SATIF-16

May 28-31, 2024

SATIF-16 Shielding aspects of Accelerators Targets and Irradiation Facilities

Treatment of low-energy heavy particle fusion reactions in PHITS

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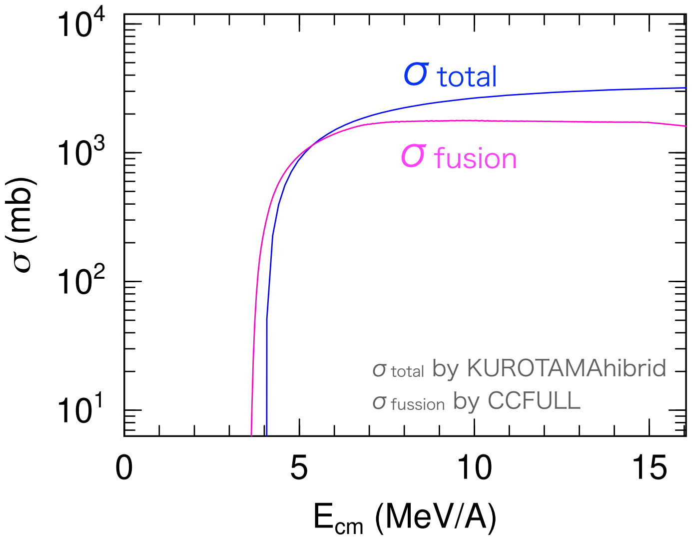
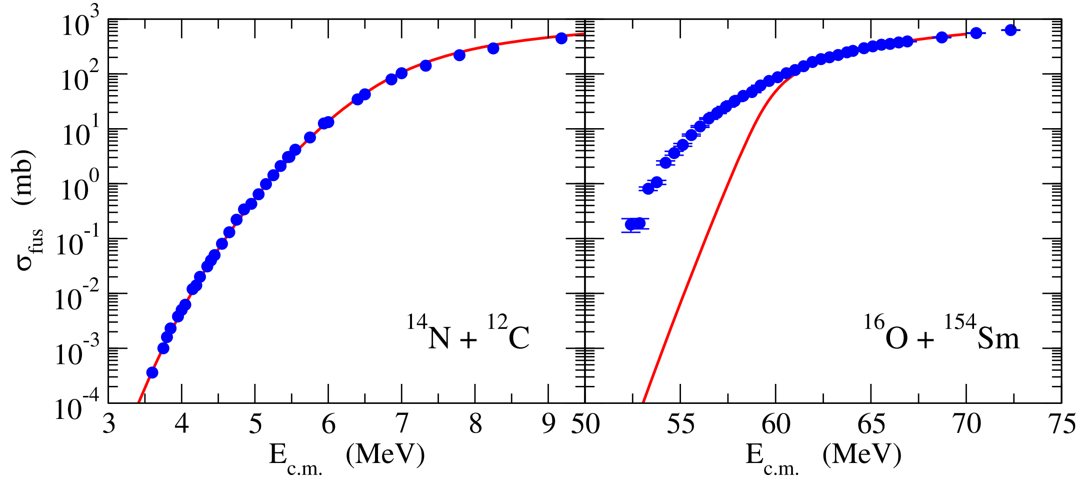
Background

of heavy ion collisions in the energy region toward the stopping

- Fusion is one of major component in the reaction cross section
- The low-energy heavy ion fusion occur even below the coulomb barrier
- The sub-barrier fusion is more pronounced for heavier mass collisions



Fusion cross sections measured and classical model



Hagino et al., Prog. Theor. Phys., Vol.128, 6 (2012)

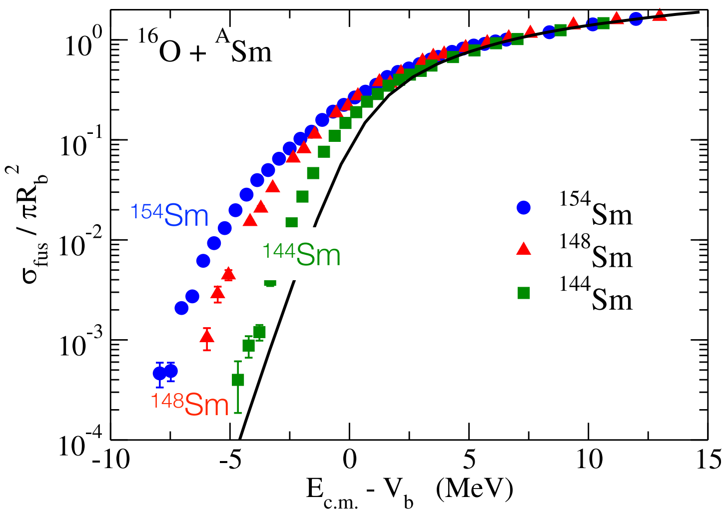
Purpose

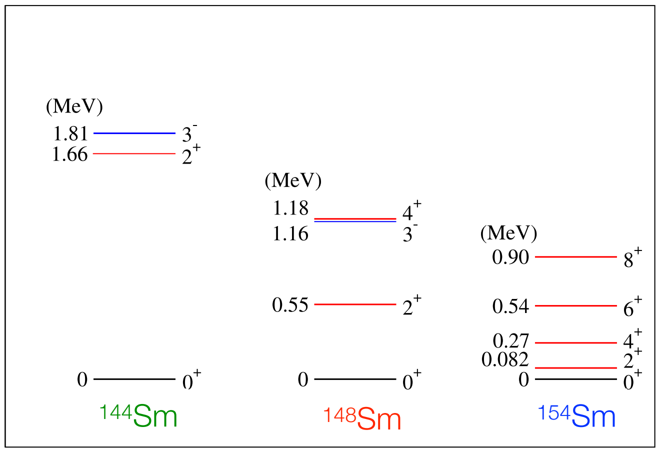
- Revising PHITS by including the low-energy heavy ion fusion cross section explicitly
- It is required providing more precise simulation to some accelerator facilities and experiments
- Previous methods; fusion occurs as results of JQMD simulations
- This methods; the CCFULL fusion cross section is used

CCFULL

Hagino et al., Prog. Theor. Phys., Vol.128, 6 (2012)

- fusion cross section model based on the quantum tunneling of many-body systems
- treats deformation of nucleus, excitation energies, and treats multiple excitations of a nucleus with finite excitation energies
- the Channel Coupling represents fusion cross sections even below sub-barrier





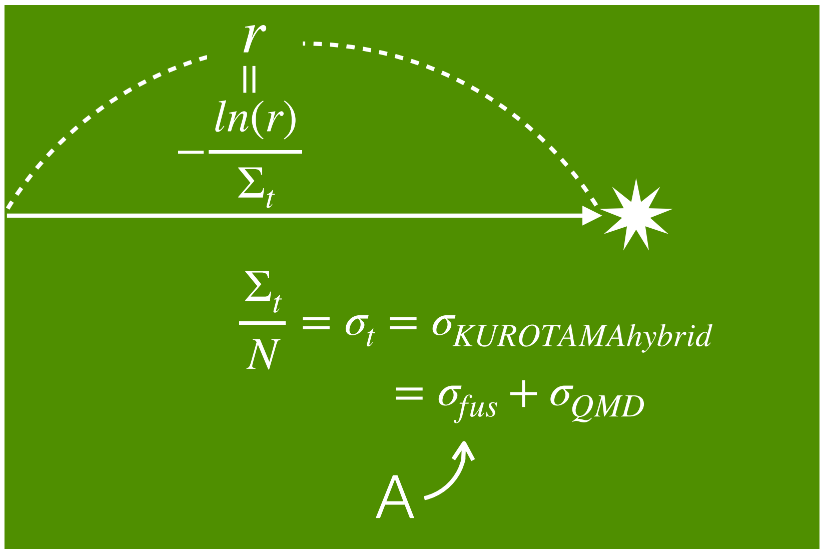
Hagino et al., Prog. Theor. Phys., Vol.128, 6 (2012)

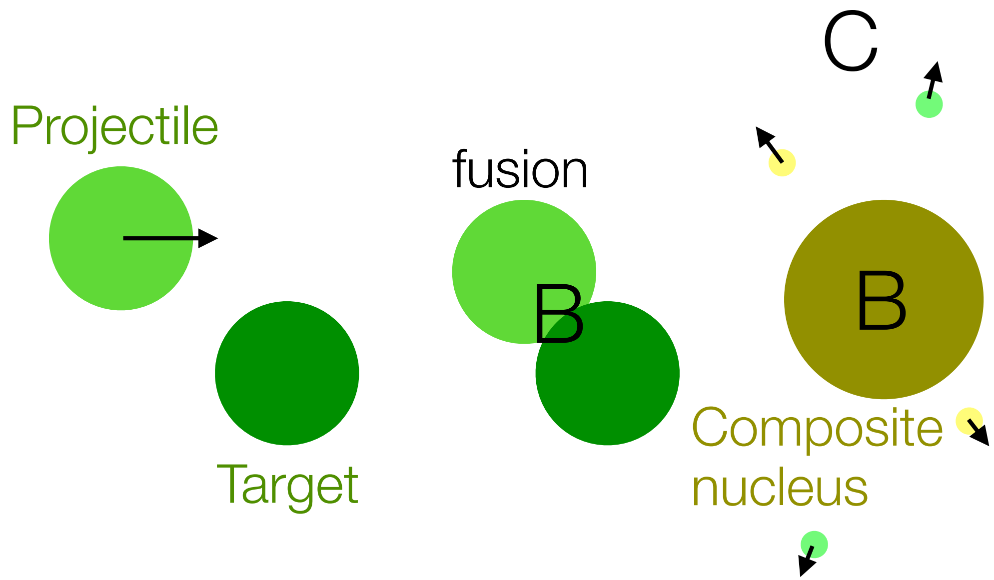
Methods

A. Fusion cross section is explicitly defined by CCFULL

B. In case of fusion reaction, a composite nucleus of projectile and target nuclei is prepared

C. Evaporation calculation is performed to composite nuclei by the statistical model GEM

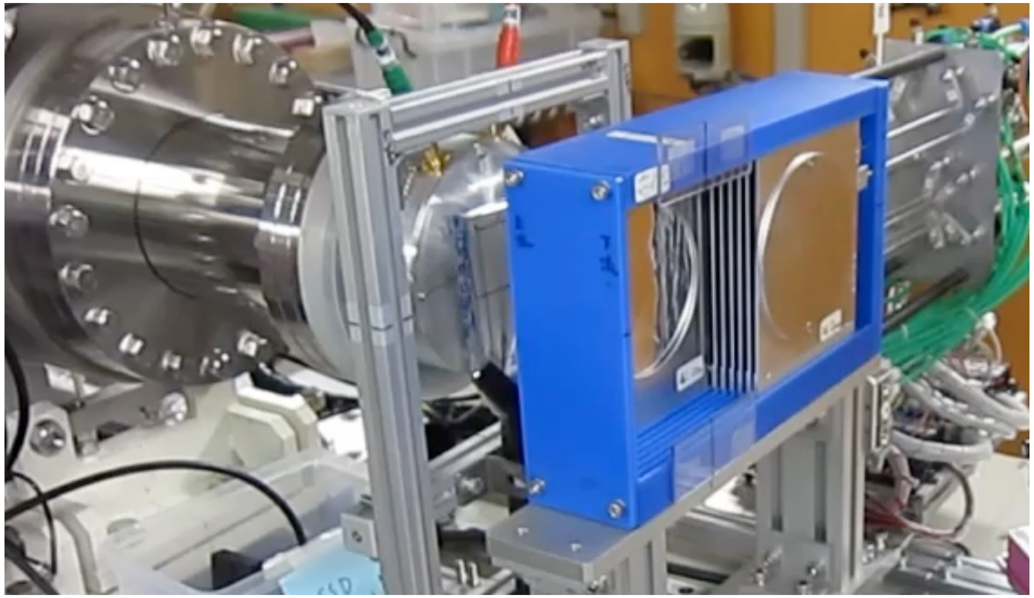




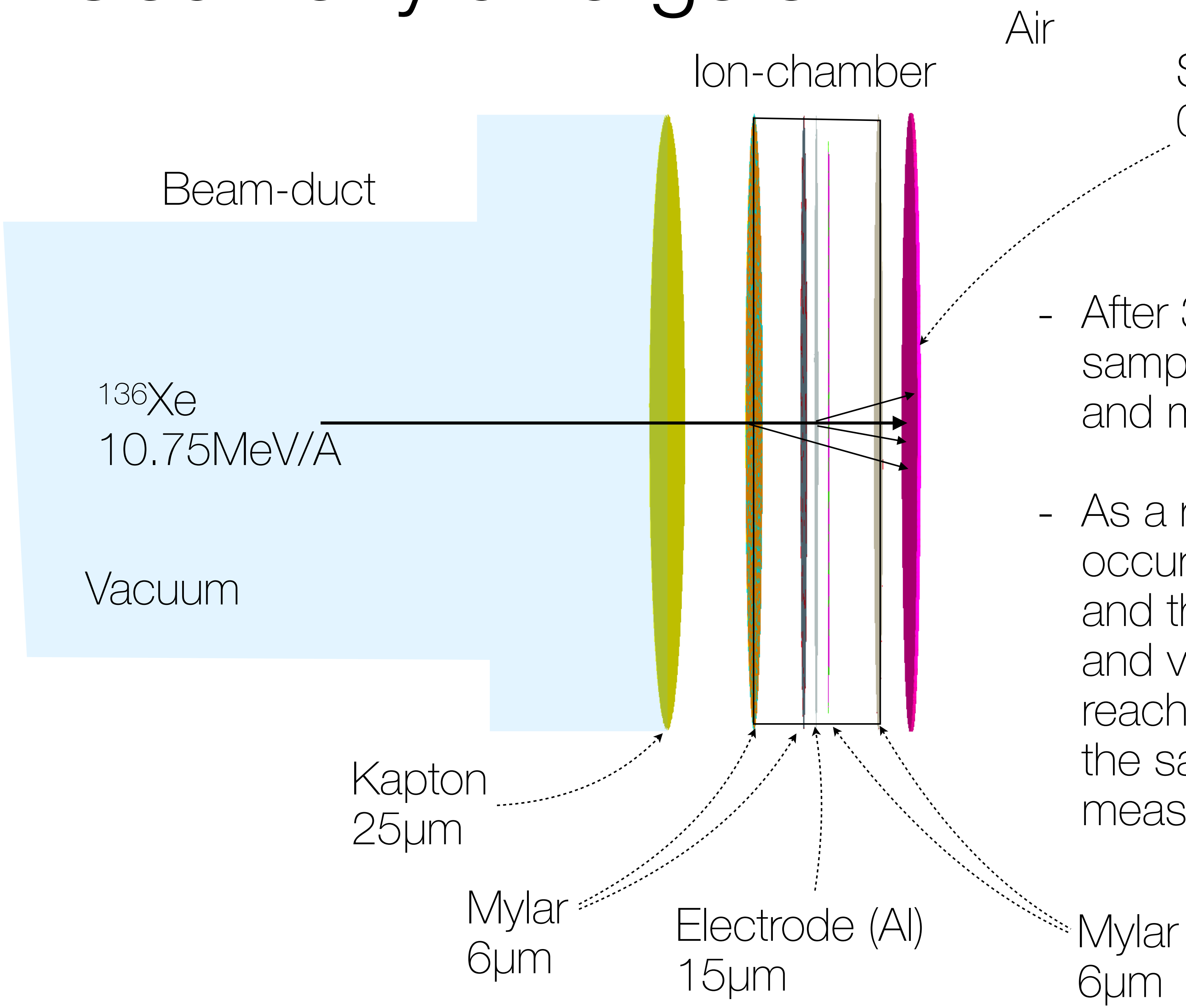
Benchmark data

[2] Kambara et al, Acc. progress report Vol 52, p158 (2019)

- ^{136}Xe 10.75 MeV/A + light mass targets
- Measured at E5A beam line, at RIKEN
- Nuclides and their production rate obtained by HP-Ge gamma rays analysis

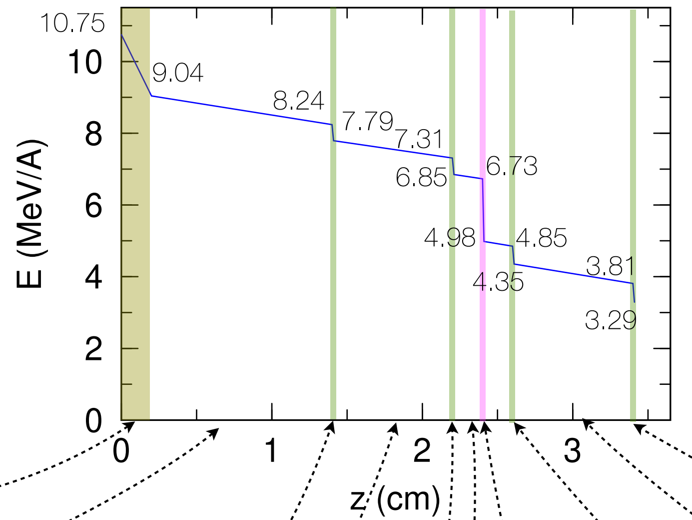


Geometry & Targets



- After 3h irradiation, the sample was removed and measured
- As a result, fusions occur between ^{136}Xe and these materials and variety of isotopes reach and stop inside the sample and measured

Projectile energies & Target nuclei



Possible fusion	Number of FUSION per source	Ratio to total
136Xe + 12C	2.262E-04	0.37
136Xe + 14N	1.398E-04	0.23
136Xe + 16O	9.578E-05	0.16
136Xe + 40Ar	2.796E-05	0.05
136Xe + 27Al	1.215E-04	0.20

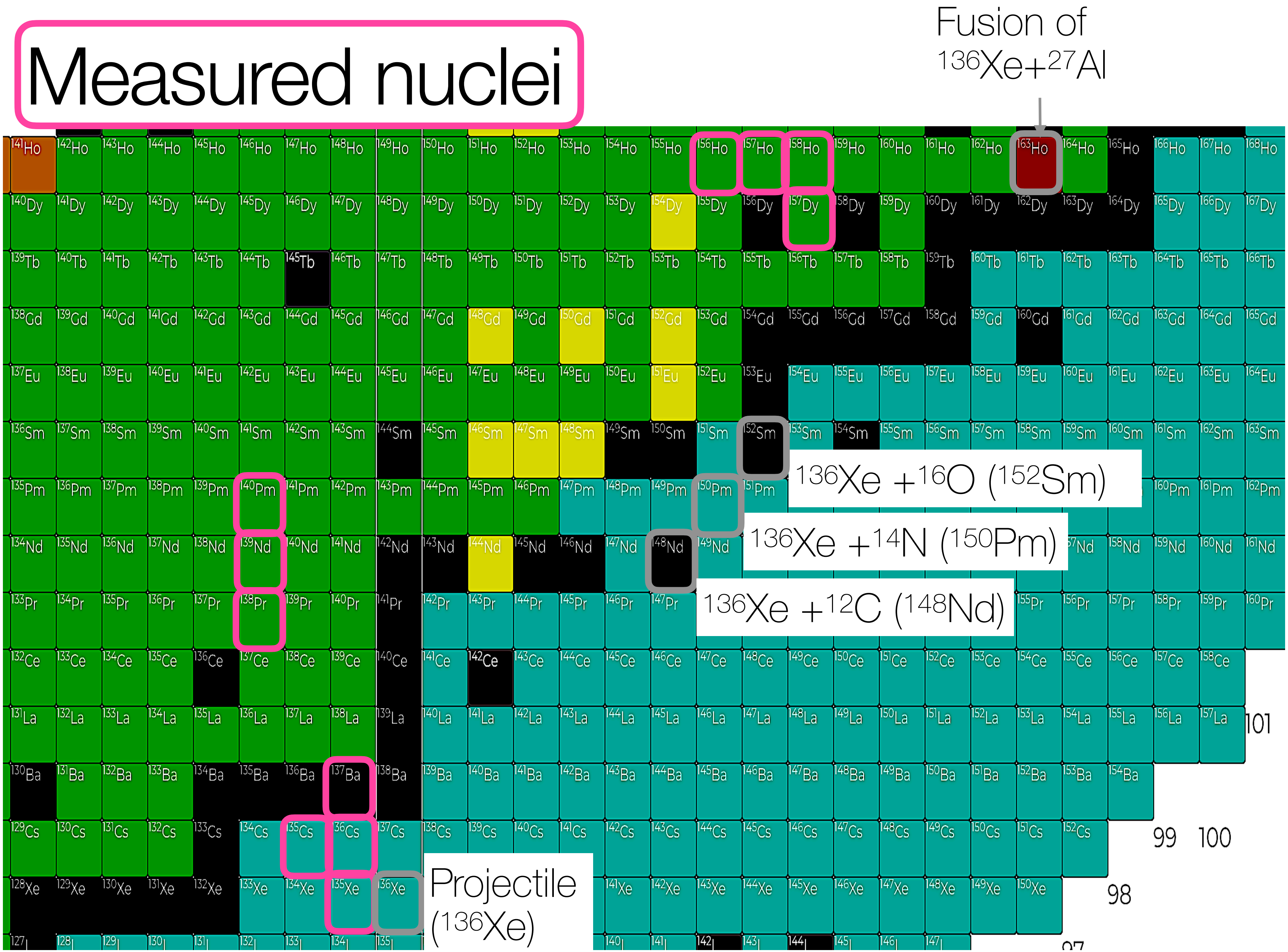
* Approximate reference value: Only ^{136}Xe+^{27}Al fusion σ is by CCFULL

^{136}Xe ions reach Sample but have too low energy to react

Measured nuclei [2]

Nuclei	halflife	unit	Z	N	A	production rate	error
Xe-135g	9.14	h	54	81	135	9.86E-05	2.97E-05
Xe-135m	15.29	m	54	81	135	1.94E-05	6.39E-06
Cs-135m	53	m	55	80	135	4.22E-06	2.01E-06
Cs-136	13.16	d	55	81	136	7.44E-05	3.62E-05
Ba-137m	2.552	m	56	81	137	2.91E-05	1.25E-05
Pr-138m	2.12	h	59	79	138	6.64E-06	2.61E-06
Nd-139m	5.5	h	60	79	139	4.01E-05	1.28E-05
Pm-140m	9.2	s	61	79	140	4.52E-06	1.97E-06
Dy-157	8.14	h	66	91	157	7.75E-06	6.55E-06
Ho-156	56	m	67	89	156	3.95E-05	1.14E-05
Ho-157	12.6	m	67	90	157	5.05E-05	1.53E-05
Ho-158	11.3	m	67	91	158	1.04E-05	3.33E-06

Measured nuclei



Additional information/condition

- Focus on heaviest fusion composite of $^{136}Xe+^{27}Al$ and its altered nuclei of Ho and Dy

- Fusion cross section of $^{136}Xe + ^{27}Al$ is calculated by CCFULL

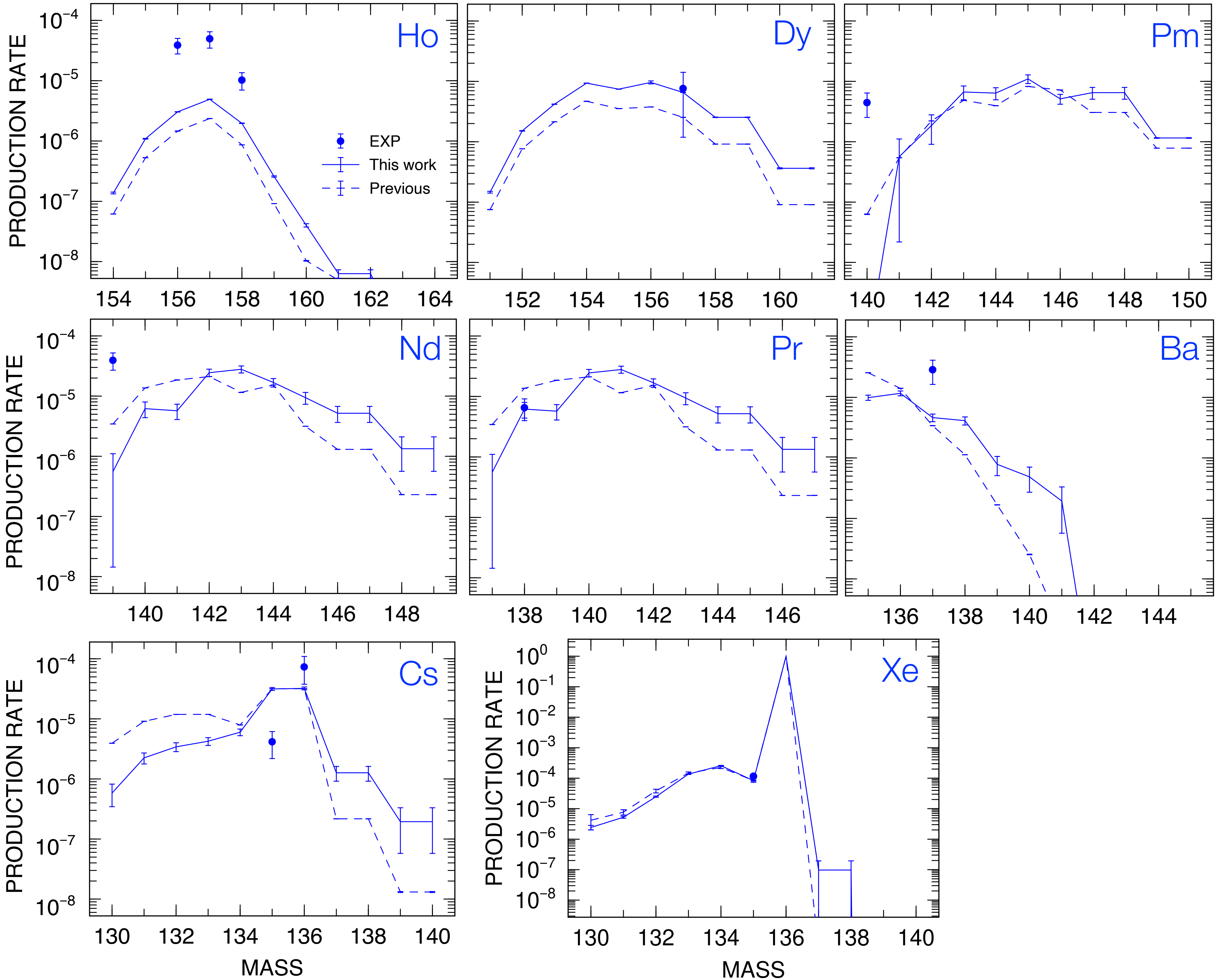
    - Global integration of CCFULL is future work
    (CCFULL requires deformation parameters and excitation energies of each nucleus, and potential value of composite nucleus)

- For other combination of $^{136}Xe + ^{12}C$, ^{14}N, ^{16}O, cross section is not prepared explicitly (original PHITS)

PHITS options

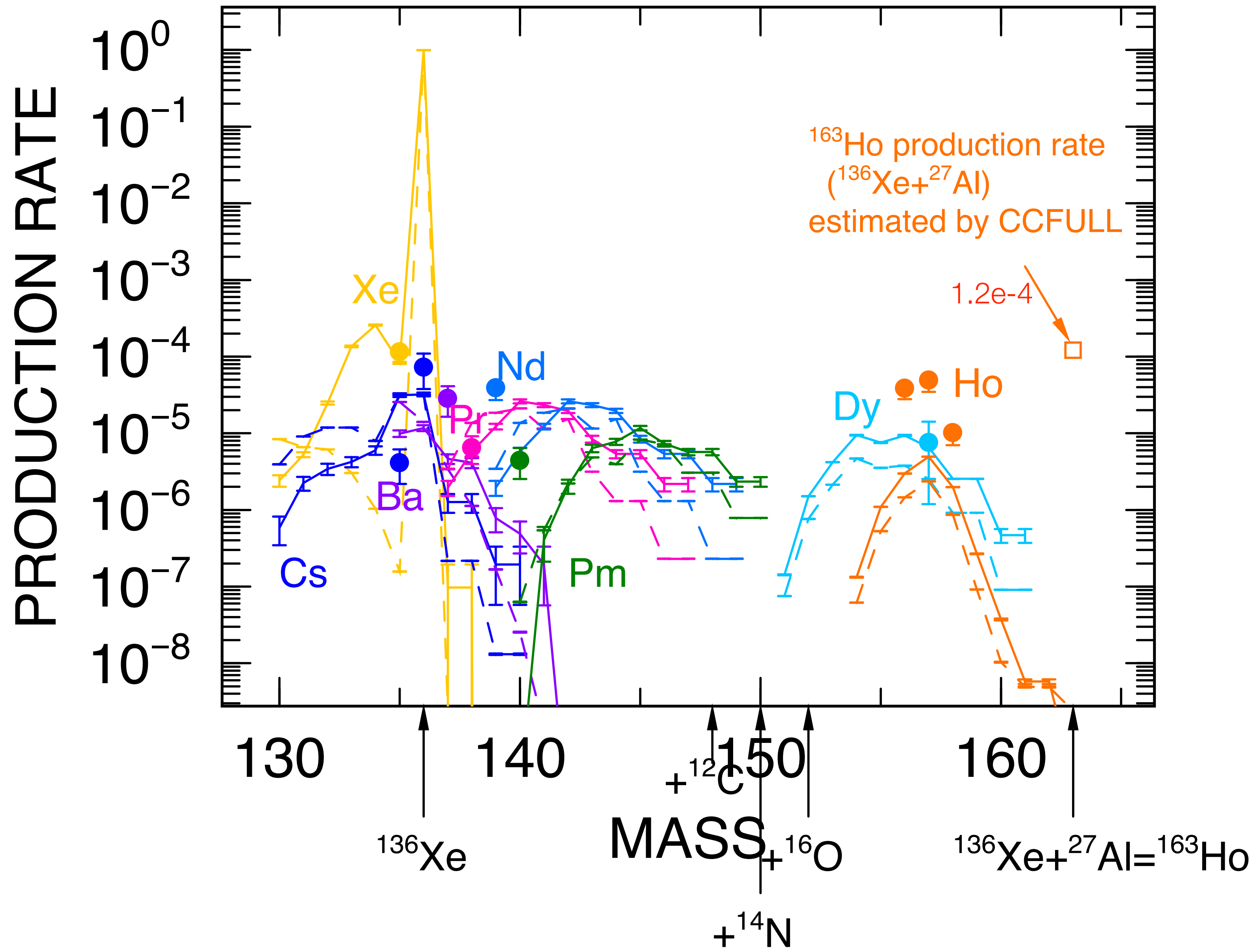
- irqmd = 2 ! (JQMD ver. 2)
- eqmdmin = 3.5 ! (MeV/u)
- eqmdnu = 3.5 ! (MeV/u)
- ngem = 2 ! 2:γ emission competes with
  !   nucleon emission

Results



Ho
Dy
Pm
Nd
Pr
Ba
Cs
Xe
EXP
This work
Previous
PRODUCTION RATE
MASS

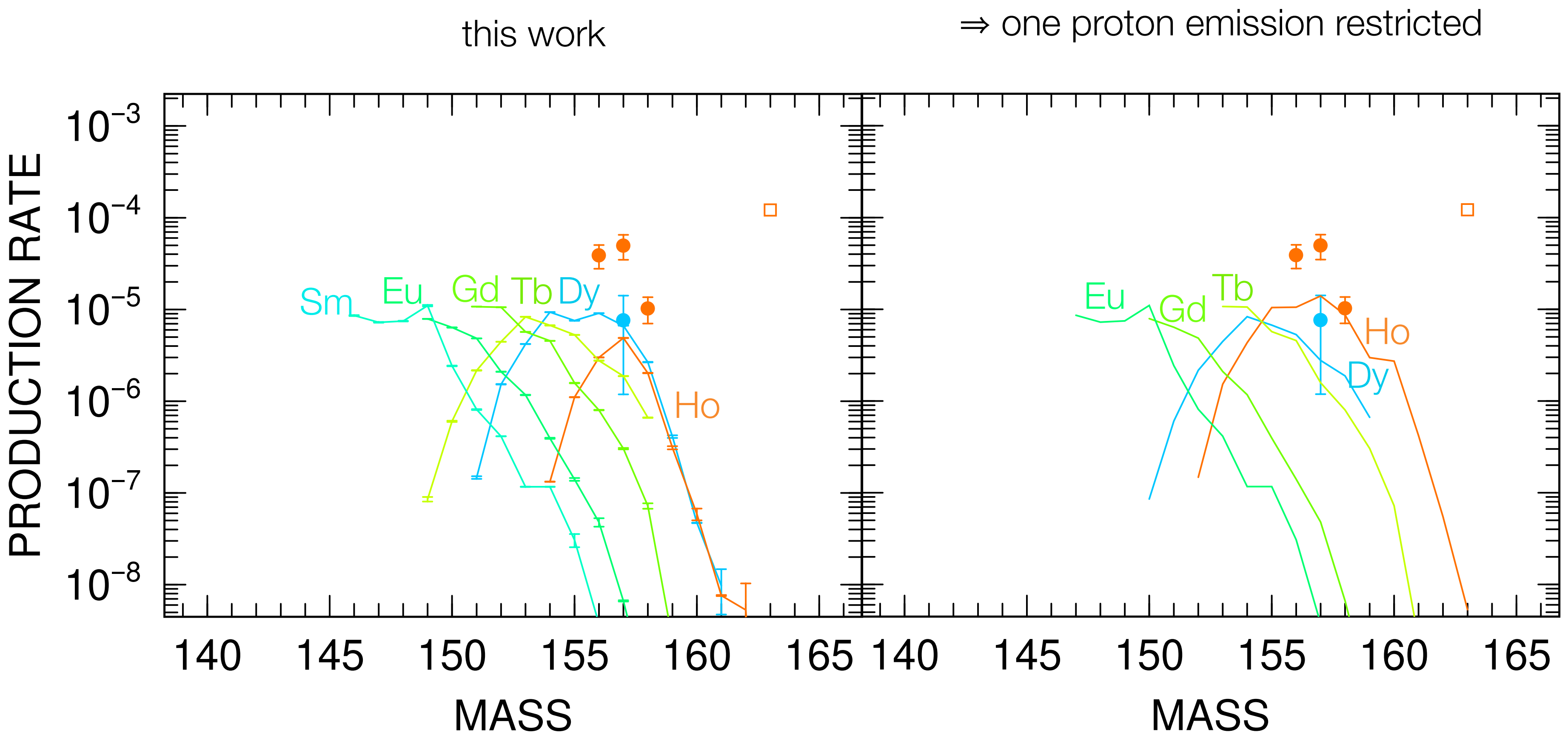
All results in one figure



Discussion

- CCFULL improves the accuracy of PHITS calculation of low-energy heavy ion fusion products by a factor of 2 or more
- Integration of CCFULL into MC is essential for low-energy heavy ion physics and application
- Still discrepancy between data and simulation
  - sum of measured production rate of Ho and Dy nuclei 1.0e-4 supports the number of fusions estimated by CCFULL of 1.2e-4
  - In PHITS, the composite nucleus of ^{163}Ho with excitation energy, emits multiple nucleons, which are distributed as other nuclei. The distribution may be improved.

A sensitivity test by limiting the number of nucleon emissions



rather flat distribution

⇒ overall shift to the right while gathering in Ho

- only one proton emission restriction changes the result very much

- may indicates a room of improvement of the statistical model of composite nucleus in low energy fusion

Summary

- Fusion cross section of low energy heavy ion may underestimate if classical model is used
- CCFULL improves the accuracy of MC calculation of low-energy heavy ion fusion
- Global integration of CCFULL is the next work
- Other treatment of fusion composite nucleus in this energy region may better represent the data

Thank you very much

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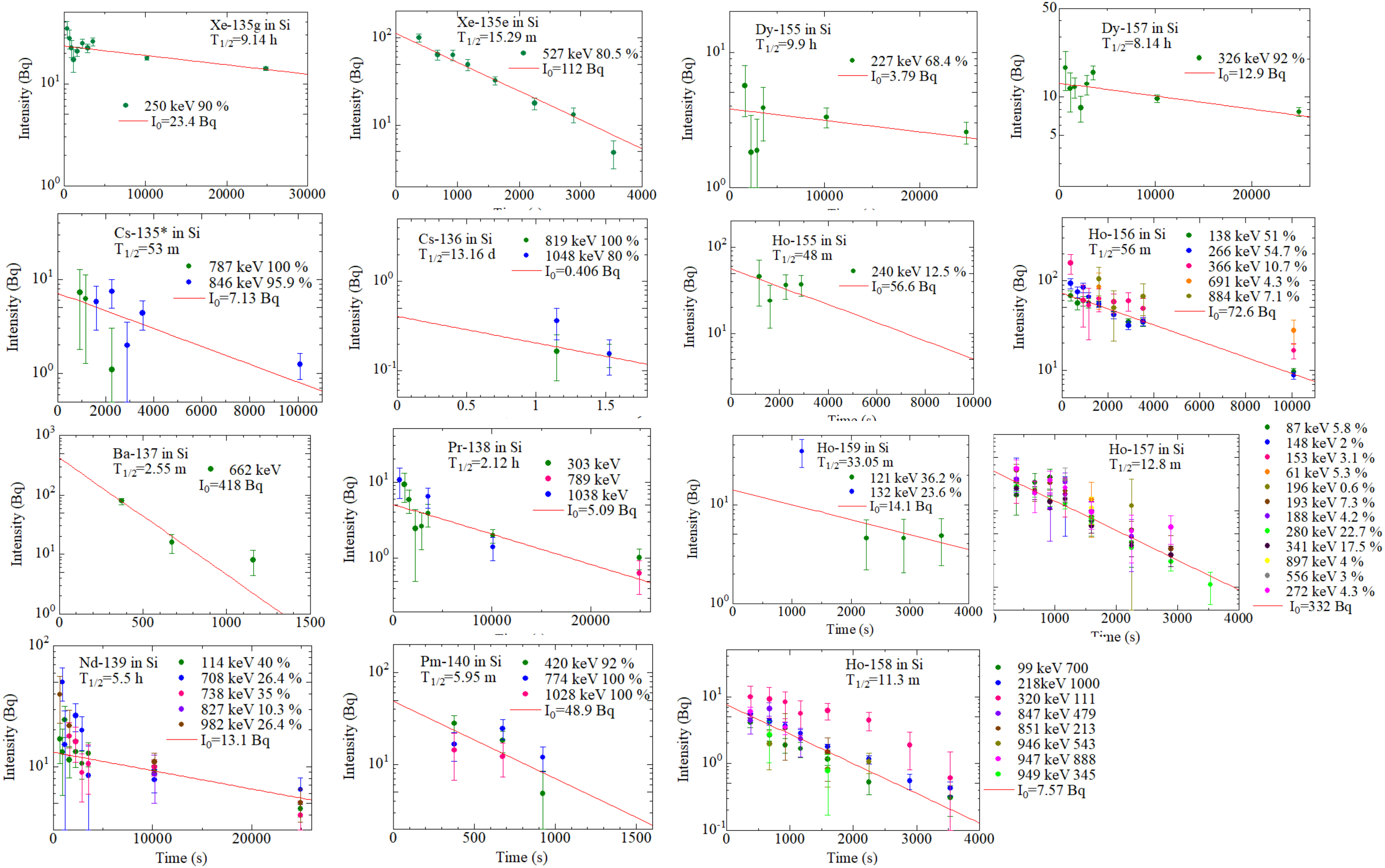
Backups & appendix

Decay analysis



Reaction Summary

	Thickness (μm)	Atom	Atomic mass (g/mol)	Atom fraction	Mass density (g/cm3)	Atomic density (/cm3)	Atomic density (/cm3)	Ein (MeV/A)	Eout (MeV/A)	σ_t (mb)	σ_f (mb)	Σt (cm-1)	Σf (cm-1)	# of interaction	# of fusion	fusion ratio
		H	1.00794	0.256399			0.02237			0.67		0.015		3.73E-05	0.000E+00	0.00
		C	12.0107	0.564114			0.04921			2.65	1.33	0.130	0.06545	3.26E-04	1.636E-04	0.50
kapton	25	N	14.0067	0.051282	1.420000	0.0872	0.00447	10.75	9.04	2.75	1.33	0.012	0.00595	3.07E-05	1.487E-05	0.48
		O	15.9994	0.128205			0.01118			2.78	1.33	0.031	0.01487	7.77E-05	3.718E-05	0.48
		N	14.0067	0.784431			0.0000391			2.56	1.33	0.000100	0.0000520	1.40E-04	7.287E-05	0.52
Air	14000	O	15.9994	0.210748	0.001205	0.0000499	0.0000105	9.04	8.24	2.58	1.33	0.000027	0.0000140	3.80E-05	1.958E-05	0.52
		Ar	39.948	0.004671			0.0000056			3.19	2.07	0.000018	0.0000117	2.51E-05	1.631E-05	0.65
		H	1.00794	0.363632			0.03460			0.30		0.010	0.00000	6.29E-06	0.000E+00	0.00
	6	C	12.0107	0.454552	1.380000	0.0951	0.04325	8.24	7.79	2.40	1.33	0.104	0.05752	6.22E-05	3.451E-05	0.56
Mylar		O	15.9994	0.181816			0.01730			2.45	1.33	0.042	0.02301	2.55E-05	1.380E-05	0.54
	0.08	Al	26.9815	1.0	2.70	0.0603	0.0603	7.79		2.68	1.33	0.1615065	0.0801	1.29E-06	6.412E-07	0.50
		N	14.0067	0.784431			0.0000391			2.32	1.33	0.000	0.0000520	7.26E-05	4.164E-05	0.57
Air	8000	O	15.9994	0.210748	0.001205	0.0000499	0.0000105	7.79	7.31	2.34	1.33	0.000	0.0000140	1.97E-05	1.119E-05	0.57
		Ar	39.948	0.004671			0.0000056			2.89	2.07	0.000	0.0000117	1.30E-05	9.321E-06	0.72
		H	1.00794	0.363632			0.02816			0.06		0.0016	0.00000	9.40E-07	0.000E+00	0.00
	6	C	12.0107	0.454552	1.380000	0.0774	0.03520	7.31	6.85	2.12	1.33	0.0746	0.04682	4.48E-05	2.809E-05	0.63
Mylar		O	26.9815	0.181816			0.01408			2.21	1.33	0.0311	0.01873	1.87E-05	1.124E-05	0.60
	0.08	Al	26.9815	1.0	2.70	0.0603	0.06026			2.38	1.33	0.143	0.08015	1.15E-06	6.412E-07	0.56
		N	14.0067	0.784431			0.0000391			2.10	1.33	0.000082	0.0000520	1.64E-05	1.041E-05	0.63
Air	2000	O	15.9994	0.210748	0.001205	0.0000499	0.0000105	6.85	6.73	2.12	1.33	0.000022	0.0000140	4.46E-06	2.797E-06	0.63
		Ar	39.948	0.004671			0.0000056			2.63	2.07	0.000015	0.0000117	2.96E-06	2.330E-06	0.79
Electrode	15	Al	26.9815	1.00	2.70	0.0603	0.0603	6.73	4.98	1.87	1.33	0.113	0.0801	1.69E-04	1.202E-04	0.71

Possible fusion	Number of FUSION per source	Ratio to total
136Xe + 12C	2.262E-04	0.37
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136Xe + 16O	9.578E-05	0.16
136Xe + 40Ar	2.796E-05	0.05
136Xe + 27Al	1.215E-04	0.20

	Material	Atoms	Density (g/cm³)	Atomic mass (g/mol)	Atom fraction	Atomic densityN	Thickness (μm)	E at Front (MeV/	E at Back (MeV/	σ_t (b)	σ_{fuss} (b)	Σ_t (cm-1)	Σ_{fuss} (cm-1)	# of total interactions per source	# of total interactions per source	# of fusion per source	# of fusion per source (actual)
1	Kapton	H C N O	1.42	1.00794 12.0107			25	10.75	9.04								
		N		14.006	0.784												

Material ID	Material	Thickness (μm)	Density (g/cm³)	E at Front (MeV/A)	E at Back (MeV/A)	dE (MeV/A)	σ_t (mb) 平均値	σ_{fuss} (mb) 平均値	Atomic density N (/cm³)	$\sigma_t N$ ×10^{-24}	$\sigma_t N$ ×10^{-24}	Σ_t (cm-1) 平均値	Σ_{fuss} (cm-1) 平均値	# of total interactions per source (formula)	# of total interactions per source (actual)	# of fusion per source (formula)	# of fusion per source (actual)
1	Kapton	25	1.42	10.75	9.04	1.71											
2	Air	14000	0.00121	9.04	8.24	0.80											
3	Mayler	6	1.38	8.24	7.79	0.45											
4	Air	8000	0.00121	7.79	7.31	0.48											
5	Maylar	6	1.38	7.31	6.85	0.46											
6	Air	2000	0.00121	6.85	6.73	0.12											
7	Al	15	2.70	6.73	4.98	1.75	1.92	1.33	6.02E+22	1.16E-01	7.99E-02	0.116	0.080	1.74E-04	1.82E-04	1.20E-04	1.27E-04
8	Air		0.00121	4.98	4.85	0.13											
9	Maylar		1.38	4.85	4.35	0.50											
10	Air		0.00121	4.35	3.81	0.54											
11	Maylar		1.38	3.81	3.29	0.52											