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Fusion dynamics far below the barrier for $^{12}C + ^{28}Si$

G. Andreetta

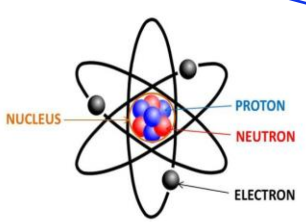
University of Padua and INFN-LNL

Istituto Nazionale di Fisica Nucleare

Heavy-ion fusion at LNL: from nuclear physics to astrophysics

- Fusion hindrance links heavy-ion sub-barrier fusion to astrophysics
- It has been recently observed even in medium-light systems
- Consequences for stellar evolution have to be clarified by further experimental and theoretical work.

Nuclear Physics



Heavy-Ion fusion

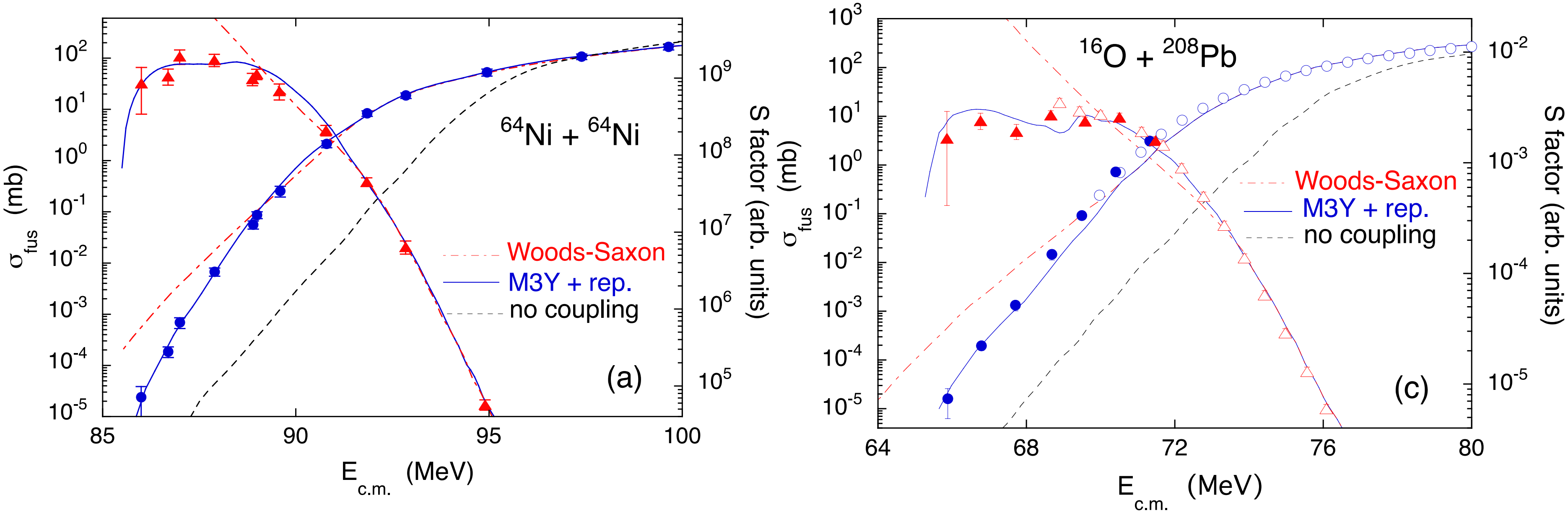
Sub-barrier hindrance

Light systems

Stellar evolution

Astrophysics

Fusion hindrance: two well-known cases



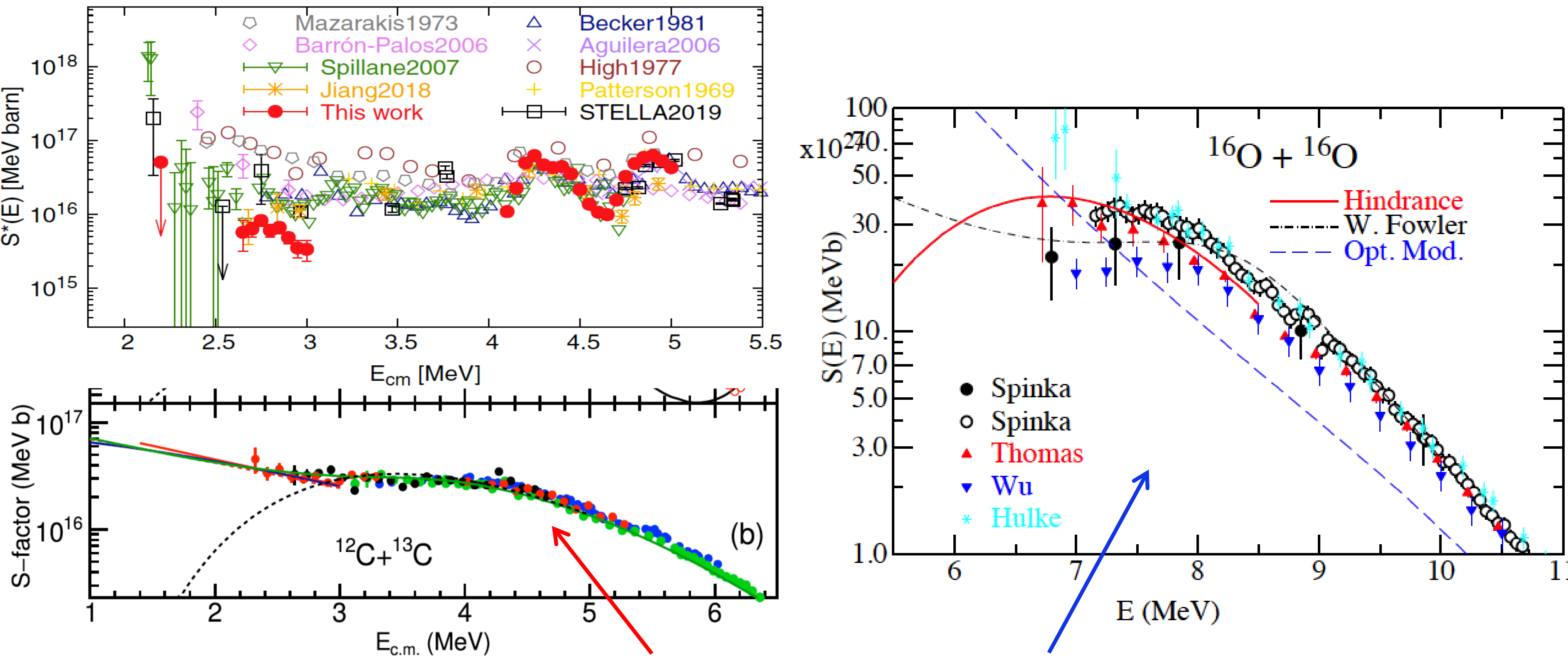
CC calculations based on a Woods-Saxon potential overpredict the excitation function at low energies

The astrophysical S factor develops a maximum at the energy where the logarithmic slope reaches the value $L_{CS} = \pi\eta/E$

C.L.Jiang et al., PRL 93 (2004) 012701

M. Dasgupta et al., PRL 99 (2007) 192701

Fusion hindrance in light systems ?

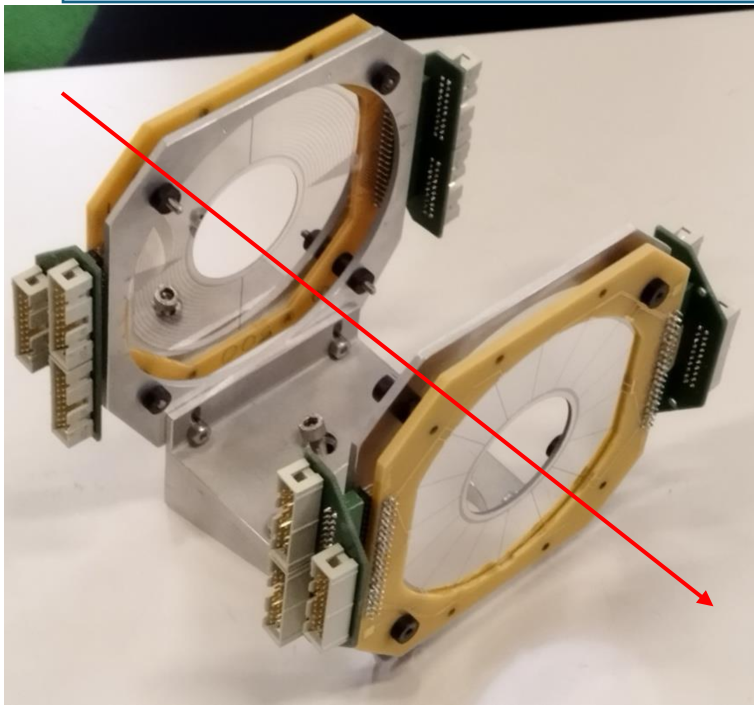


Astrophysical S factors of $^{12}C+^{12,13}C$ .... and .... $^{16}O+^{16}O$

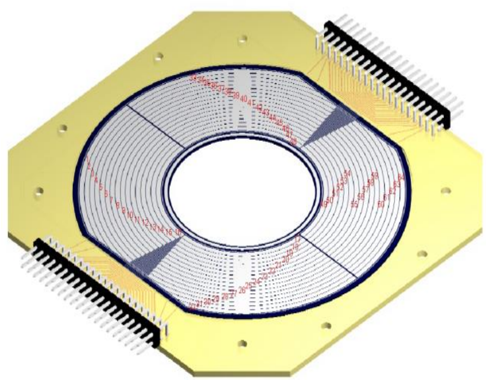
The existence of fusion hindrance in light systems of astrophysical interest is neither well established nor understood

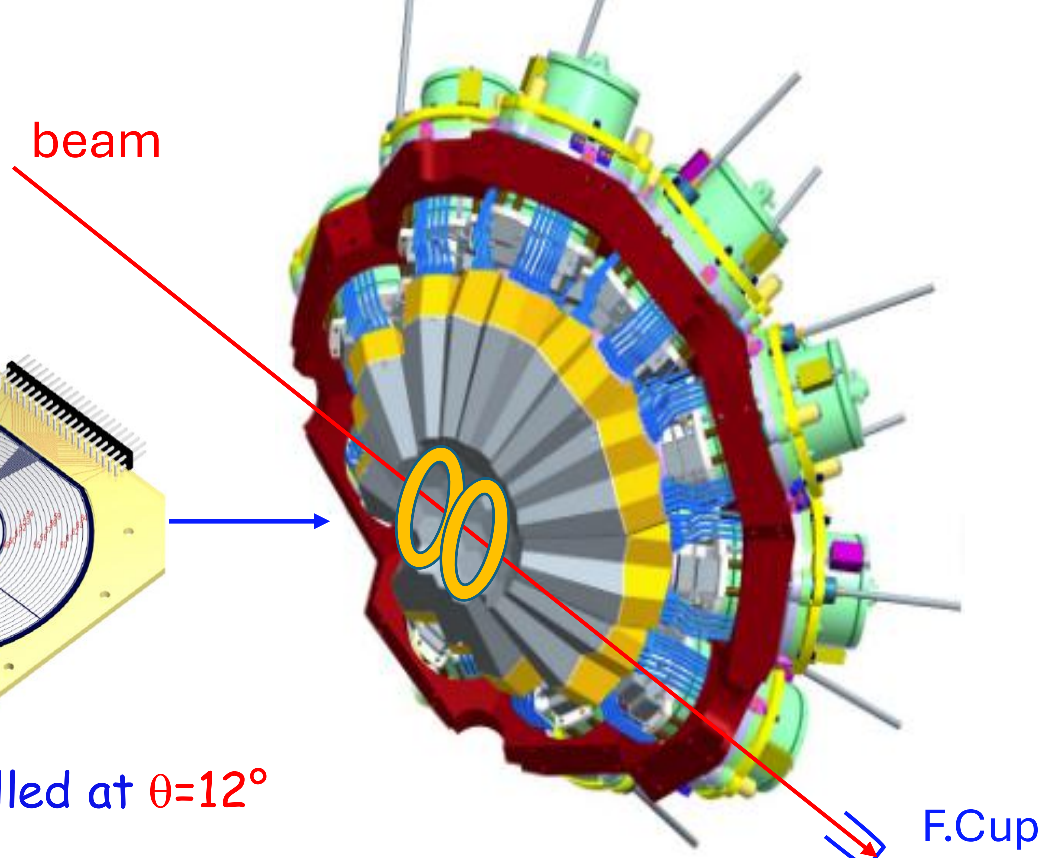
W. P. Tan et al. PRL 124,192702 (2020)
N.T.Zhang et al., PLB 801, 135 (2020)
C.L.Jiang et al., EPJA 57, 235 (2021)

Coincidences AGATA-DSSD for ^{12}C + ^{28}Si



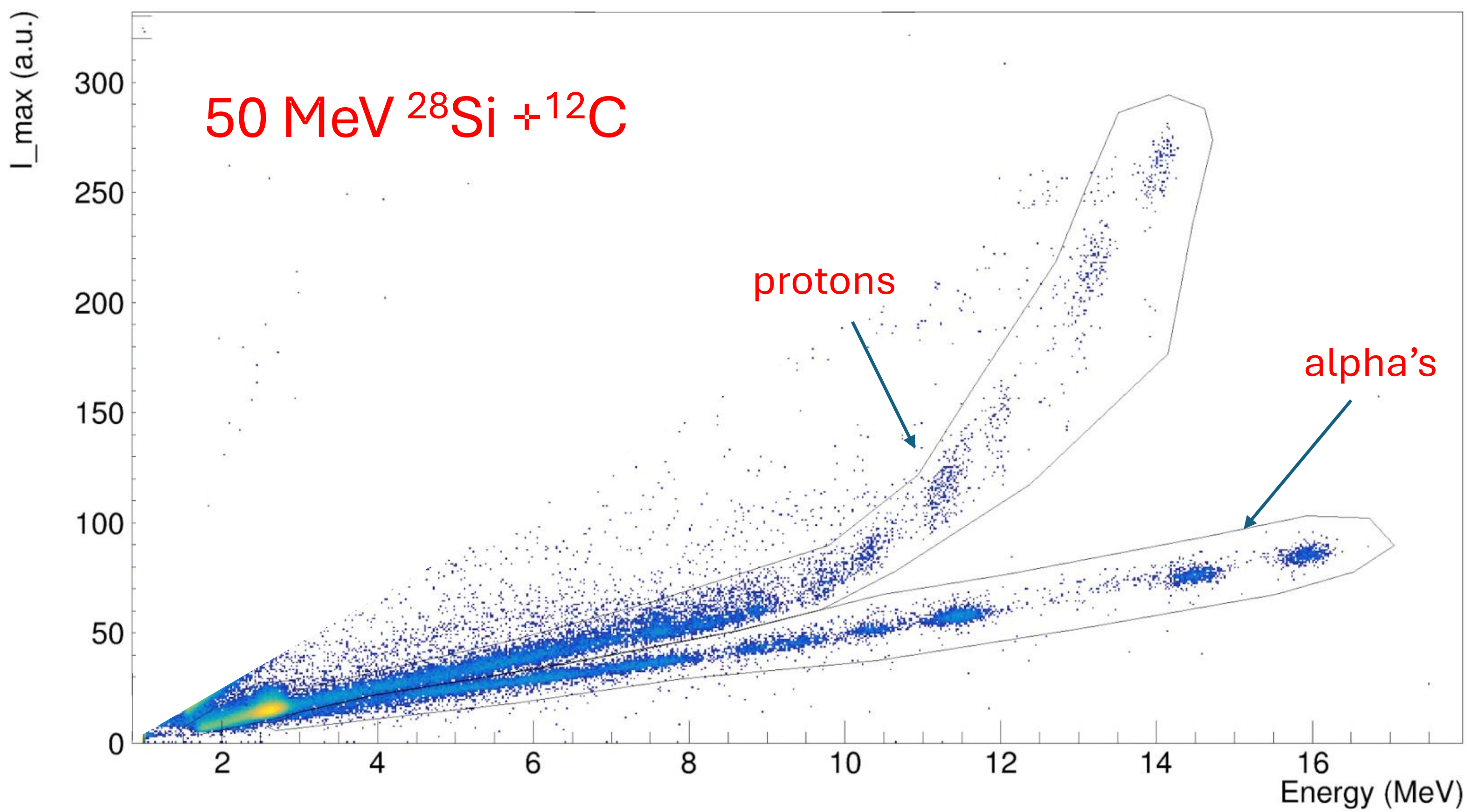
- S1 detectors (Micron), ø = 4", at 5 cm from the target, upstream and downstream of the target
- thicknesses of 1500 μm and 1000 μm, ~20% solid angle coverage





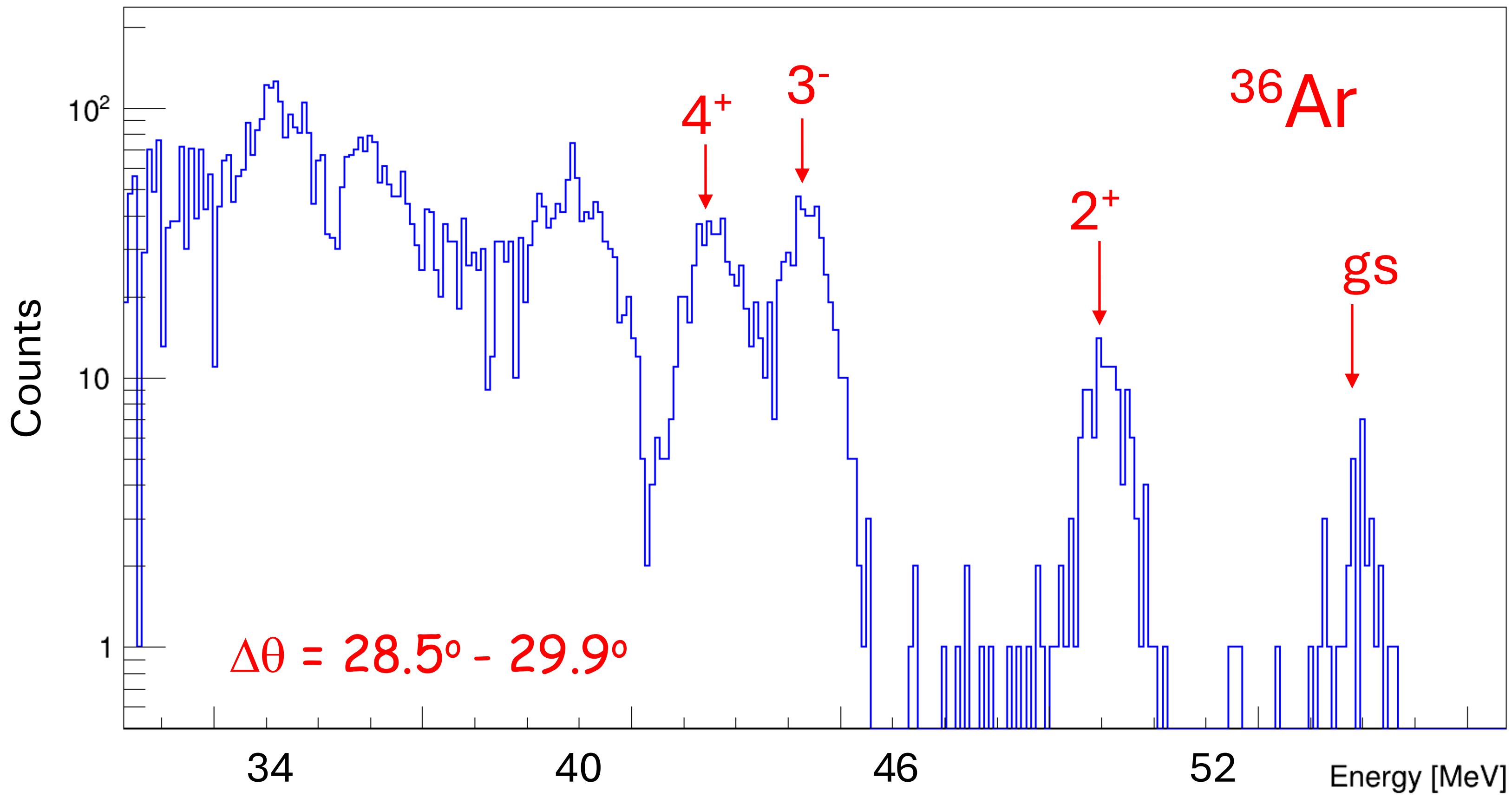
Two monitor detectors installed at θ=12° to normalize the fusion yield

Identification of evaporated particles



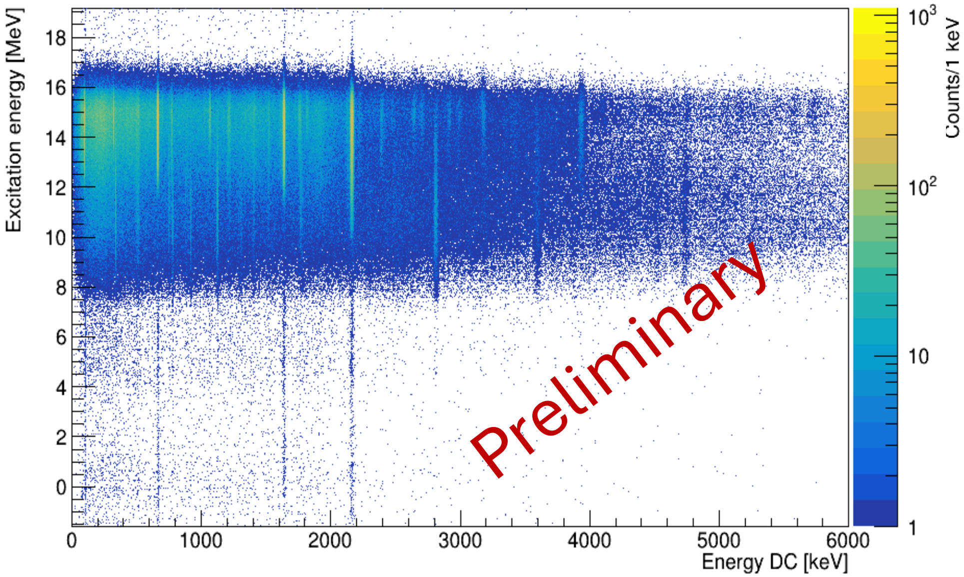
Light-charged particles detected by the DSSD are identified through pulse shape discrimination psd, using their Energy and the maximum of the signal derivative (IMAX)

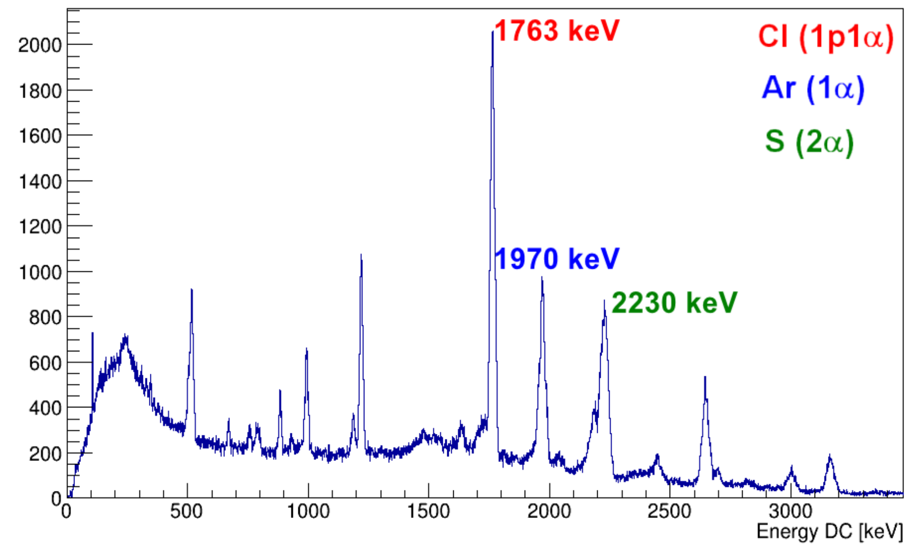
50 MeV $^{28}Si + ^{12}C$, α particle energies



α–particles detected by the forward DSSD and identified via psd.
Particle groups populating states in ^{36}Ar are identified.

α - gated coincidences with γ-rays

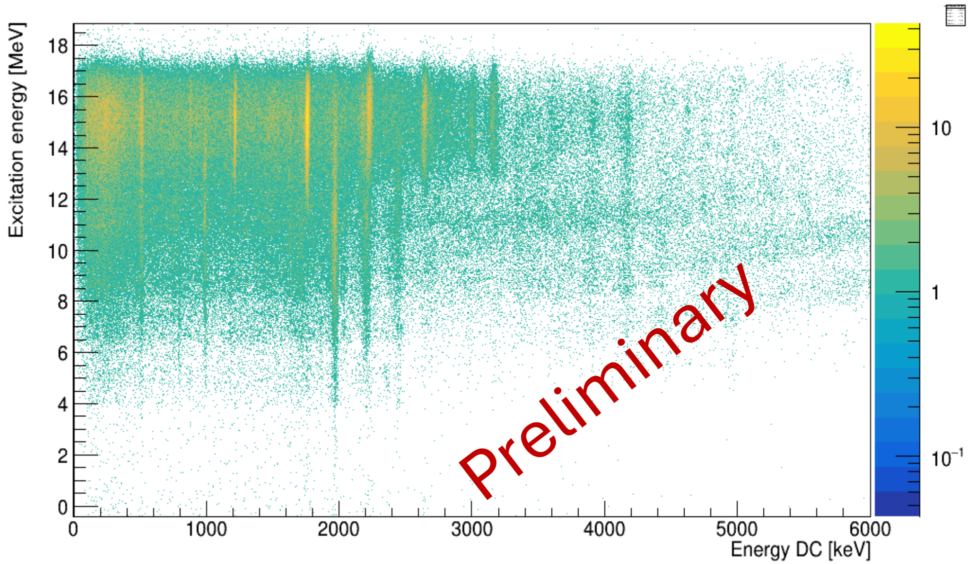


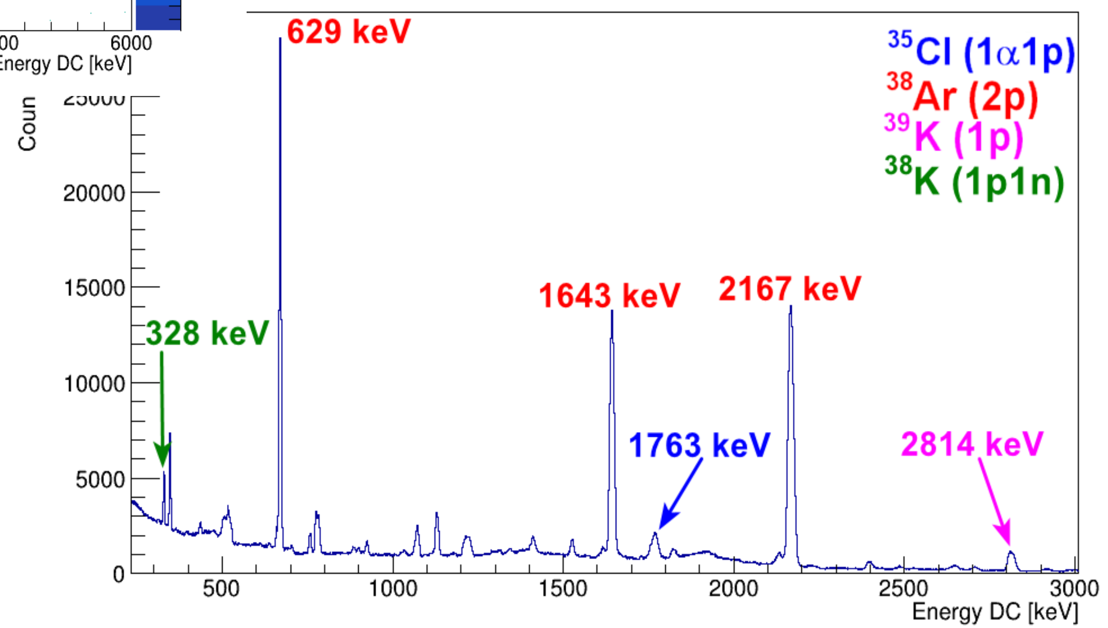


- The energy of the evaporated particle correlated to its angle gives information on the total excitation of the system and can be used to select different channels

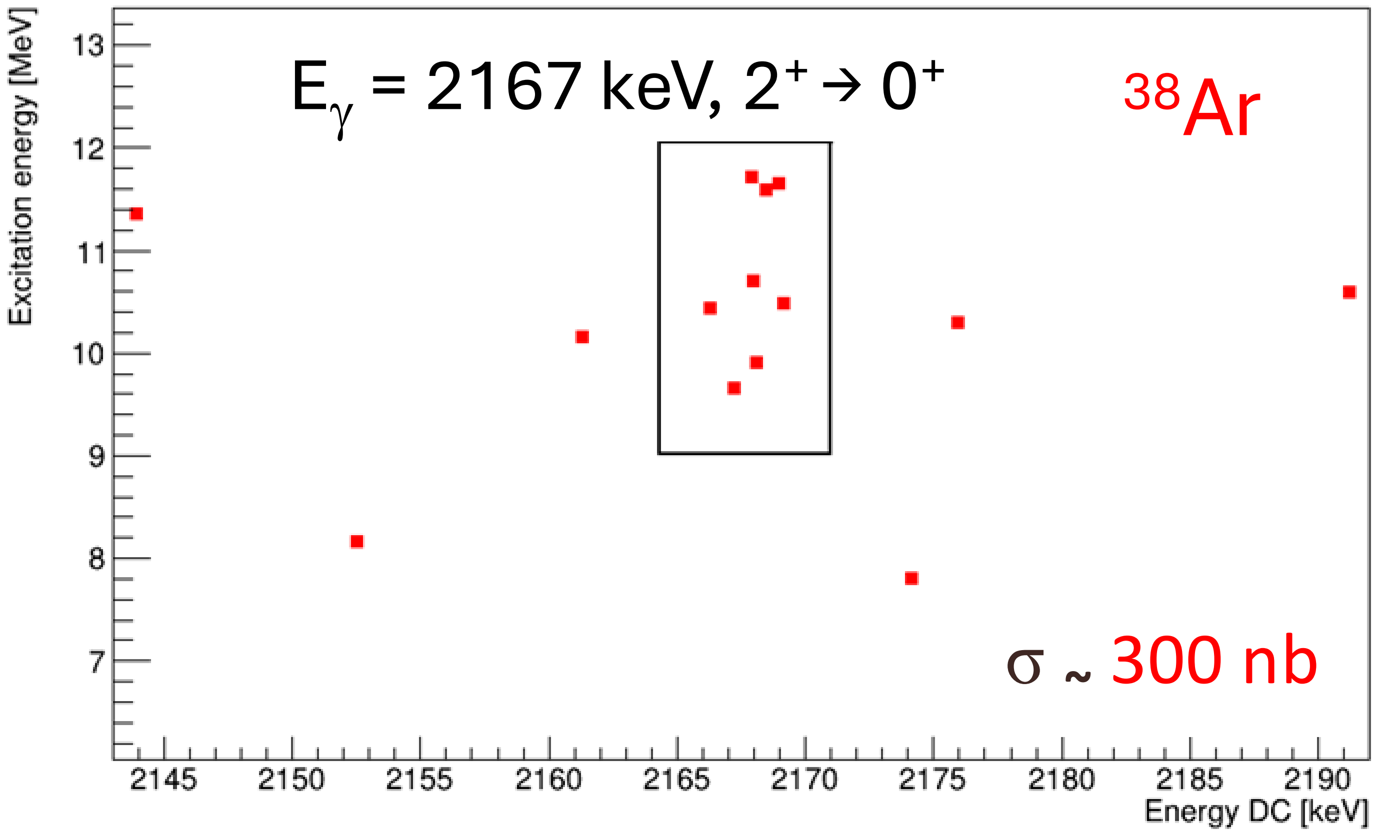
- this can be seen correlating the γ-ray energy with the reconstructed excitation energy

p - gated coincidences with γ-rays



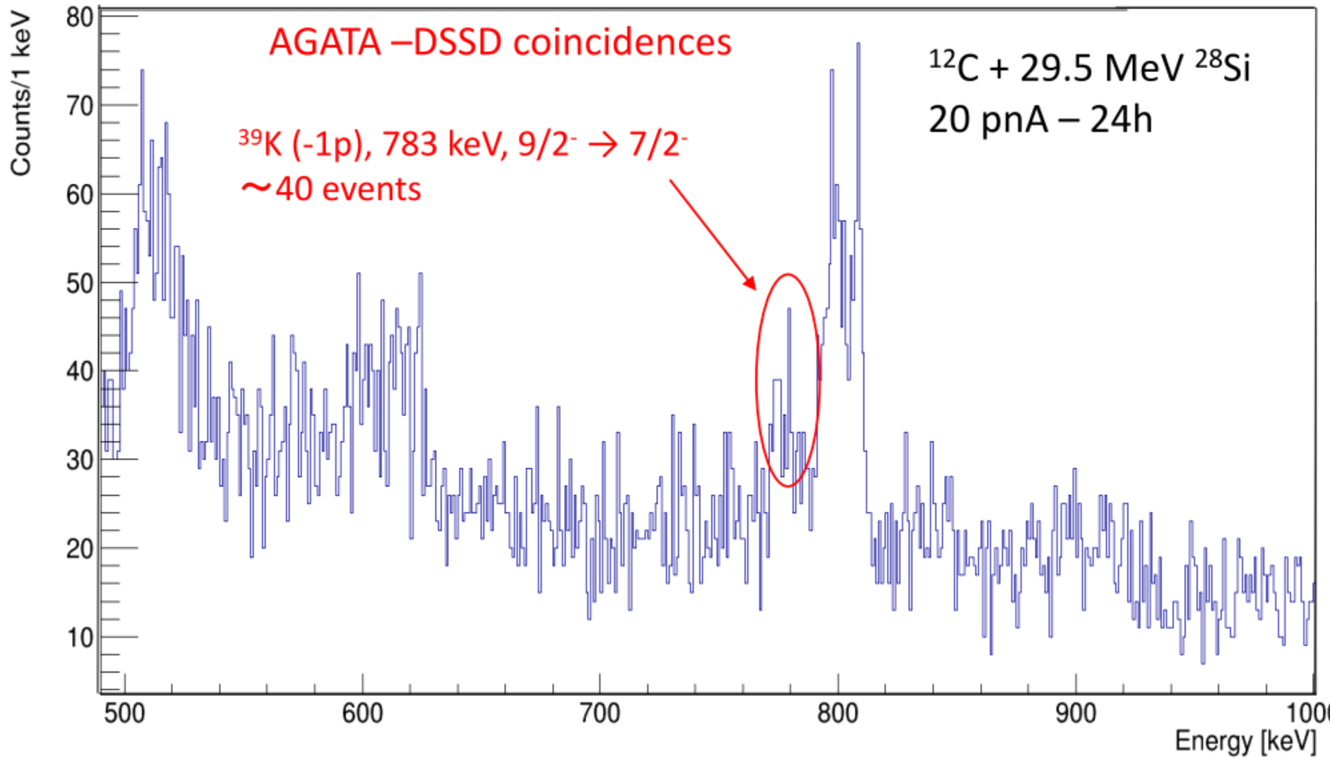


31 MeV $^{28}Si + ^{12}C$



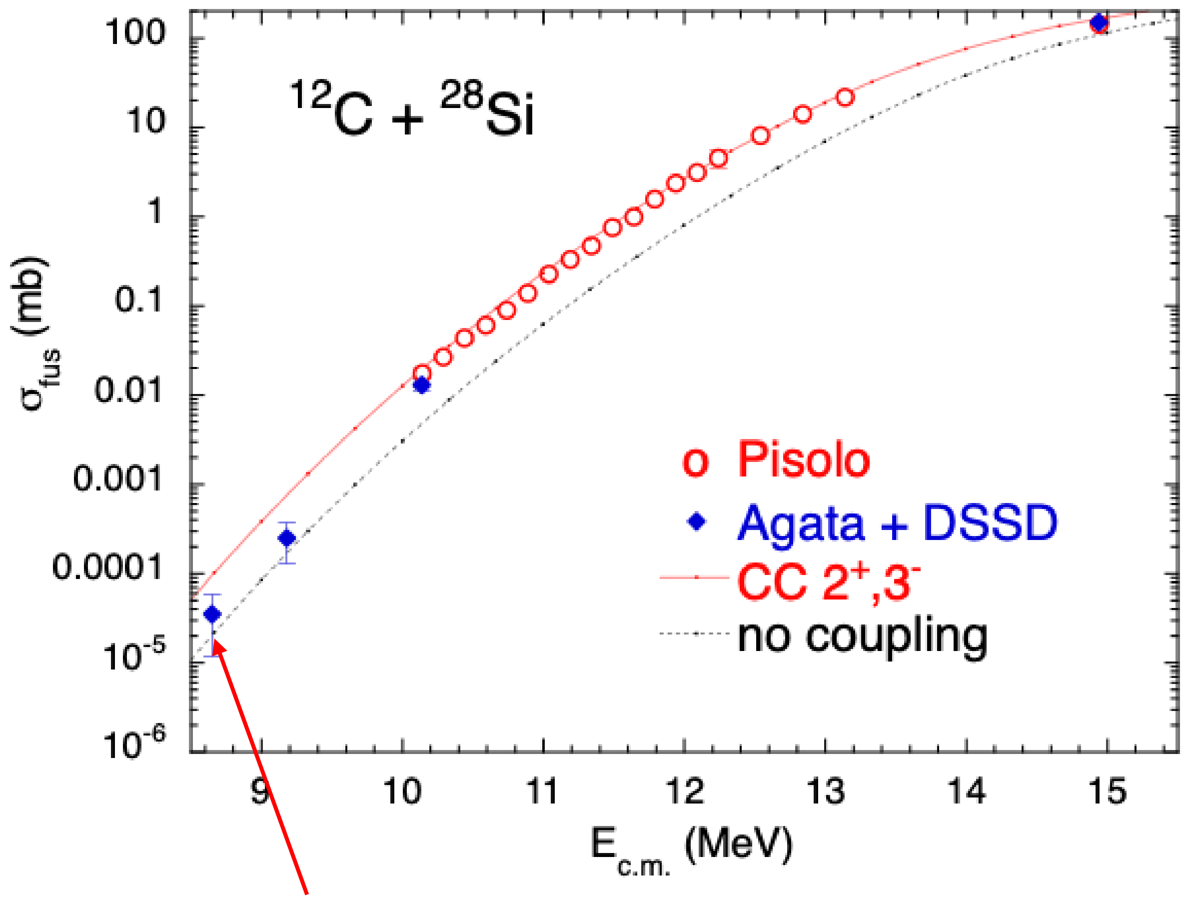
ER exc. energy vs γ-ray energy plot, obtained by α-particle events observed in the forward DSSD

γ-spectrum in coincidence with the forward DSSD at 29.5 MeV



The total fusion cross section is ≈ 40 nb. The 783 keV transition of the 1p evaporation channel (^{39}K) can be observed, which is estimated ~20% of the total fusion yield

Fusion excitation function of $^{12}C + ^{28}Si$



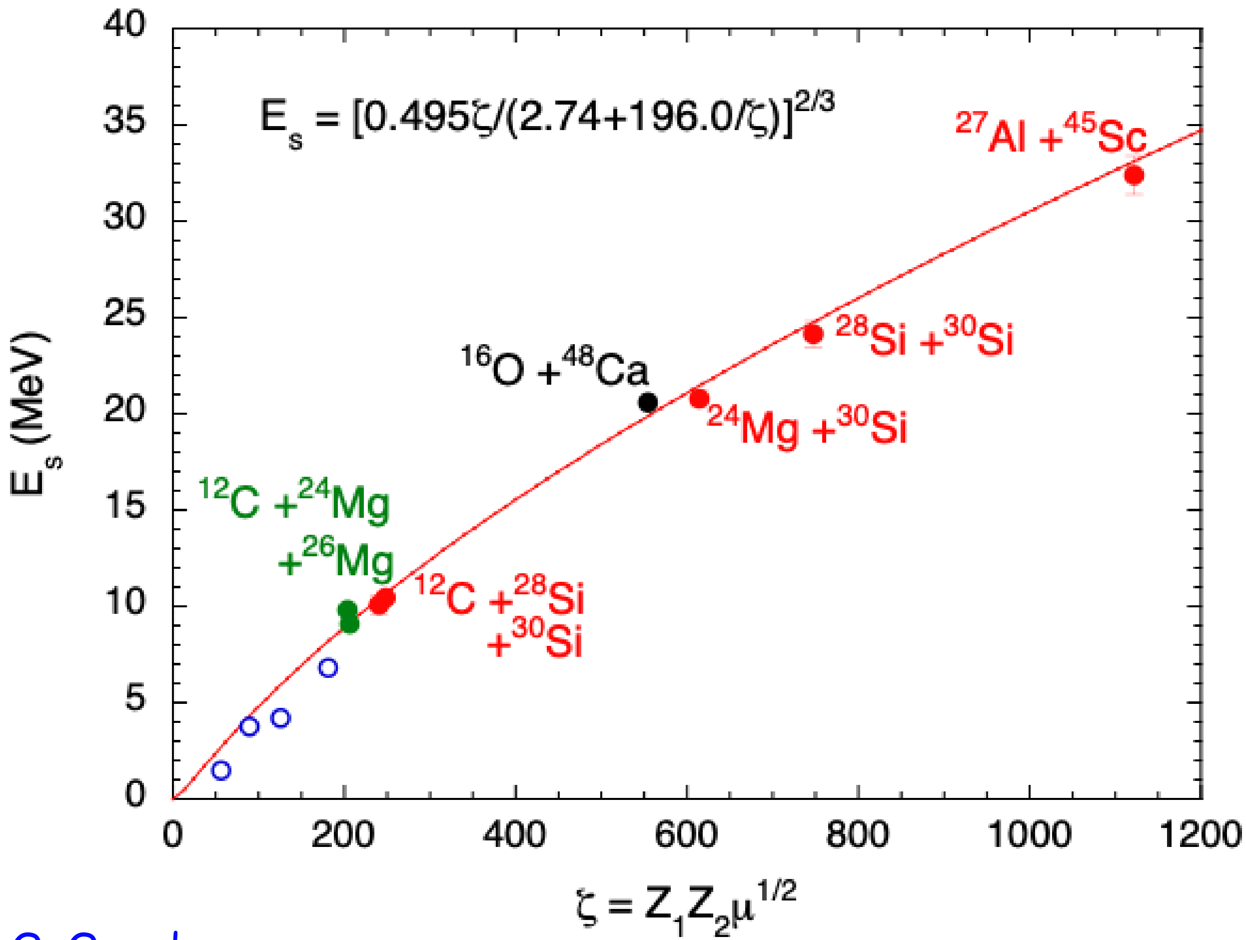
The lowest cross section is σ = 35±23 nb

Threshold energies for hindrance in light systems

$^{12}C+^{28}Si$ (Q_{fus} = +13.4 MeV) has a ζ parameter close to the lighter systems important for stellar evolution.

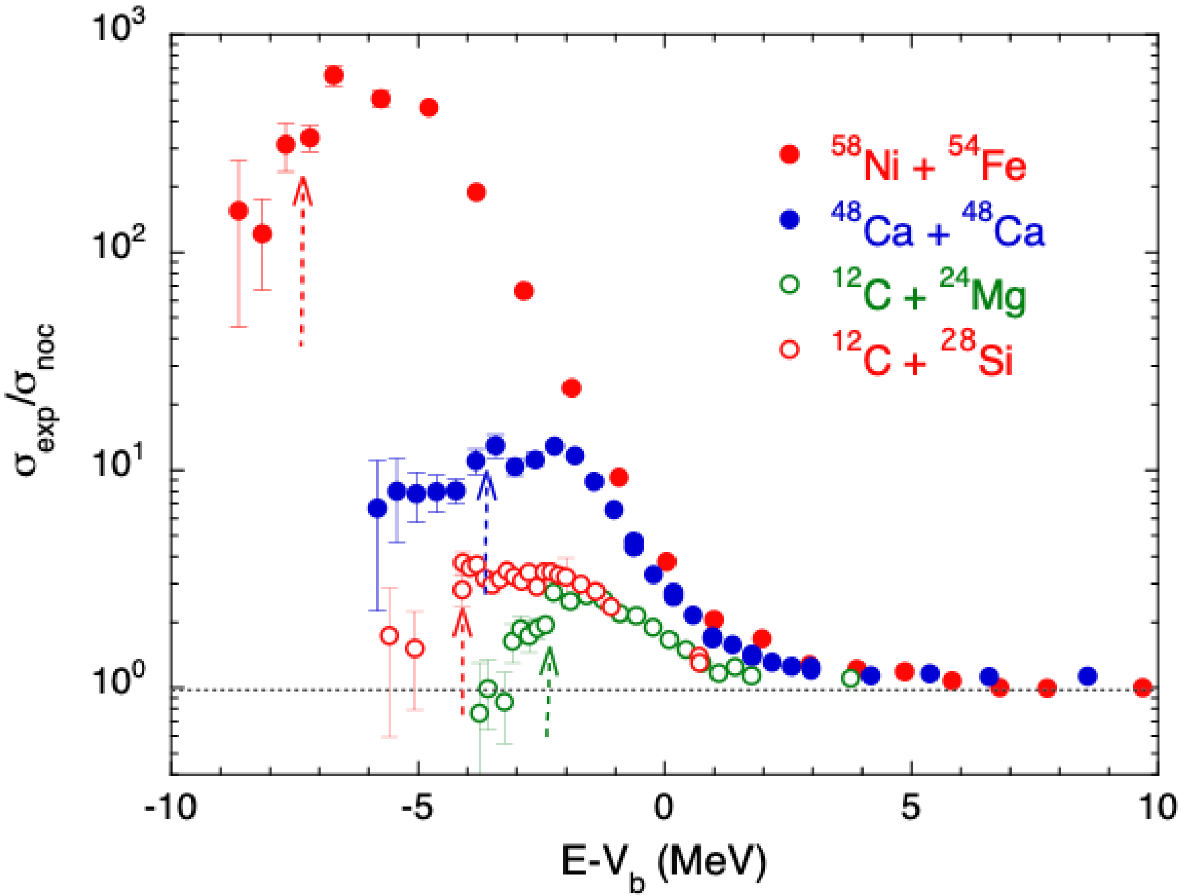
The case of $^{12}C+^{30}Si$ we studied some years ago (PRC 97, 024610), is nearby and shows a similar threshold for hindrance.

The original fit parameters (Jiang, PRC 79, 044601) have been updated, including the C+Mg,Si data



N.B. the open points of C+C, O+O and B+B are obtained from extrapolations

Ratios between experimental cross sections and no coupling calculations



- The arrows mark the hindrance thresholds for the various systems.
- For lighter systems, the ratios are consistent with one far below the barrier.

→ The coupling strengths are strongly damped at low energies.

Summary

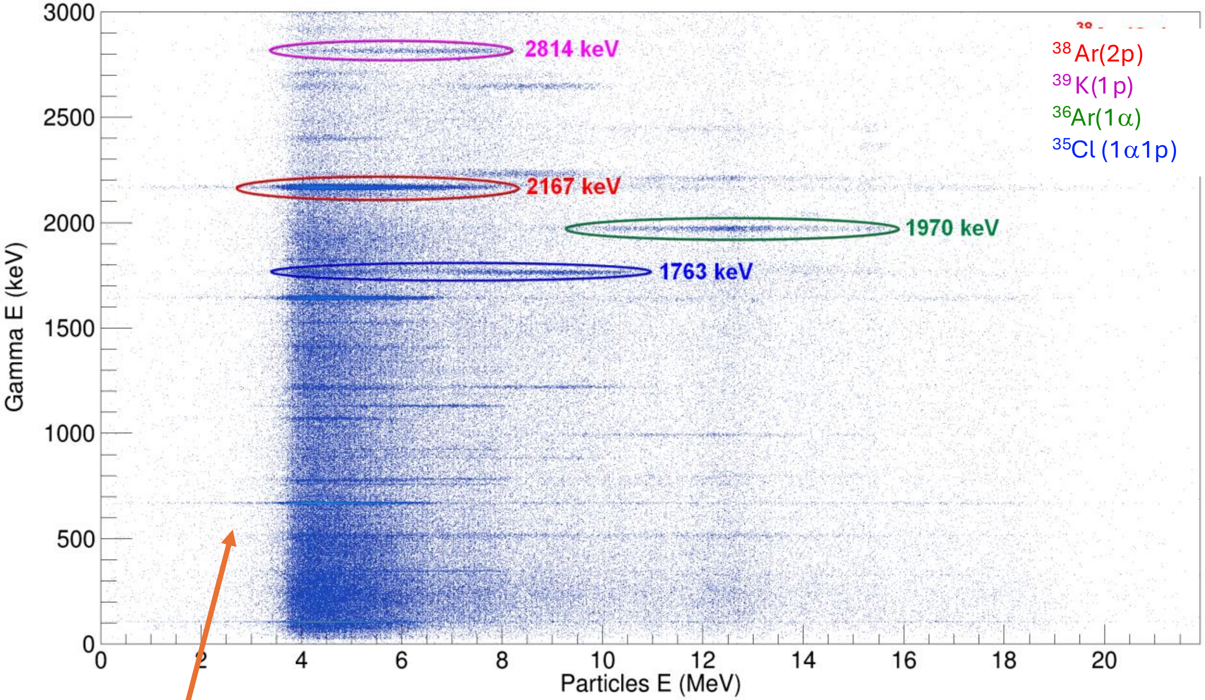
- General features for the fusion hindrance phenomenon
- Its relevance in astrophysics
- The case of $^{12}C + ^{28}Si$ measured at LNL using AGATA+DSSD γ-particle coincidences
- Identification of evaporated particles via psd
- Measured fusion cross sections down to 35 nb
- Hindrance has been observed with a threshold following a phenomenological trend
- The lowest energy points are consistent with one-dimensional barrier tunnelling

The collaboration

G. Montagnoli[1,2,*], M. Del Fabbro[1,3], A. M. Stefanini[4], M. Balogh[4], A. Goasduff[4], G. Andreetta[1,4], F. Angelini[1,4], J. Benito[1,2,5], A. Bonhomme[6], D. Brugnara[4], G. Colucci[7], L. Corradi[4], S. Courtin[6], R. Depalo[8], A. Ertoprak[4], E. Fioretto[4], F. Galtarossa[2], B. Gongora Servin[3,4], A. Gottardo[4], A. Gozzelino[4], M. Heine[6], M. Mazzocco[1,2], D. Mengoni[1,2], B. Million[9], E. Monpribat[6], R. Nicolas Del Alamo[1,2], J. Pellumaj[4], R.M. Perez Vidal[4], S. Pigliapoco[2], E. Pilotto[1,2], M. Polettini[1,2], K. Rezynkina[2], M. Rocchini[10], D. Stramaccioni[1,4], S. Szilner[11], A. Trzcinska[7], J. Valiente Dobon[4], L. Zago[1,4], and I. Zanon[12]

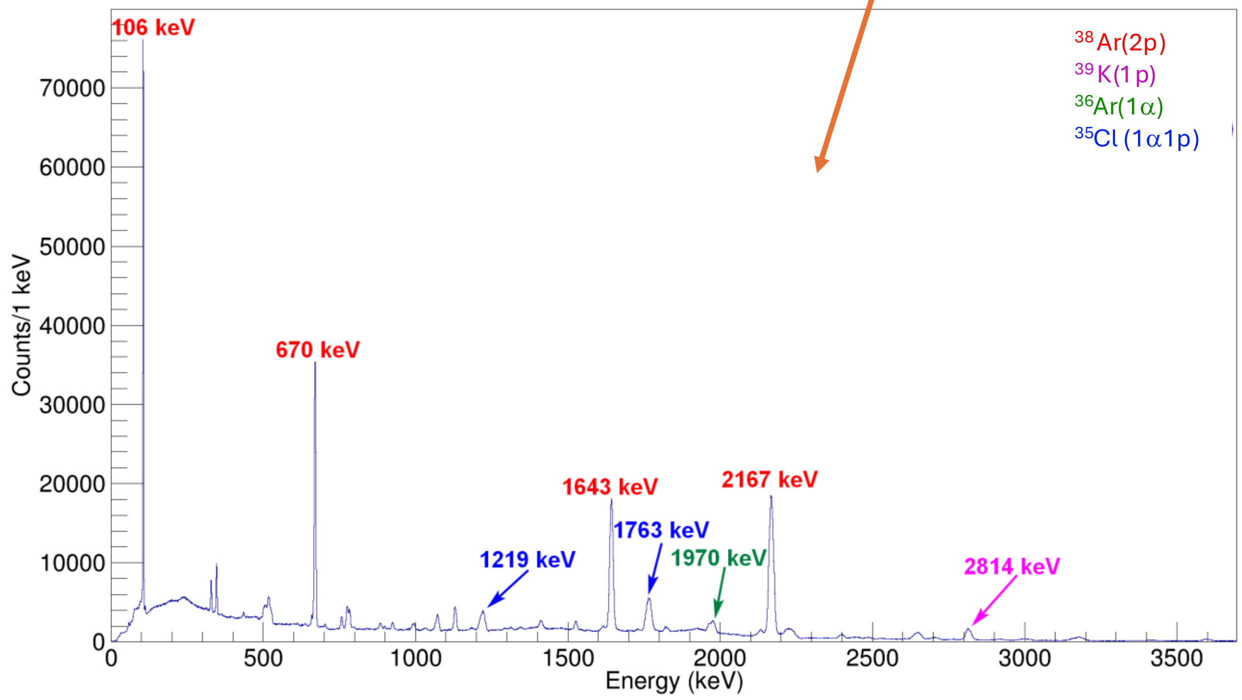
[1]Univ. of Padova, Italy,
[2]INFN-Padova, Italy,
[3]Univ. of Ferrara, Italy,
[4]INFN-Lab. Naz. di Legnaro, Padova, Italy,
[5]Univ. Complutense de Madrid, Spain,
[6]IPHC/CNRS Strasbourg, France,
[7]HIL, Univ. Warsaw, Poland,
[8]Univ. of Milano, Italy,
[9]INFN-Milano, Italy,
[10]INFN-Firenze, Italy,
[11]Ruđer Bošković Institute, Zagreb, Croatia,
[12]Univ. of Stockholm, Sweden

End



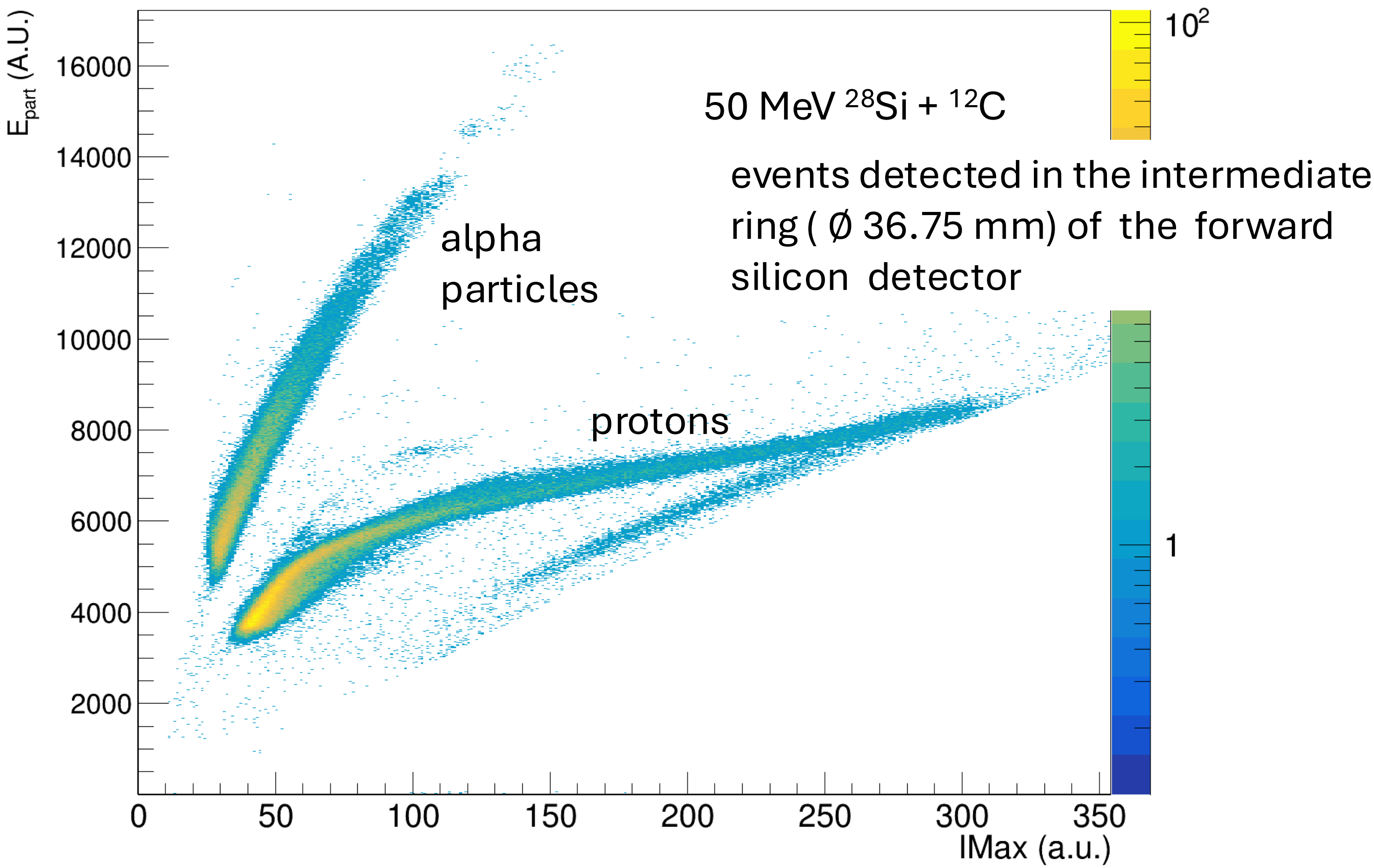
$^{28}Si+^{12}C$, $\sigma_{fus} \approx 140$ mb

γ–energy spectrum at 50 MeV ^{28}Si beam energy, in coincidence with the forward DSSD



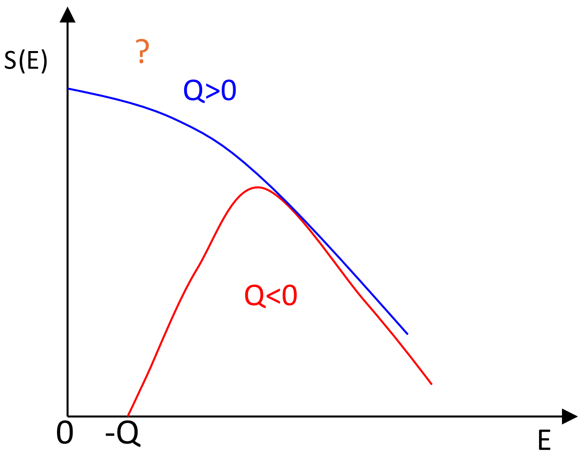
γ–energy vs particle energy matrix at 50 MeV ^{28}Si beam energy, in coincidence with the ring at 26.2° of the forward DSSD

Identification of evaporated particles



Light-charged particles detected by the DSSD are identified through pulse shape analysis, using their energy E_{part} vs the maximum of the signal derivative (IMAX)

Is there something special with light systems that have $Q_{fus} > 0$?



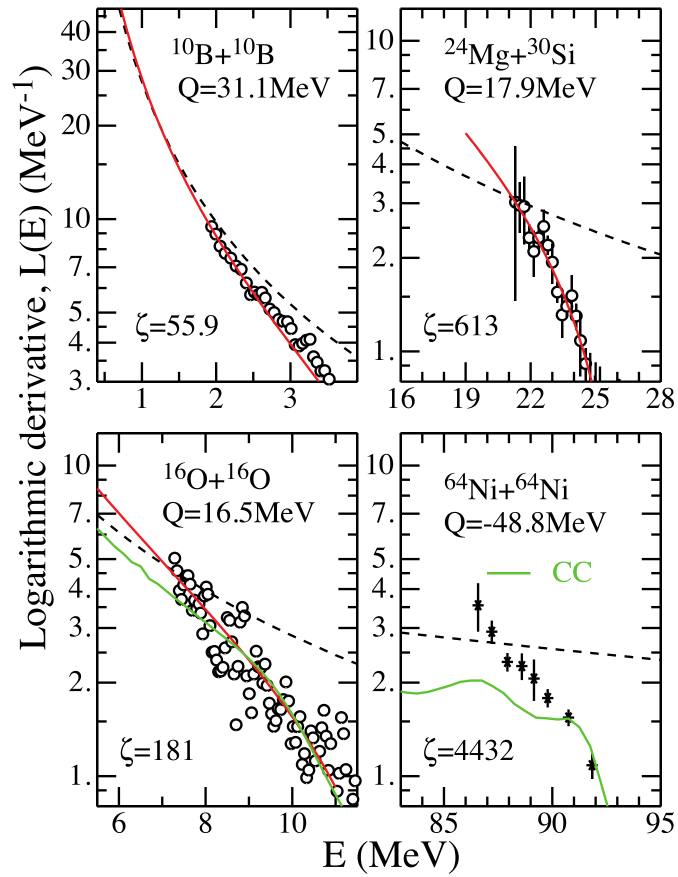
	E_{min}	$e^{2\pi\eta}$	S(E)
Q<0	-Q	finite	0
Q>0	0	$\rightarrow\infty$	finite ?

The astrophysical S-factor $S(E) = E\sigma(E)e^{2\pi\eta}$

For $Q_{fus} > 0$ S(E) may not show any maximum

For light systems, L(E) and $L_{cs}(E)$ are two nearly parallel curves so the crossing point (if existing) is rather undetermined

The S factor maximum becomes broader



Features of several dedicated set-ups

Set-up	ε_γ (%)	ε_{part} (%)	ε_{tot} (%)	I_{beam}(pμA)
Argonne Gammasphere + Si array	8	25	2	~ 0.6 ^{12}C
Notre Dame HPGe + Si array	1.7	30	0.5	> 10 ^{16}O
Strasbourg-Orsay $LaBr_3$ array + STELLA	6	25	1.5	~ 0.5 ^{12}C
Legnaro AGATA + 2 DSSD	10	20	2	0.1 ^{28}Si

C.L. Jiang et al., NIM A 682, 12 (2012)
X. Fang et al., PRC 96, 045804 (2017)
S. Courtin et al., EPJ Web of Conf. 163, 00011 (2017)

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Astrophysical S-factor and logarithmic slope L(E)

$$S(E) = E\sigma(E)e^{2\pi\eta}$$

$$\eta = 0.157\frac{Z_1 Z_2}{\sqrt{\varepsilon}} \text{ where } \varepsilon = E/\mu$$

$$L(E) = \frac{d}{dE}\ln\left[S(E)\, e^{-2\pi\eta}\right] = \frac{1}{\left[S(E)\, e^{-2\pi\eta}\right]}\frac{d}{dE}\left[S(E)\, e^{-2\pi\eta}\right]$$

da cui

$$\frac{d}{dE}\left[S(E)\, e^{-2\pi\eta}\right] = e^{-2\pi\eta}\frac{dS(E)}{dE} + S(E)\frac{de^{-2\pi\eta}}{dE}$$

e quindi

$$\frac{dS(E)}{dE} = S(E)\left[L(E) + 2\pi\frac{d\eta}{dE}\right] = S(E)\left[L(E) - \frac{\pi\eta}{E}\right]$$

$L(E) = d[\ln(E\sigma)]/dE$

$dS/dE = S(E)[L(E) - \pi\eta/E]$

S has a maximum when $dS/dE = 0$, i.e. when $L(E) = \pi\eta/E = L_{CS}$

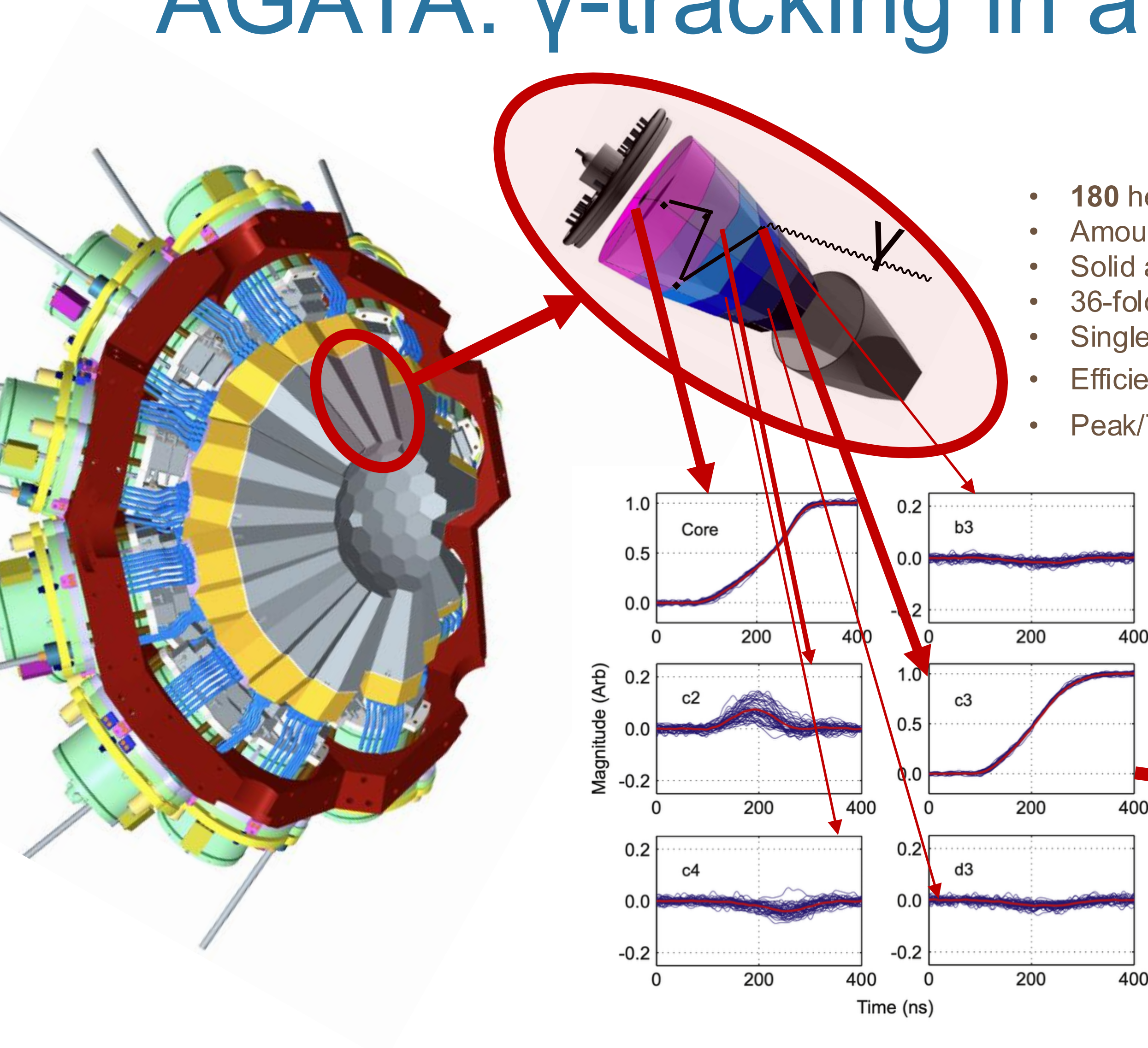
The energy $E = E_S$ where this happens (if it happens !) has been usually taken as the threshold energy for hindrance.

From the empirical systematics of Jiang et al. one obtains

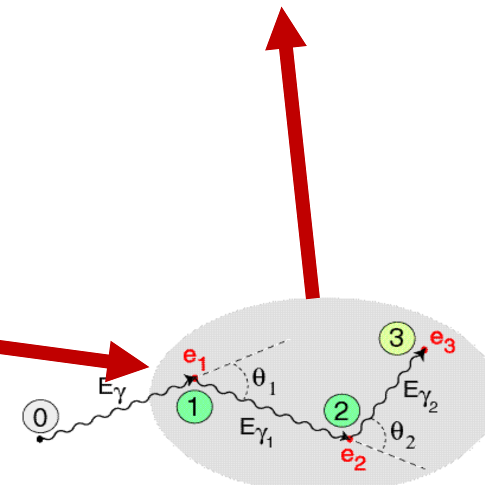
$E_S \approx 0.356\ [Z_1 Z_2 \sqrt{\mu}]^{2/3}$ MeV

C.L.Jiang et al., PRC 73, 014613 (2006)

AGATA: γ-tracking in a nutshell



- **180** hexagonal crystals in 60 ATCs
- Amount of germanium: 360 kg
- Solid angle coverage: 82 %
- 36-fold segmentation: 6480 segments
- Singles rate: > 50 kHz
- Efficiency: 43% (M_g=1)
- Peak/Total: 58% (M_g=1)



E_{lab} = 30 MeV

	Z	N	A	events	percent
n	20	19	**39 Ca**	357	3.57%
p	19	20	**39 K**	7871	78.7%
α	18	18	**36 Ar**	1772	17.7%
	TOTAL			10000	100

50 MeV

Z	N	A	events	percent	
20	19	**39 Ca**	664	6.64%	n
19	20	**39 K**	4292	42.9%	p
19	19	**38 K**	191	1.91%	pn
18	20	**38 Ar**	365	3.65%	2p
18	18	**36 Ar**	1816	18.2%	α
17	18	**35 Cl**	2672	26.7%	αp
TOTAL			10000	100	

PACE4 – 12C+28Si calculated yields of evaporation channels ~30 % below the barrier (30 MeV) and ~13 % above (50 MeV)