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Evaluation of fusion-evaporation cross-section calculations

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ABSTRACT

Calculated fusion-evaporation cross sections from five different codes are compared to experimental data. The present comparison extents over a large range of nuclei and isotopic chains to investigate the evolution of experimental and calculated cross sections. All models more or less overestimate the experimental cross sections. We found reasonable agreement by using the geometrical average of the five model calculations and dividing the average by a factor of 11.2. More refined analyses are made for example for the ^{100}Sn region.

1. Introduction

On Earth, 255 stable nuclides are available for nuclear physics studies. In addition, 31 quasi stable nuclides having a half-life comparable to or longer than the age of the Earth exist. All other nuclei must be created in order to be usable for experimental studies. Different types of nuclear reactions exist to produce these unstable and radioactive nuclei.

Two methods can be used to create basically all bound or quasi bound (i.e. bound for a short laps of time) nuclei lighter than the projectile or target nuclei: spallation or fragmentation. Spallation reactions are usually induced by light particles (protons or neutrons) on heavier stable target nuclei. In these spallation reactions, the incident light projectile ejects nucleons from the target nucleus by nucleon-nucleon collisions and the excited fragment (often called pre-fragment) evaporates light particles (protons, neutrons, α particles) to get rid of excitation energy. With e.g. incident proton energies of a few hundred MeV up to 1 or 2 GeV, basically all nuclei, bound or quasi bound, but lighter than the target nucleus itself, can be produced. However, as these spallation reactions are basically always "thick-target" reactions, the reaction products have to diffuse out of the target to become useful. As this takes some time and depends very sensitively on the chemistry of the element of interest, short-lived nuclides of condensable elements are very difficult to produce by this means.

Fragmentation reactions employ heavy-ion induced reactions on different heavy-ion targets. Therefore, target as well as projectile fragmentation can be used. Target fragmentation suffers from the same problem as spallation reactions: the products have to diffuse from the target itself. Therefore, this process is again limited to relatively volatile isotopes with sufficiently long half-lives. In projectile fragmentation reactions, one can use "thin targets" which allows the products to recoil out of the target due to the incident projectile energy. This approach is basically universal and allows all nuclides lighter than the projectile to be produced. However, there are at least two drawbacks of projectile fragmentation: i) it needs high-energy heavy-ion accelerators and ii) the beam quality of these fragment beams is rather bad.

In deep-inelastic or transfer reactions, two heavy nuclei interact with each other at energies around the Fermi energy (typically 20–60 MeV/A) and nucleons are transferred from one nucleus to the other producing thus more or less neutron-rich or neutron-deficient isotopes. However, as the number of nucleons transferred is limited, mainly nuclei relatively close to stability in the vicinity of the projectile and the target nuclei are produced.

In nuclear fission, a very heavy nucleus, e.g. ^{238}U or ^{252}Cf, fissions by creating two medium-mass nuclides. This fission process can be induced (e.g. by proton, neutron or γ-ray impact) or spontaneous. Due to the curvature of the nuclear valley of stability, the heavy fissioning nuclei have always an excess of neutrons compared to lighter nuclei. Therefore, nuclear fission always produces neutron-rich isotopes in the mass range of A ≈ 50–170.

Finally, neutron-deficient nuclides can be produced by fusing two lighter nuclei. In this case, the situation is reversed compared to fission. The light stable nuclei that interact are proton-rich compared to the heavier nuclei in the valley of stability. For example, the reaction of a stable ^{40}Ca nucleus with a stable ^{58}Ni nucleus produces as the compound nucleus, i.e. the sum of all nucleons, ^{98}Cd, a nucleus which is 8 neutrons more neutron-deficient than the most neutron-deficient stable isotope of the element cadmium.

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Table 1
Experimental cross sections from literature. Given are the mass and charge number of the nuclei of interest, the mass and charge number of the projectile and target nuclei, respectively, the incident beam energy, the experimental cross section and its error if available, and the reference.

A	Z	A_p	Z_p	A_t	Z_t	E (MeV)	Cross section (mb)	Error (mb)	Ref.
Light N ≈ Z nuclei									
64	30	12	6	54	26	37	1.60E+02	7.00E+00	[21]
64	31	54	26	12	6	150	7.90E+01		[22]
64	32	40	20	27	13	102	4.00E−01	6.00E−02	[23]
64	32	54	26	12	6	165	6.40E−01	7.00E−02	[21]
64	32	54	26	12	6	150	3.40E−01	9.00E−02	[22]
64	32	54	26	12	6	165	5.00E−01	3.00E−01	[24]
64	32	12	6	58	28	40	2.00E−01	5.00E−02	[25]
68	34	58	28	12	6	175	3.80E−02	1.60E−02	[24]
68	34	58	28	12	6	220	2.00E−01	5.00E−02	[26]
72	36	16	8	58	28	55	1.00E−01	3.00E−02	[25]
72	36	58	28	16	8	170	6.00E−02	2.50E−02	[27]
76	38	54	26	24	12	175	1.00E−02	5.00E−03	[24]
80	40	58	28	24	12	190	1.00E−02	5.00E−03	[28]
80	39	58	28	24	12	190	2.00E+00	1.00E+00	[28]
80	38	58	28	24	12	190	4.40E+01	4.00E+00	[28]
^{100}Sn region									
95	45	58	28	50	24	250	1.10E+00	4.00E−01	[29]
97	45	58	28	50	24	250	3.40E+00	2.00E−01	[29]
98	46	58	28	50	24	250	2.20E+01	2.00E+00	[29]
98	47	58	28	50	24	250	3.00E−01	6.00E−02	[29]
99	47	58	28	50	24	250	3.60E+00	4.00E−01	[29]
99	48	58	28	50	24	249	3.20E−02	2.00E−02	[30]
99	48	58	28	50	24	249	3.20E−02	2.00E−02	[30]
99	48	50	24	58	28	225	2.50E−02	8.00E−03	[30]
99	48	58	28	58	28	348	1.10E−02	8.00E−03	[30]
99	48	58	28	58	28	371	2.80E−02	2.10E−02	[30]
99	48	58	28	58	28	394	3.10E−02	2.00E−02	[30]
100	47	58	28	50	24	250	3.90E+00	2.00E−01	[29]
100	47	50	24	58	28	225	3.90E+00		[29]
100	48	50	24	58	28	225	1.00E+00		[31]
100	49	50	24	58	28	225	1.00E−03		[31]
100	49	58	28	50	24	319	2.60E−03		[30]
100	49	58	28	58	28	325	8.00E−04		[30]
100	49	58	28	58	28	348	1.70E−03		[30]
100	49	58	28	58	28	371	1.70E−03		[30]
100	49	58	28	58	28	394	1.60E−03		[30]
100	50	50	24	58	28	225	4.00E−05		[31]
101	47	58	28	50	24	250	4.70E+01	3.00E+00	[29]
101	48	58	28	50	24	250	1.80E+01	2.00E+00	[29]
101	50	58	28	50	24	249	1.60E−05	4.00E−06	[30]
101	50	58	28	50	24	250	1.00E−05		[30]
101	50	58	28	58	28	325	9.00E−06	4.00E−06	[30]
101	50	58	28	58	28	348	1.30E−05	3.00E−06	[30]
101	50	58	28	58	28	371	2.80E−05	1.00E−05	[30]
101	50	58	28	58	28	394	7.00E−06	4.00E−06	[30]
102	48	58	28	50	24	250	6.30E+01	1.90E+01	[29]
102	49	58	28	50	24	249	9.00E−01	5.00E−01	[30]
102	49	58	28	50	24	249	1.30E+00	7.00E−01	[30]
102	49	58	28	50	24	348	1.10E+00	6.00E−01	[30]
102	49	58	28	58	28	325	1.20E+00	6.00E−01	[30]
102	49	58	28	58	28	348	1.20E+00	6.00E−01	[30]
102	49	58	28	58	28	348	7.00E−01	3.00E−01	[30]
102	49	58	28	58	28	371	1.00E+00	5.00E−01	[30]
102	49	58	28	58	28	394	9.00E−01	4.00E−01	[30]
102	50	58	28	52	24	225	2.00E−03		[32]
103	47	58	28	50	24	250	3.60E+00	4.00E−01	[29]
103	48	58	28	50	24	250	2.70E+01	2.00E+00	[29]
103	49	58	28	50	24	250	6.40E+00	8.00E−01	[29]
104	48	58	28	50	24	250	1.79E+02	7.00E+00	[29]
104	49	58	28	50	24	250	5.80E+01	1.60E+01	[29]
104	50	58	28	50	24	250	1.80E+00	2.00E−01	[29]
105	49	58	28	50	24	250	1.16E+02	6.00E+00	[29]
105	50	58	28	50	24	250	1.00E+01	2.00E+00	[29]
Ba nuclei									
114	56	58	28	58	28	222− −248	2.00E−04	1.00E−04	[33]
114	56	58	28	58	28	203− −244	2.00E−04	1.00E−04	[34]
116	56	58	28	60	28	209− −249	3.00E−03	1.00E−03	[34]
116	56	58	28	63	29	249− −284	8.00E−04	4.00E−04	[34]
117	56	58	28	63	29	249− −284	5.50E−02	2.00E−02	[34]
118	56	58	28	63	29	249− −284	1.90E−02	6.00E−03	[34]
Heavier nuclei									
171	79	78	36	96	44	361	1.10E−03		[35]
171	79	78	36	96	44	359	2.00E−03		[35]
171	79	78	36	96	44	363	6.00E−04		[35]
170	79	78	36	96	44	386	9.00E−05		[35]
173	80	78	36	102	46	384	4.00E−06		[35]
172	80	78	36	96	44	361	4.00E−06		[35]
171	80	78	36	96	44	361	2.00E−06		[35]
176	81	78	36	102	46	384	3.00E−06		[35]
172	80	78	36	96	44	375	9.00E−06		[36]
173	80	80	36	96	44	400	1.50E−05		[36]
174	80	80	36	96	44	375	3.30E−04		[36]
Proton emitter: pn channel									
185	83	92	42	95	42	410	1.00E−04		[37]
185	83	92	42	95	42	420	6.00E−05		[38]
Proton emitter: p2n channel									
109	53	58	28	54	26	195	1.00E−02		[39]
109	53	58	28	54	26	220	1.60E−02	4.00E−03	[40]
109	53	58	28	54	26	240	3.00E−03		[41]
109	53	58	28	54	26	229	5.00E−02		[42]
109	53	58	28	54	26	250	4.00E+01	$+4.00E+01$ $-2.00E+01$	[43]
109	53	58	28	58	28	250	3.00E+01	$+3.00E+01$ $-1.50E+01$	[43]
113	55	58	28	58	28	250	3.00E+01		[43]
147	69	58	28	92	42	260	1.80E−02		[44]
151	71	58	28	96	44	266	7.00E−02	1.00E−02	[45]
161	75	58	28	106	48	270	6.30E−03	1.80E−03	[46]
167	77	78	36	92	42	357	1.10E−01		[47]
171	79	78	36	96	44	389	2.00E−03		[47]
171	79	78	36	96	44	370	6.00E−04		[48]
171	79	78	36	96	44	361	1.10E−03		[35]
171	79	78	36	96	44	359	2.00E−03		[35]
171	79	78	36	96	44	363	6.00E−04		[35]
177	81	78	36	102	46	370	3.00E−05		[49]
Proton emitter: p3n channel									
108	53	58	28	54	26	240− −255	5.00E−04		[50]
112	55	58	28	58	28	259	5.00E−04		[51]
146	69	58	28	92	42	287	1.00E−03		[52]
150	71	58	28	96	44	297	2.56E−03		[53]
150	71	58	28	96	44	292	3.05E−03		[54]
160	75	58	28	106	48	300	1.00E−03		[55]
166	77	78	36	92	42	384	6.30E−03		[47]
176	81	78	36	102	46	384	3.00E−06		[35]
Proton emitter: p4n channel									
117	57	58	28	64	30	310	2.00E−04		[56]
117	57	58	28	64	30	295,310	2.40E−04	$+2.40E-04$ $-1.20E-04$	[57]
131	63	40	20	96	44	222	9.00E−05		[58]
141	67	54	26	92	42	285,305	2.50E−04		[58]
141	67	54	26	92	42	315	3.00E−05		[59]
145	69	58	28	92	42	315	5.00E−04		[60]
145	69	92	42	58	28	512	2.00E−04		[61]
155	73	58	28	102	46	315,320	6.00E−05		[62]
165	77	78	36	92	42	384	2.00E−04		[47]
Proton emitter: p5n channel									
130	63	78	36	58	28	432	9.00E−06	$+9.00E-06$ $-4.50E-06$	[63]
140	67	54	26	92	42	315	3.00E−06		[59]
Proton emitter: p6n channel									
121	59	36	18	92	42	240	3.00E−07	$+3.00E-07$ −1. (0E−07	[64]
135	65	50	24	92	42	310	3.00E−06		[65]