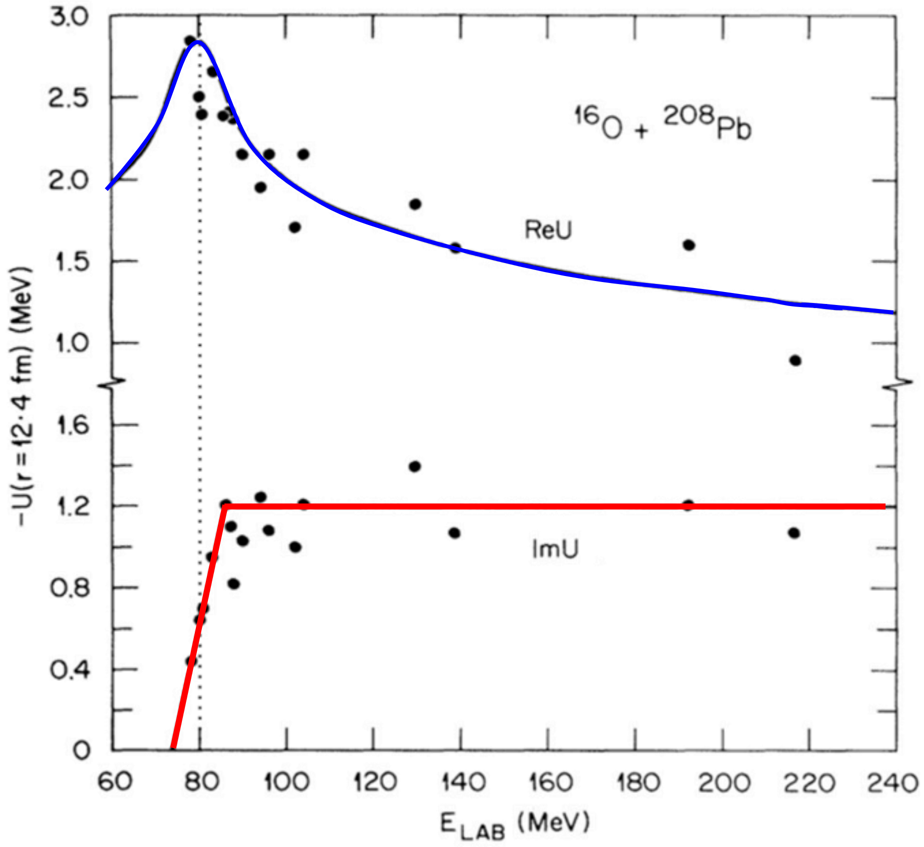


1. Elastic scattering: $^{12}C + ^{64}Zn$



Threshold anomaly pattern

M. A. Nagarajan et al., ***Phys. Rev. Lett. 54, 1136 (1985)***



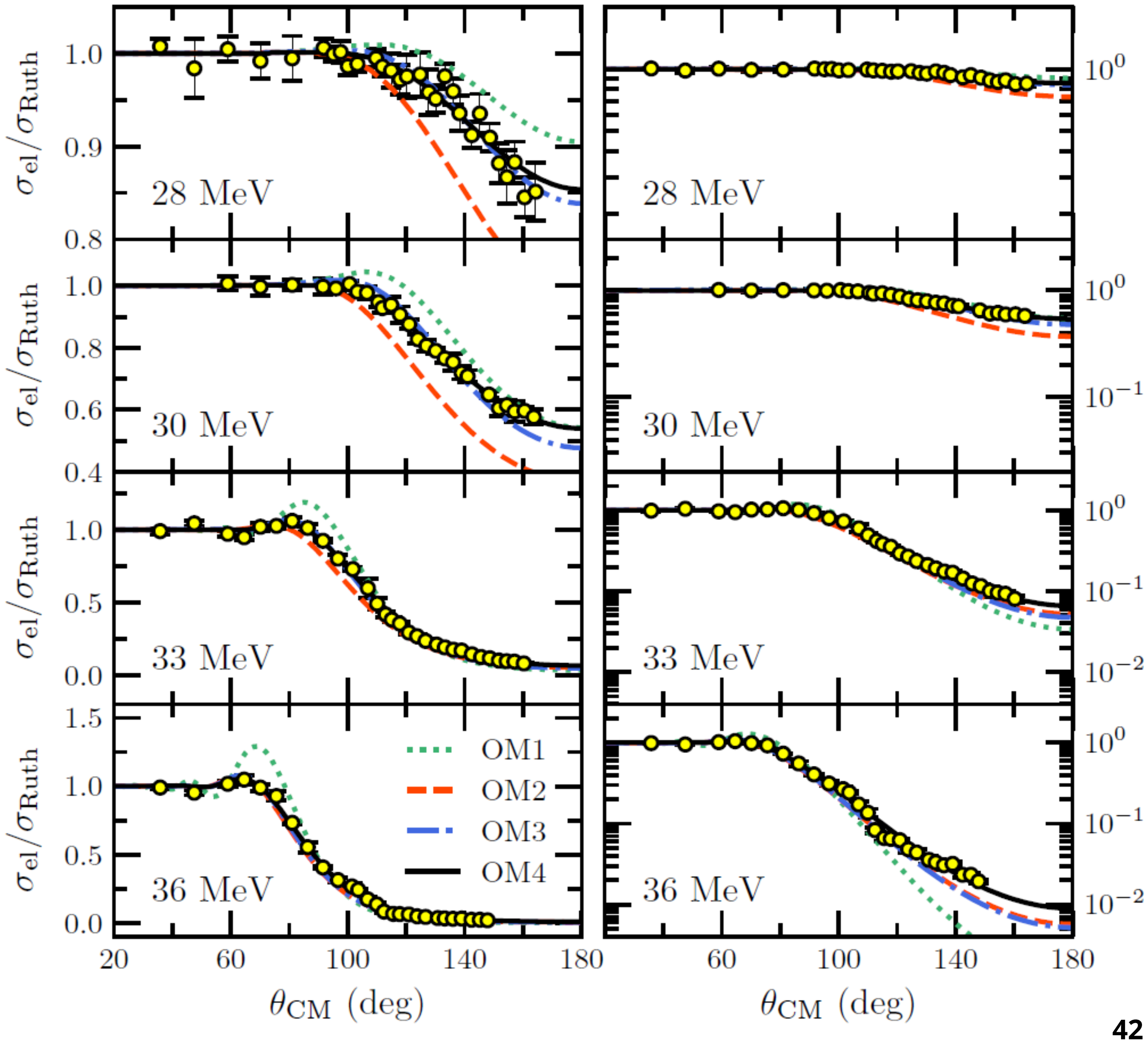
1. Elastic scattering: $^{13}C + ^{64}Zn$

28 MeV	N_r	N_i	χ^2_{red}
OM1	1	–	3.9
OM2	1	0.78	10
OM3	1	0.25 ± 0.02	0.7
OM4	0.73 ± 0.21	0.34 ± 0.06	0.6

30 MeV	N_r	N_i	χ^2_{red}
OM1	1	–	21
OM2	1	0.78	55
OM3	1	0.21 ± 0.03	4.0
OM4	0.69 ± 0.04	0.42 ± 0.02	0.4

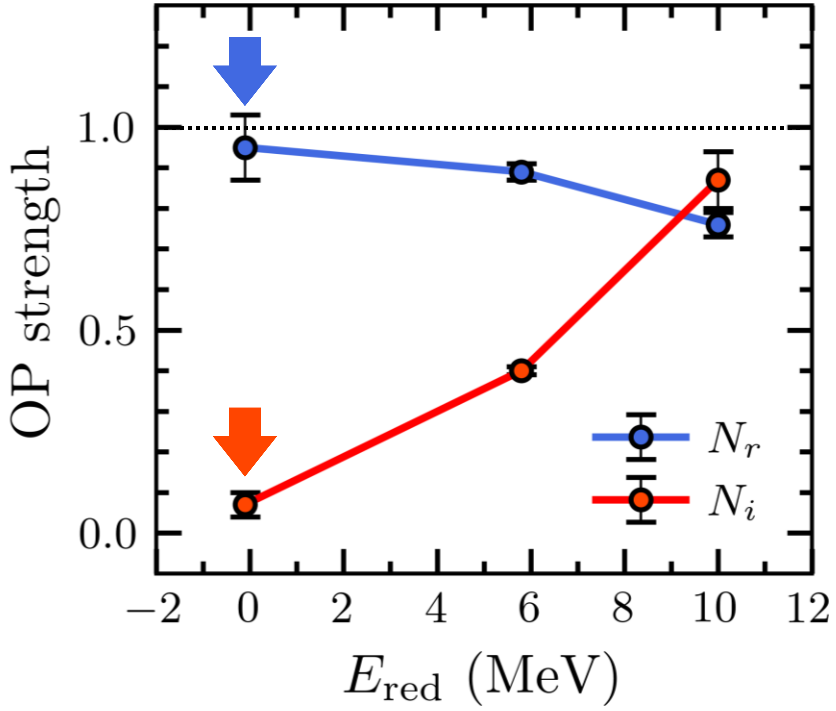
33 MeV	N_r	N_i	χ^2_{red}
OM1	1	–	40
OM2	1	0.78	24
OM3	1	0.37 ± 0.06	12
OM4	0.86 ± 0.02	0.46 ± 0.03	2.0

36 MeV	N_r	N_i	χ^2_{red}
OM1	1	–	79
OM2	1	0.78	23
OM3	1	0.68 ± 0.12	22
OM4	0.79 ± 0.04	0.73 ± 0.03	5.9

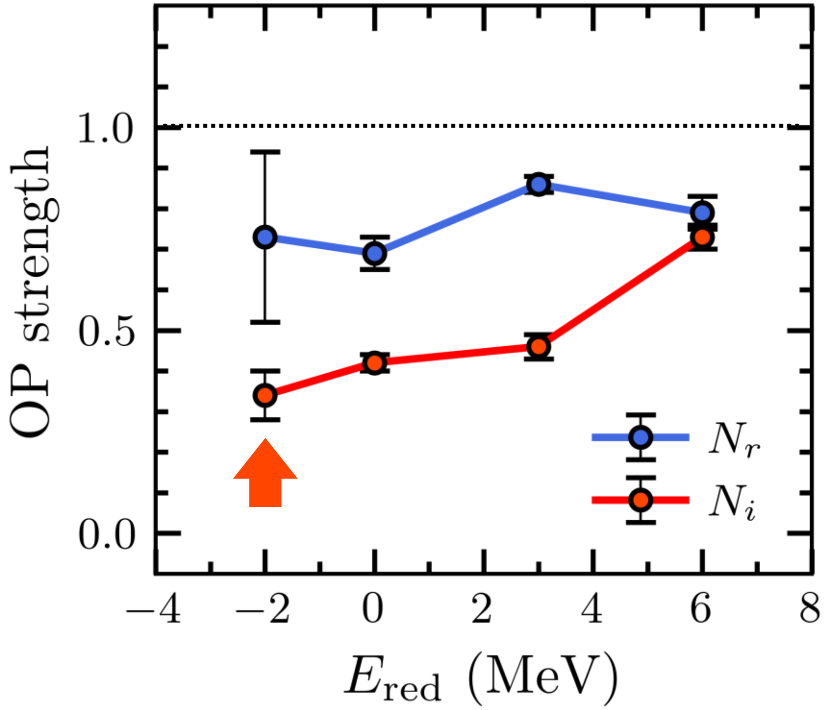


$^{12,13}C + ^{64}Zn$ comparison

$^{12}C + ^{64}Zn$

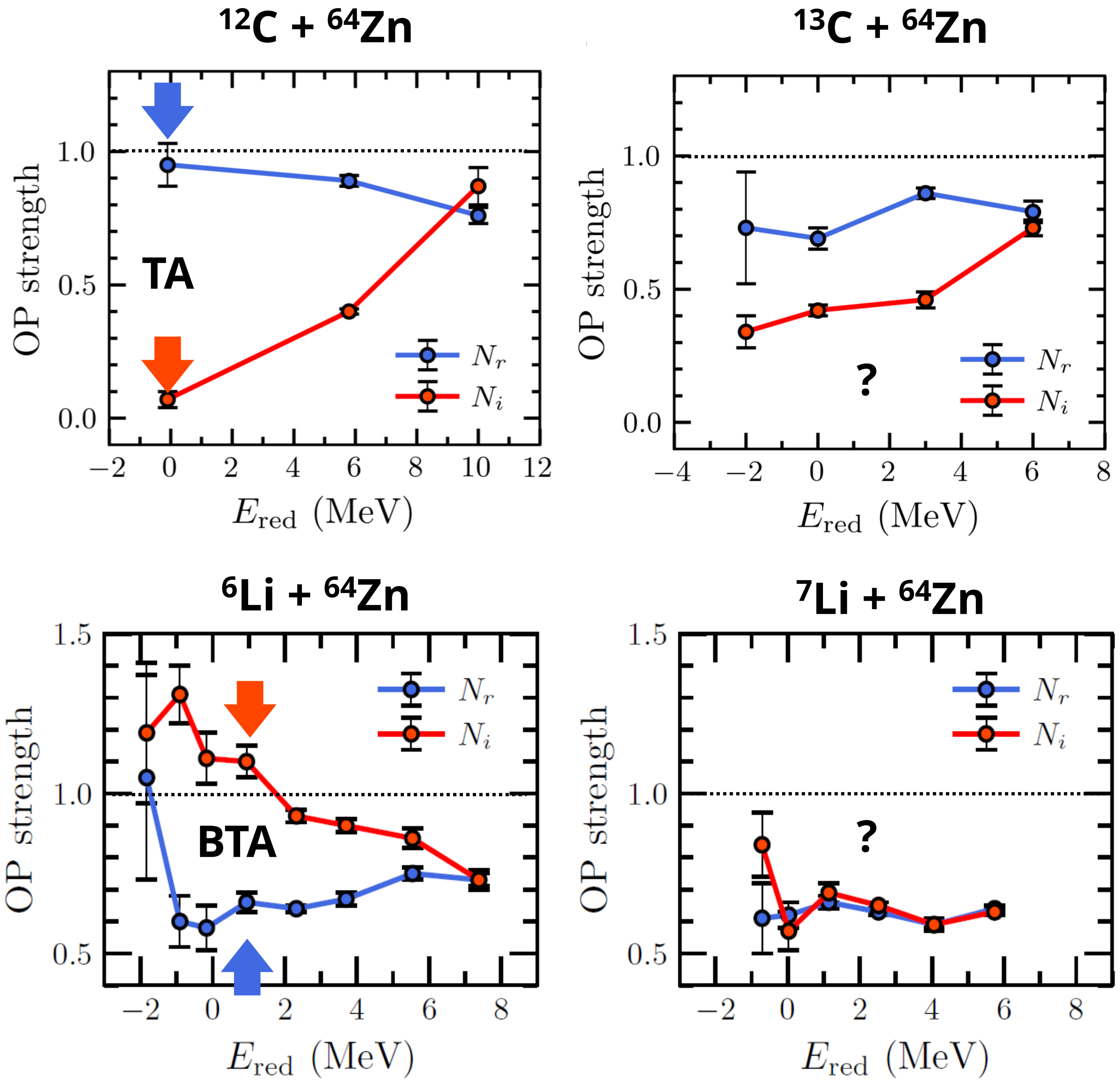


$^{13}C + ^{64}Zn$



Threshold anomaly pattern

Significant imaginary strength
at sub-barrier energies



Further investigation on the dispersion relation

OP strengths (N_r, N_i)

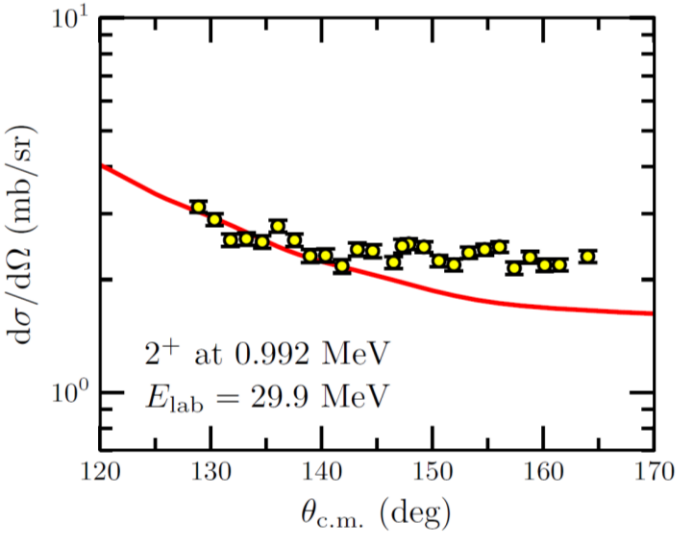
Opening/closing reaction channels

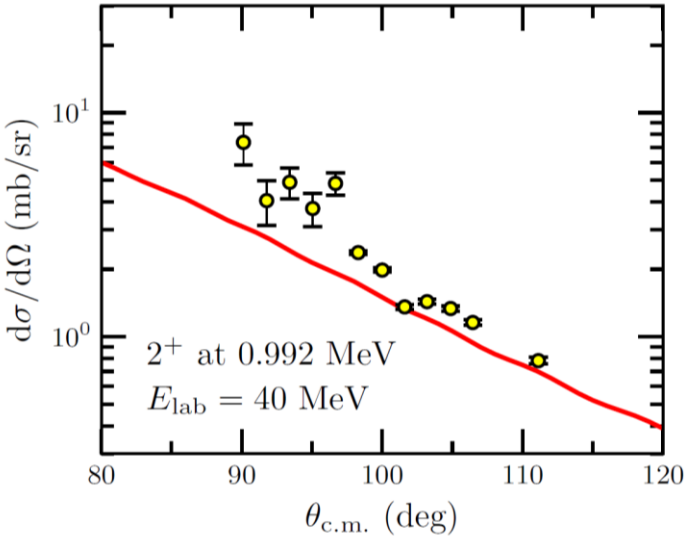
Nuclear structure

THANK YOU

lgarrido2@us.es

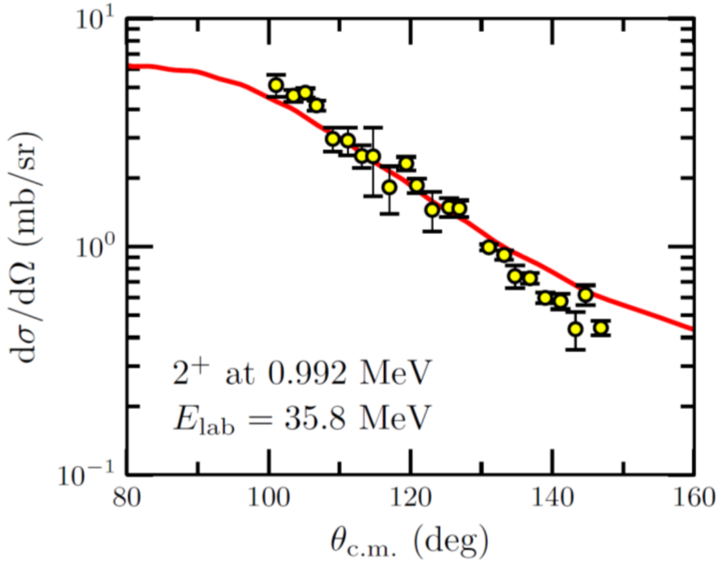
2. Inelastic scattering: 2^+ state at 0.992 MeV (^{64}Zn)
3. Inelastic scattering: 3^- state at 2.999 MeV (^{64}Zn)

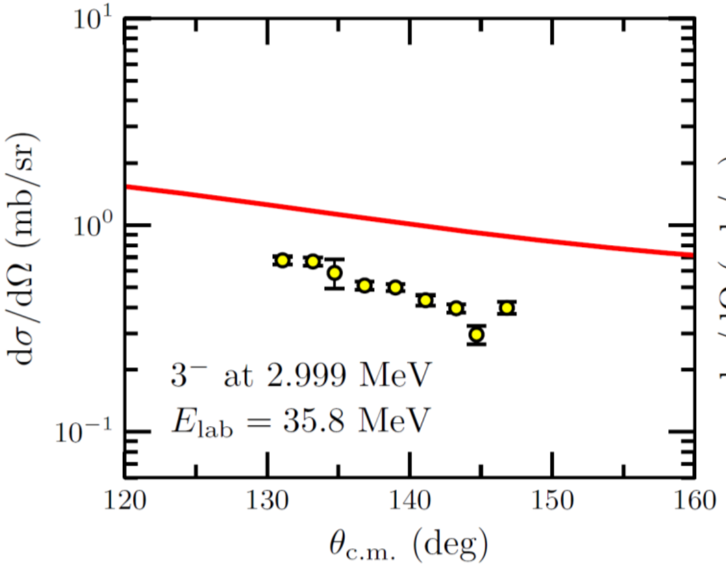


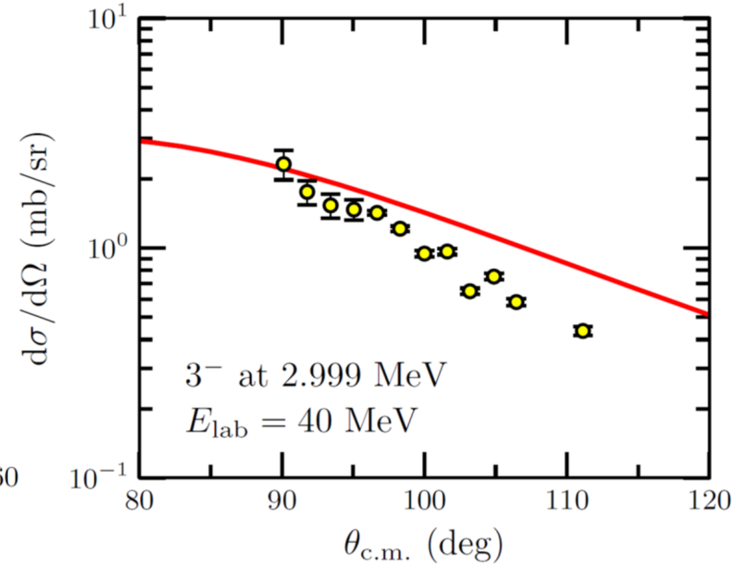


nucleus	J^π	E^*	λ	$B(E\lambda)$	δ_λ
^{64}Zn	2^+	0.992	2	168	1.18
^{64}Zn	3^-	2.999	3	34	1.02
^{12}C	2^+	4.440	2	3.97	1.42
^{12}C	3^-	9.641	3	0.251	1.66
		(MeV)		(10^{-3} e^2b^λ)	(fm)

The **OM1** internal potential was used as the **initial interaction** and the reaction channels were coupled





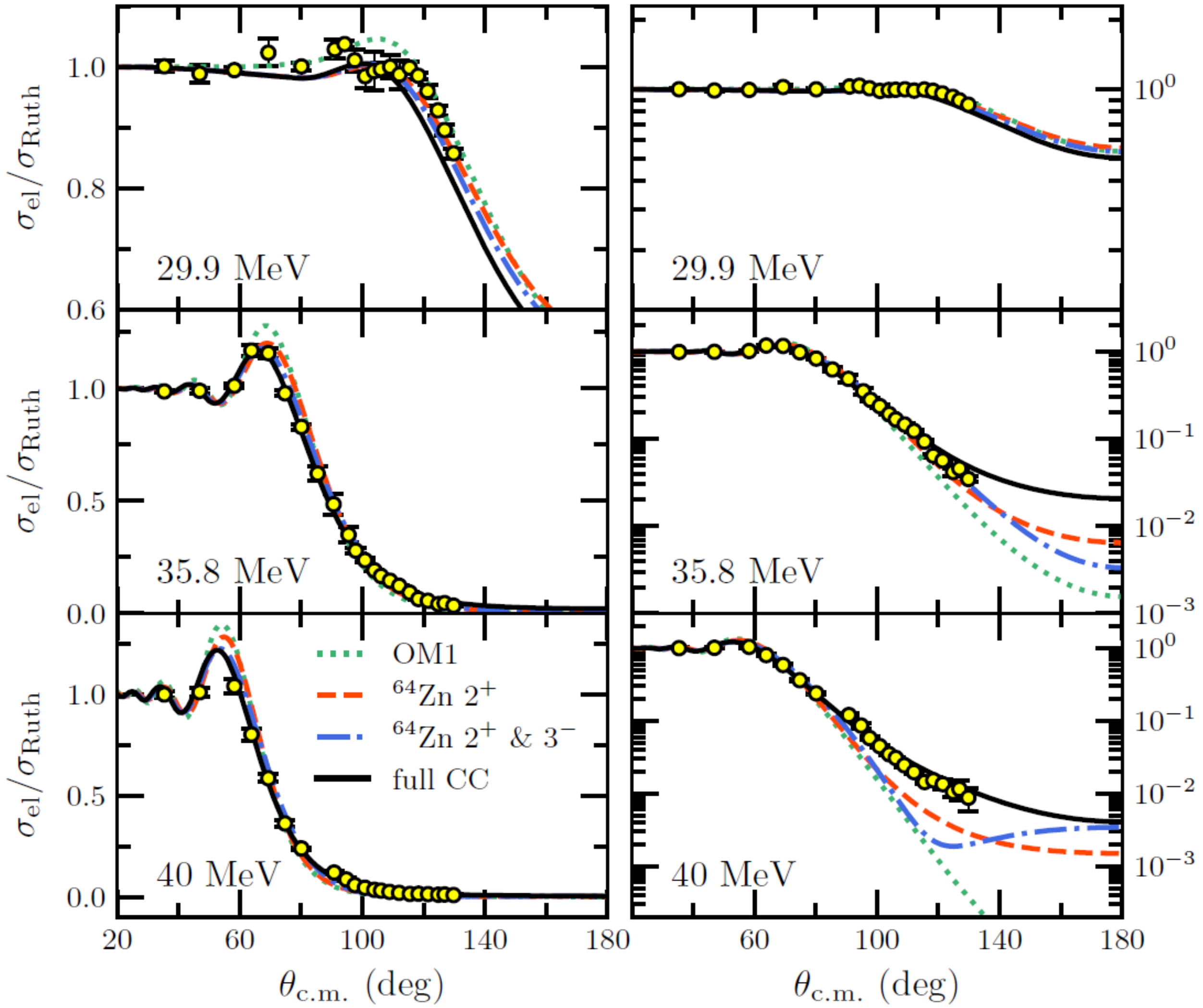


L. Garrido-Gómez et al., ***Phys. Rev. C 113, 044607 (2026)***

2. Inelastic scattering: 2^+ state at 0.992 MeV (^{64}Zn)
3. Inelastic scattering: 3^- state at 2.999 MeV (^{64}Zn)

L. Garrido-Gómez et al., ***Phys. Rev. C 113, 044607 (2026)***

$^{12}C + ^{64}Zn$



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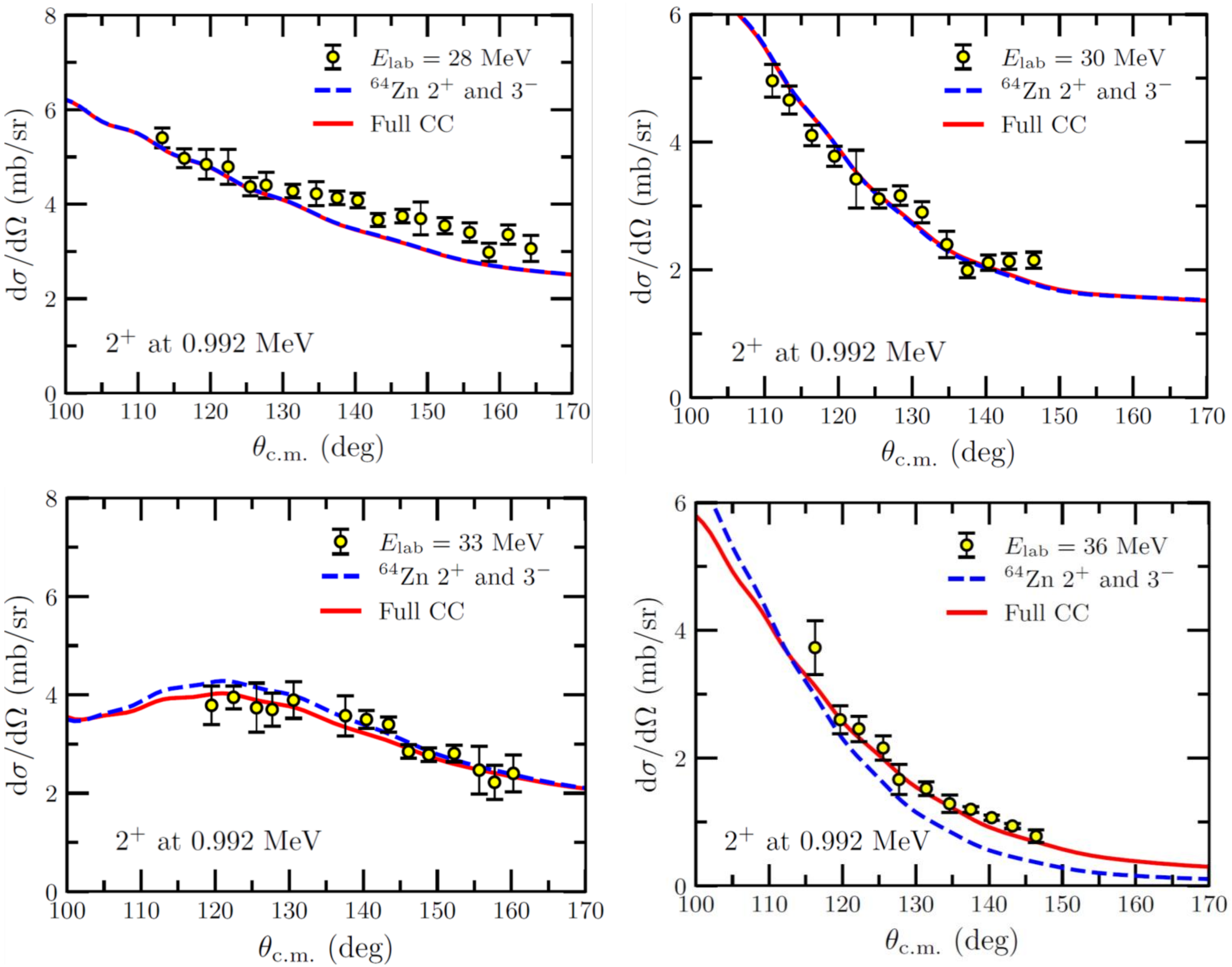

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^{13}C	$1/2^+$	3.089	1	0.152	0.116
^{13}C	$3/2^-$	3.685	2	1.27	1.12
		(MeV)		(10^{-3} e^2b^λ)	(fm)

The **OM1** internal potential was used as the **initial interaction** and the reaction channels were coupled

Good description of the inelastic angular distributions (**no free parameters**)

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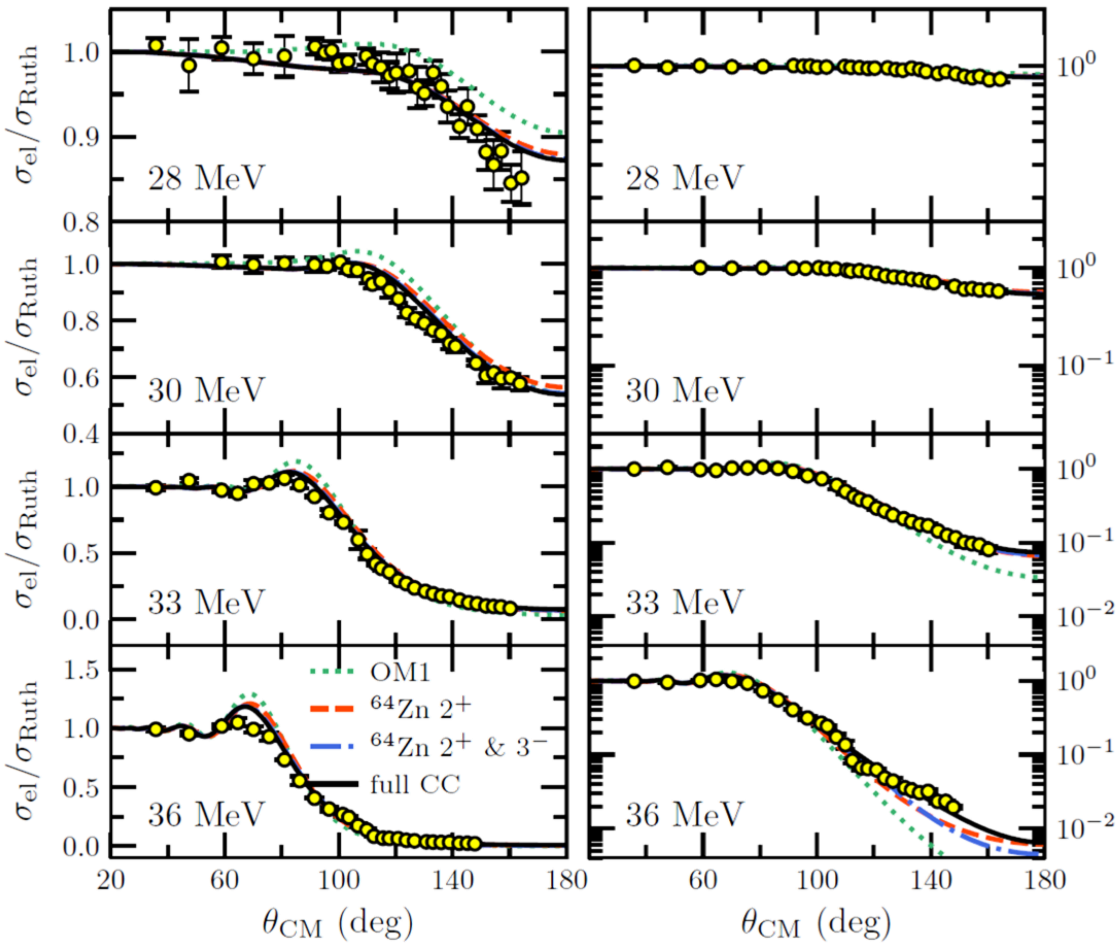

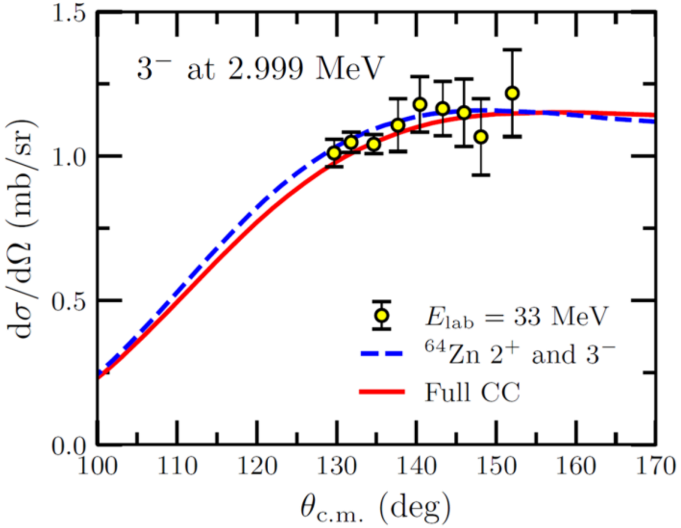

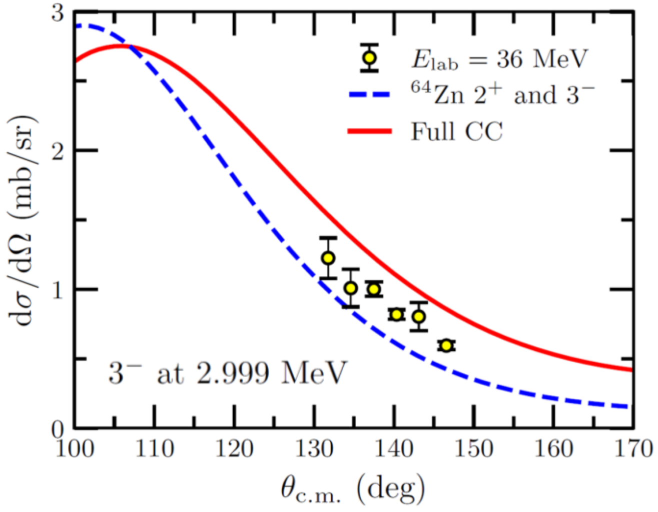

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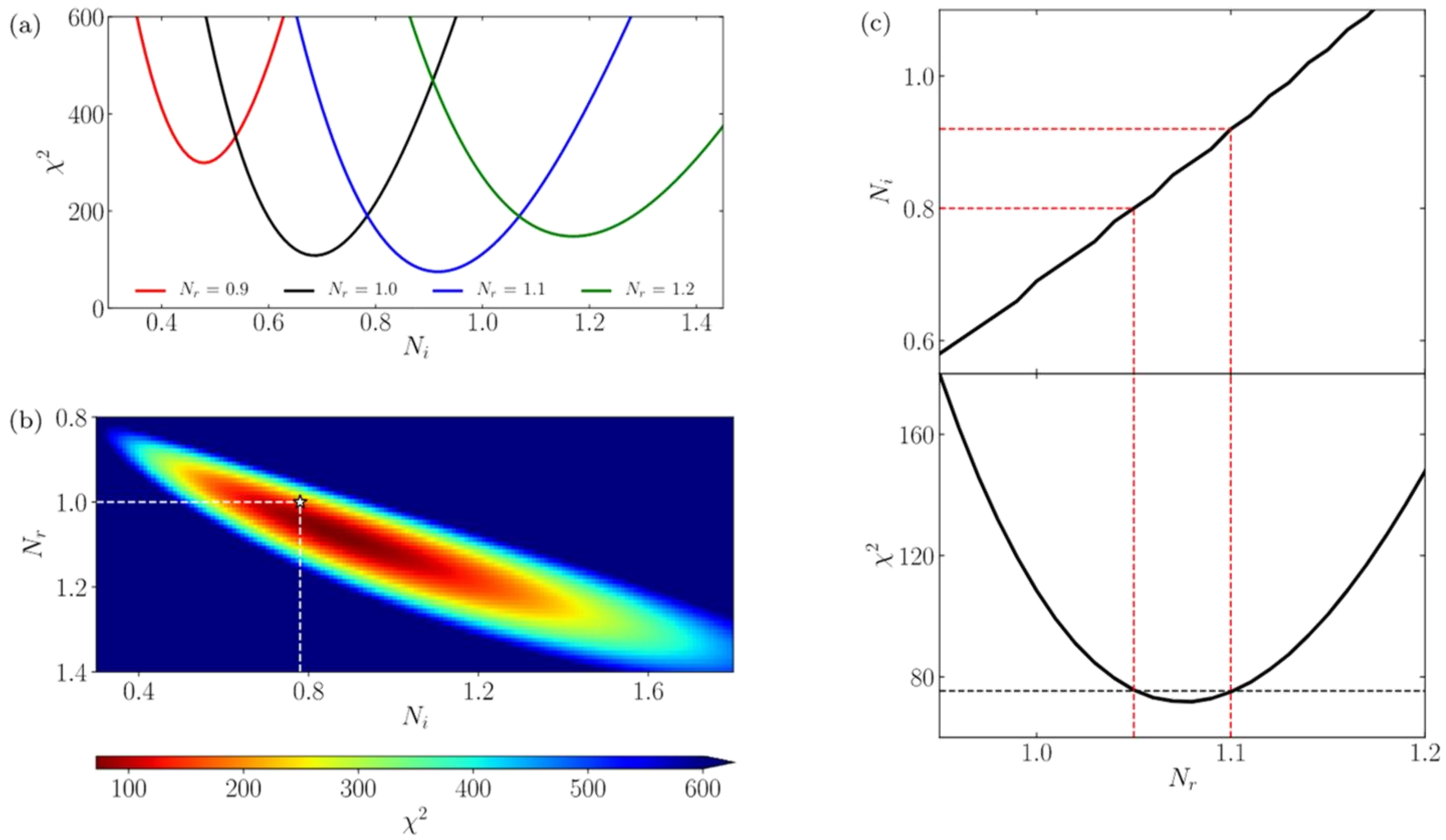
Good description of the inelastic angular distributions (**no free parameters**)

Uncertainties in OP strengths



W. H. Press et al.
Numerical Recipes: The Art of Scientific Computing, 3rd ed.
Cambridge University Press, 2007.

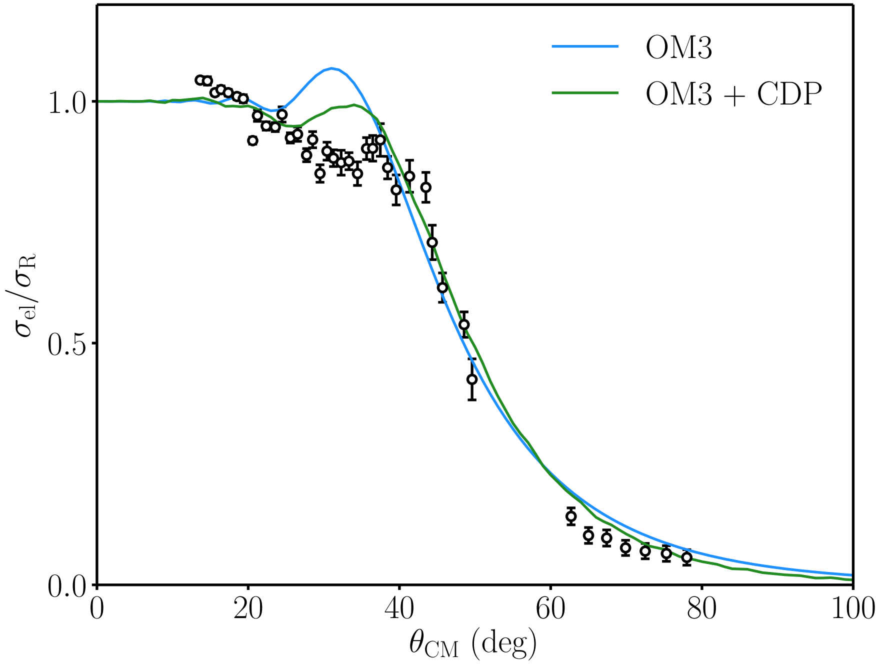
$\Delta\chi^2$ as a Function of Confidence Level p and Number of Parameters of Interest ν

	ν					
p	1	2	3	4	5	6
68.27%	1.00	2.30	3.53	4.72	5.89	7.04
90%	2.71	4.61	6.25	7.78	9.24	10.6
95.45%	4.00	6.18	8.02	9.72	11.3	12.8
99%	6.63	9.21	11.3	13.3	15.1	16.8
99.73%	9.00	11.8	14.2	16.3	18.2	20.1
99.99%	15.1	18.4	21.1	23.5	25.7	27.9

$\chi^2_{min} + 2.3 * \chi^2_{min} / \nu$

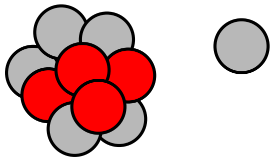
The case of $^{11}Be + ^{64}Zn$

Adding Coulomb effects



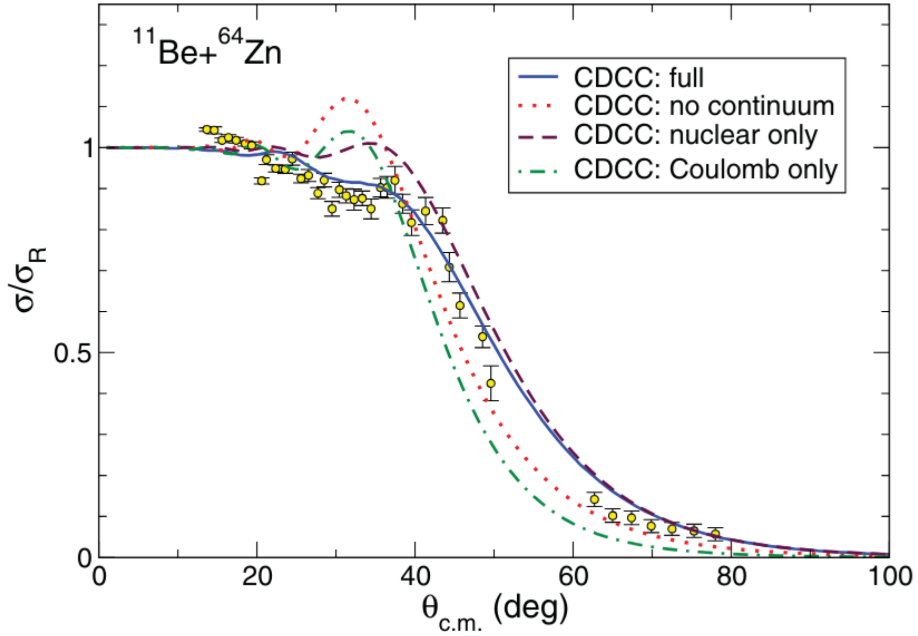
(χ^2_{red} = 30)
(χ^2_{red} = 14)

$$U_{CDP} \propto \frac{Z_t}{v} \int_{\varepsilon_b}^{\infty} d\varepsilon \, \frac{dB(E1)}{d\varepsilon}$$



$^{11}Be \rightarrow {}^{10}Be + n$

Adding complex nuclear effects



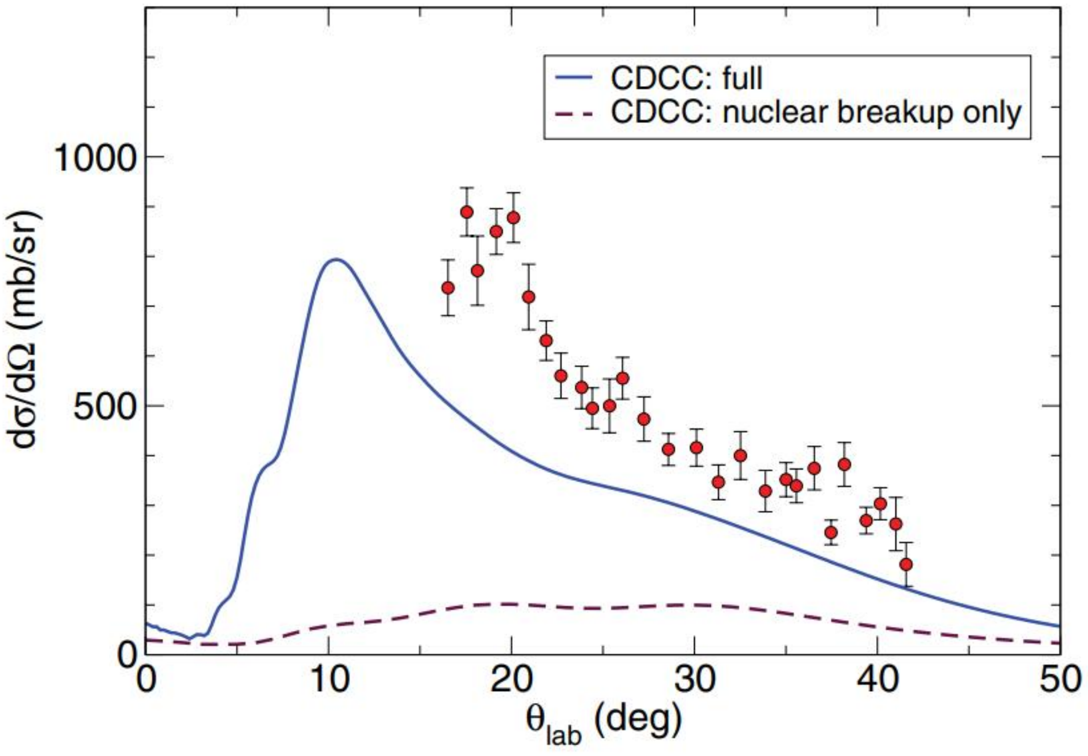
Phys. Rev. C **85**, 054607 (2012)
A. Di Pietro *et al.*

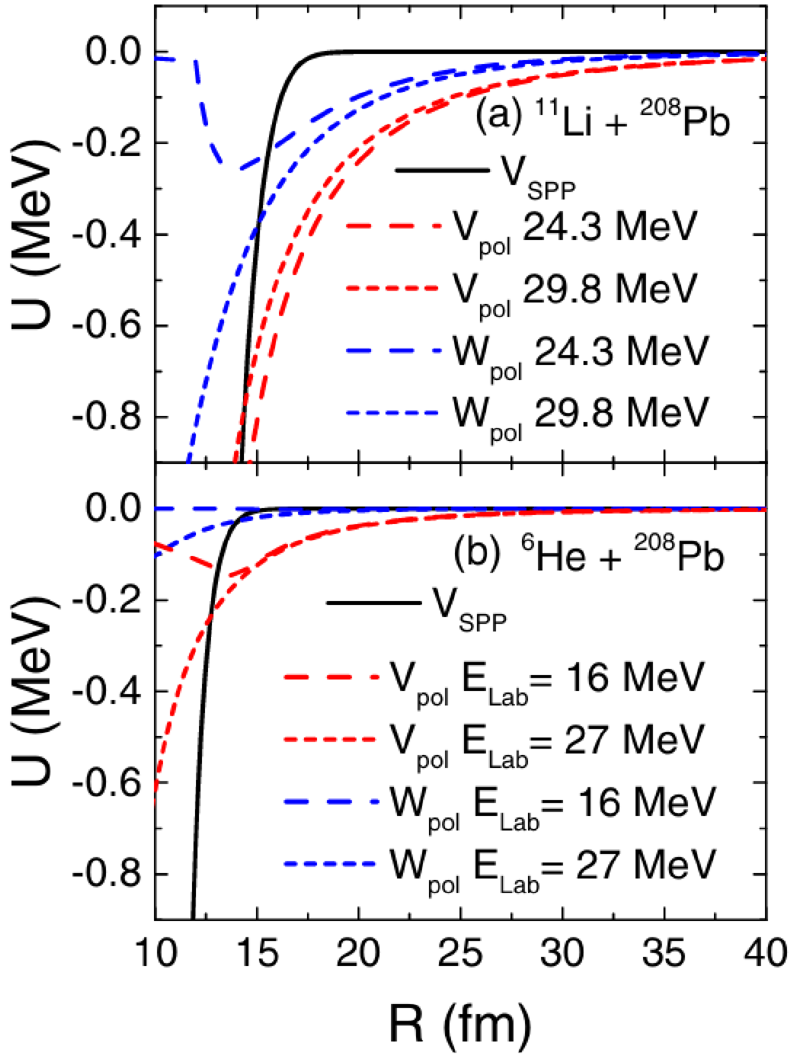
The case of exotic nuclei

Phys. Rev. C **92**, 014604 (2015)

J. P. Fernández-García *et al.*

Breakup CS in $^{11}Be + ^{64}Zn$



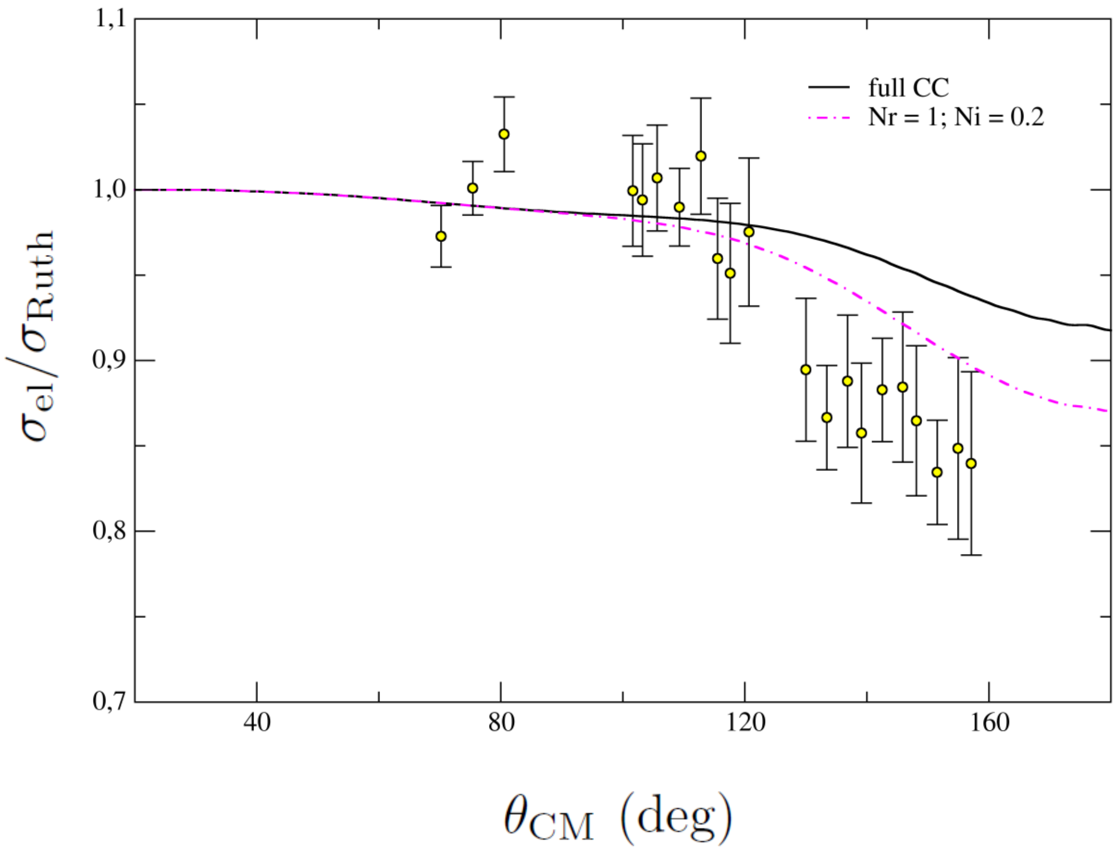


Phys. Rev. C **85**, 054607 (2012)

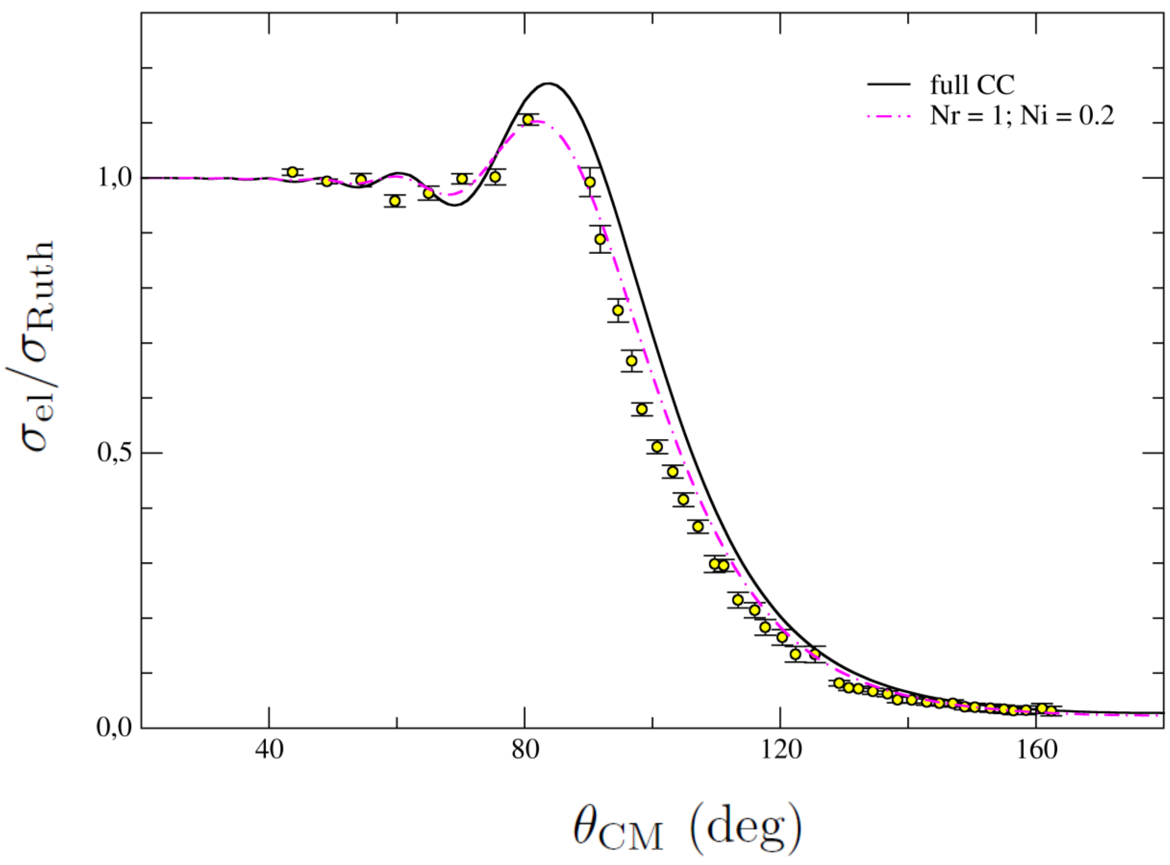
A. Di Pietro *et al.*

Adding imaginary strength to CC calculations

12C+120Sn @ 38.7 MeV



12C+120Sn @ 46.7 MeV



Adding imaginary strength to CC calculations

13C + 64Zn @ 36 MeV