National University of Mongolia

NUCLEAR RESEARCH CENTER

Systematical Analysis of (n,2n) Reaction Cross Sections for 14 – 15 MeV Neutrons

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Introduction

- Fast neutron induced nuclear reaction cross section data are necessary for both **nuclear energy technology** and the **understanding of fundamental nuclear physics problems**.
  - ➢ Radioactive nuclides produced in the reactor usually have short half-life.
  - ➢ So, direct measurement of their neutron cross sections is difficult. Therefore, model formulae are important to predict these cross sections theoretically.
- Biomedical applications such as production of radioisotopes and cancer therapy: **$^{100}Mo(n,2n)^{99}Mo$**
- Accelerator driven transmutation of the long-lived radioactive nuclear wastes to short lived or stable isotopes
- Material irradiation experiments concerning research and development for fusion reactor technology.
- Study on the existence of Dineutron.

Introduction

The purpose of this work:

- In this work, in the framework of the statistical model we deduced some theoretical formulae for the (n,2n) cross section using the evaporation model, constant nuclear temperature approximation and Weizsäker’s formula for binding energy.
- Known experimental data of the (n,2n) cross sections at 14 - 15 MeV neutrons are analyzed with the help of the obtained formulae.

Statistical Model formulae

In the framework of the statistical model based on the Bohr's assumption of a compound mechanism the cross section formula for (n,x) reaction is expressed as:

$$\sigma(n,x)=\sigma_c(n)\frac{2S_x+1}{2S_n+1}\frac{M_x}{M_n}e^{\frac{Q_{n,x}-V_x}{\Theta}}\left\{\frac{1-\frac{W_{n,x}}{\Theta}e^{-\frac{W_{n,x}}{\Theta}}-e^{-\frac{W_{n,x}}{\Theta}}}{1-\frac{E_n}{\Theta}e^{-\frac{E_n}{\Theta}}-e^{-\frac{E_n}{\Theta}}}\right\}$$

≈ 1

G.Khuukhenkhuu *et al. J NUCL SCI TECHNOL*, Supp. 2, Vol. 1, 2001, pp. 782-784.

Following formula, which is similar to Cuzzocrea's *et al*. and Ericson's formulas, is obtained:

$$\sigma(n,2n)=\sigma_c(n)\frac{2S_{2n}+1}{2S_n+1}\frac{M_{2n}}{M_n}e^{\frac{Q_{n,2n}-V_{2n}}{\Theta}}$$

Here: $\sigma_c(n)$ is the compound nucleus formation cross section;

$$\sigma_c(n)=\pi(R+\lambda\!\!\!^{-}_n)^2$$

S_n and S_{2n} are the spin of the incident neutron and emitted $2n$ respectively;
M_n and M_{2n} are the masses of the neutron and $2n$ respectively;
$Q_{n,2n}$ is the reaction energy;
V_{2n} is the Coulomb potential for $2n$;
Θ is the thermodynamic temperature;

Here: R is the radius of the target nucleus;
$\lambda\!\!\!^{-}_n$ is the wavelength of the incident neutron divided by 2π.

Statistical Model formulae

The Coulomb potential for neutrons $V_{2n} = 0$. So, taking into account the spin and mass of neutrons from the formula (2) we get:

$$\sigma(n,2n) = 4\pi(R + \lambdabar_n)^2 e^{\frac{Q_{n,2n}}{\Theta}}$$

Using the Weizsäker's formula for binding energy we can obtain following expressions for the target and residual nuclei:

$$E_i = \alpha A - \beta A^{2/3} - \gamma \frac{Z^2}{A^{1/3}} - \xi \frac{(N-Z)^2}{A} \pm \frac{\delta_i}{A^{3/4}}$$

Reaction energy: $Q_{n2n} = E_f - E_i$

$$E_f = \alpha(A-1) - \beta(A-1)^{2/3} - \gamma \frac{Z^2}{(A-1)^{1/3}} - \xi \frac{(N-1-Z)^2}{A-1} \pm \frac{\delta_f}{(A-1)^{3/4}}$$

(n,2n) cross section formula:

$$\sigma(n,2n) = 4\pi(R + \lambdabar_n)^2 \exp\left\{ \frac{-\alpha - \beta\left((A-1)^{2/3} - A^{2/3}\right) - \gamma\left(\frac{Z^2}{(A-1)^{1/3}} - \frac{Z^2}{A^{1/3}}\right) - \xi\left(1 - \frac{4Z^2}{A(A-1)}\right) \pm \frac{\delta_f}{(A-1)^{3/4}} \mp \frac{\delta_i}{A^{3/4}}}{\Theta} \right\}.$$

Statistical Model formulae

In the case of A >> 1 can be obtain the following formulae for systematical analysis of the (n,2n) cross sections:

$$\frac{\sigma(n,2n)}{\pi(R+\bar{\lambda}_n)^2} = C\exp(-K\frac{Z^2}{A^2})$$

Here: *Z* and *A* are proton and mass numbers of the target nuclei;

The parameters *K* and *C* are expressed as:

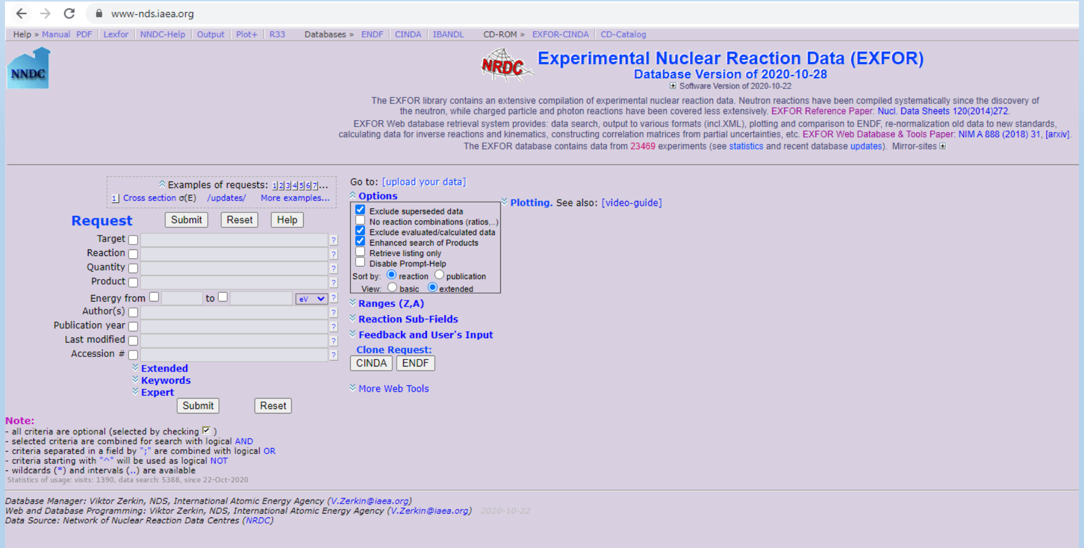
$$K = \frac{4\xi}{\Theta}$$

$$C = 4\exp\left\{\frac{-\alpha-\beta\left((A-1)^{2/3}-A^{2/3}\right)-\gamma\left(\frac{Z^2}{(A-1)^{1/3}}-\frac{Z^2}{A^{1/3}}\right)\pm\frac{\delta_f}{(A-1)^{3/4}}\mp\frac{\delta_i}{A^{3/4}}+\xi}{\Theta}\right\}$$

Systematical analysis of (n,2n) reaction cross sections

In this paper the library of neutron cross sections known as EXFOR, IAEA.
We've analyzed **147** experimental (n,2n) cross section data at the neutron energy of 14 – 15 MeV from EXFOR.

https://www-nds.iaea.org/exfor/



Target nuclei	A	N	Z	E, (MeV)	σ(n,2n) (mb)	Δσ(n,2n) (mb)	Authors
Li	6	3	3	14.06	78.1	4.1	Mather *et al.* (1969)
Li	7	4	3	14.06	49.7	3.2	Mather *et al.* (1969)
Be	9	5	4	14.1	478	14	Takahashi *et al.* (1987)
B	11	6	5	14.06	19	4	Mather *et al.* (1969)
C	12	6	6	14.1	6	6	Ashby *et al.* (1958)
C	13	7	6	14.28	255	25	Frehaut *et al.* (1978)
N	14	7	7	14.64	7.28	0.29	Sakane *et al.* (2001)
F	19	10	9	14.69	50.4	2.7	Ikeda *et al.* (1988)
Na	23	12	11	14.87	41.7	0.9	Hanlin *et al.* (1992)
Al	27	14	13	14.09	7.8	0.5	Wallner *et al.* (2003)
P	31	16	15	14.64	13.2	0.71	Sakane *et al.* (2001)
Cl	35	18	17	14.57	10.28	0.8	Molla *et al.* (1997)
K	39	20	19	14.66	4.55	0.25	Filatenkov (2016)
Ca	40	20	20	14.69	8	2	Braun *et al.* (1968)
Ca	48	28	20	14.7	850	35	Anders *et al.* (1985)
Sc	45	24	21	14.8	320	24	J.Luo *et al.* (2013)
Ti	46	24	22	14.72	42	2.3	Ikeda *et al.* (1998)
V	50	27	23	14.3	258	39	Greenwood *et al.* (1992)
Cr	50	26	24	14.6	21.2	1.2	Ribansky *et al.* (1985)
Cr	52	28	24	14.47	351	14.49	Mannhart *et al.* (2007)
Mn	55	30	25	14.58	812.9	28.9	Hanlin *et al.* (1980)
Fe	54	28	26	14.64	9	1.8	Sakane *et al.* (2001)
Fe	56	30	26	14.82	545.4	27.3	Wallner *et al.* (2011)
Hg	196	116	80	14.68	2220	170	Kasugai *et al.* (2001)
Hg	198	118	80	14.68	2060	130	Kasugai *et al.* (2001)
Hg	204	124	80	14.68	2140	100	Kasugai *et al.* (2001)
Tl	203	122	81	14.7	1970	110	Kiraly *et al.* (2001)
Tl	205	124	81	14.76	1895	143	Frehaut *et al.* (1980)
Pb	204	122	82	14.5	2161	172.45	Filatenkov (2016)
Pb	206	124	82	14.76	2028	155	Frehaut *et al.* (1980)
Pb	207	125	82	14.76	1976	161	Frehaut *et al.* (1980)
Pb	208	126	82	14.1	2380	140	Simakov *et al.* (1992)
Bi	209	126	83	14.74	2293	371.47	Filatenkov (2016)
Th	232	142	90	14.7	1177	78.86	Chatani *et al.* (1991)
U	238	146	92	14.62	732	58	Raics *et al.* (1990)

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Systematical analysis of (n,2n) reaction cross sections

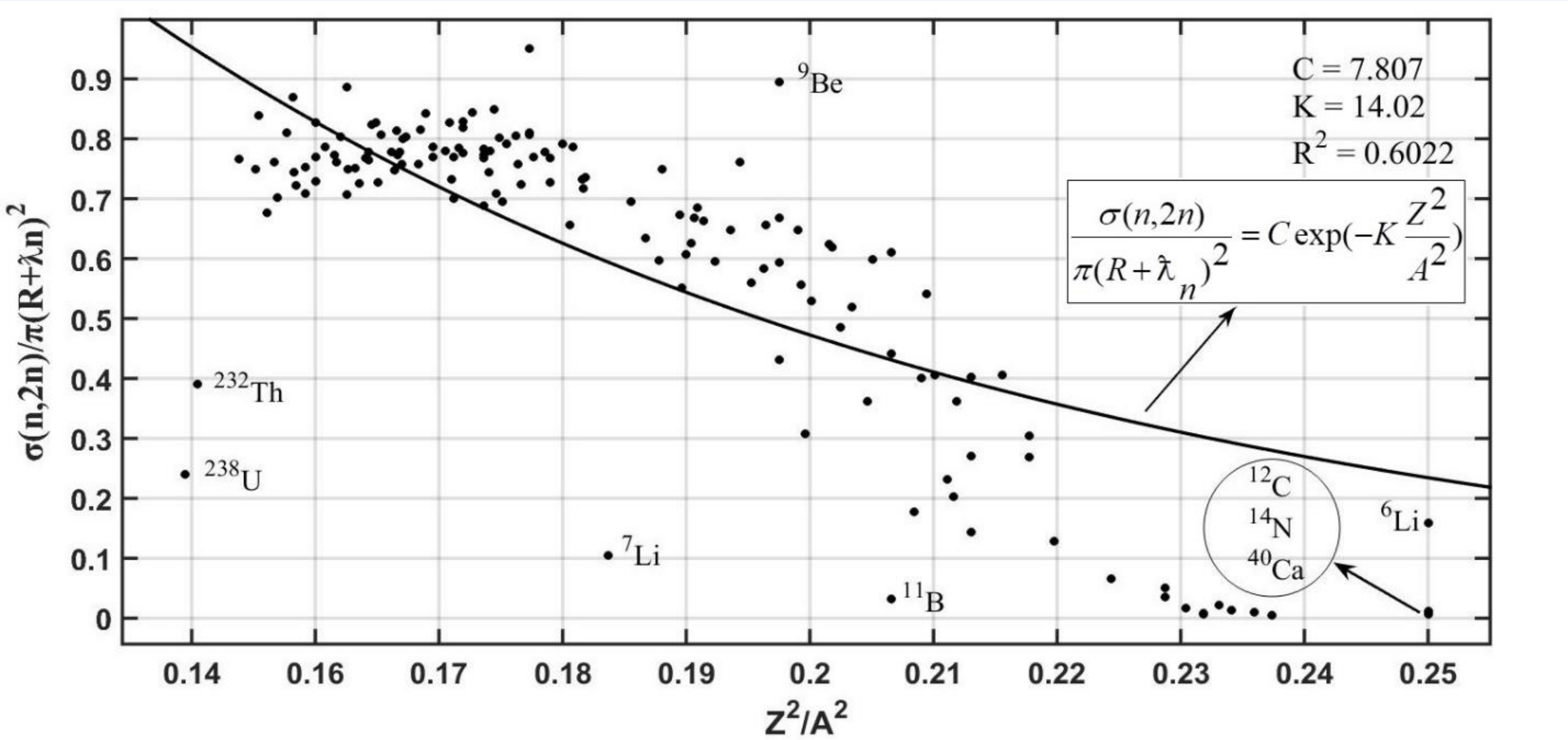

Figure 1. The dependence of the reduced (n,2n) cross sections on parameter Z^2/A^2

Discussions

A total cross section for fast neutrons can be approximated as following:

$$\sigma_n^{tot} = \sigma^{tot}(n,2n) + \sigma^{tot}(n,\gamma) + \sigma^{tot}(n,\alpha) + \sigma^{tot}(n,p) + \sigma^{tot}(n,3n) + \ldots \approx \sigma^{tot}(n,2n) \approx \pi(R + \lambda\!\!\!^{-}_n)^2.$$

^{197}Au: $$\sigma_n^{tot} = \underset{2154mb}{\sigma^{tot}(n,2n)} + \underset{1.1mb}{\sigma^{tot}(n,\gamma)} + \underset{0.35mb}{\sigma^{tot}(n,\alpha)} + \underset{2.2mb}{\sigma^{tot}(n,p)} + \underset{61mb}{\sigma^{tot}(n,3n)} + \ldots$$

^{127}I: $$\sigma_n^{tot} = \underset{1655mb}{\sigma^{tot}(n,2n)} + \underset{1.12mb}{\sigma^{tot}(n,\gamma)} + \underset{1.2mb}{\sigma^{tot}(n,\alpha)} + \underset{11.7mb}{\sigma^{tot}(n,p)} + \underset{38.5mb}{\sigma^{tot}(n,3n)} + \ldots$$

if we take into account the pre-equilibrium and direct mechanisms the total (n,2n) cross section can be obtained as follows:

$$\sigma_n^{tot} \approx \sigma^{tot}(n,2n) \approx \pi(R + \lambda\!\!\!^{-}_n)^2 \approx \sigma^{comp}(n,2n) + \sigma^{pre}(n,2n) + \sigma^{dir}(n,2n)$$

$$\sigma^{nonstat}(n,2n) = \sigma^{pre}(n,2n) + \sigma^{dir}(n,2n)$$

$$\sigma^{nonstat}(n,2n) = \sigma^{tot}(n,2n) - \sigma^{comp}(n,2n) = \pi(R + \lambda\!\!\!^{-}_n)^2 - C\pi(R + \lambda\!\!\!^{-}_n)^2 \exp(-K\frac{Z^2}{A^2}) = \pi(R + \lambda\!\!\!^{-}_n)^2 \left(1 - C\exp(-K\frac{Z^2}{A^2})\right).$$

The reduced (n,2n) cross section is expressed as:

$$\frac{\sigma^{nonstat}(n,2n)}{\pi(R + \lambda\!\!\!^{-}_n)^2} = \left(1 - C\exp(-K\frac{Z^2}{A^2})\right).$$

Discussions

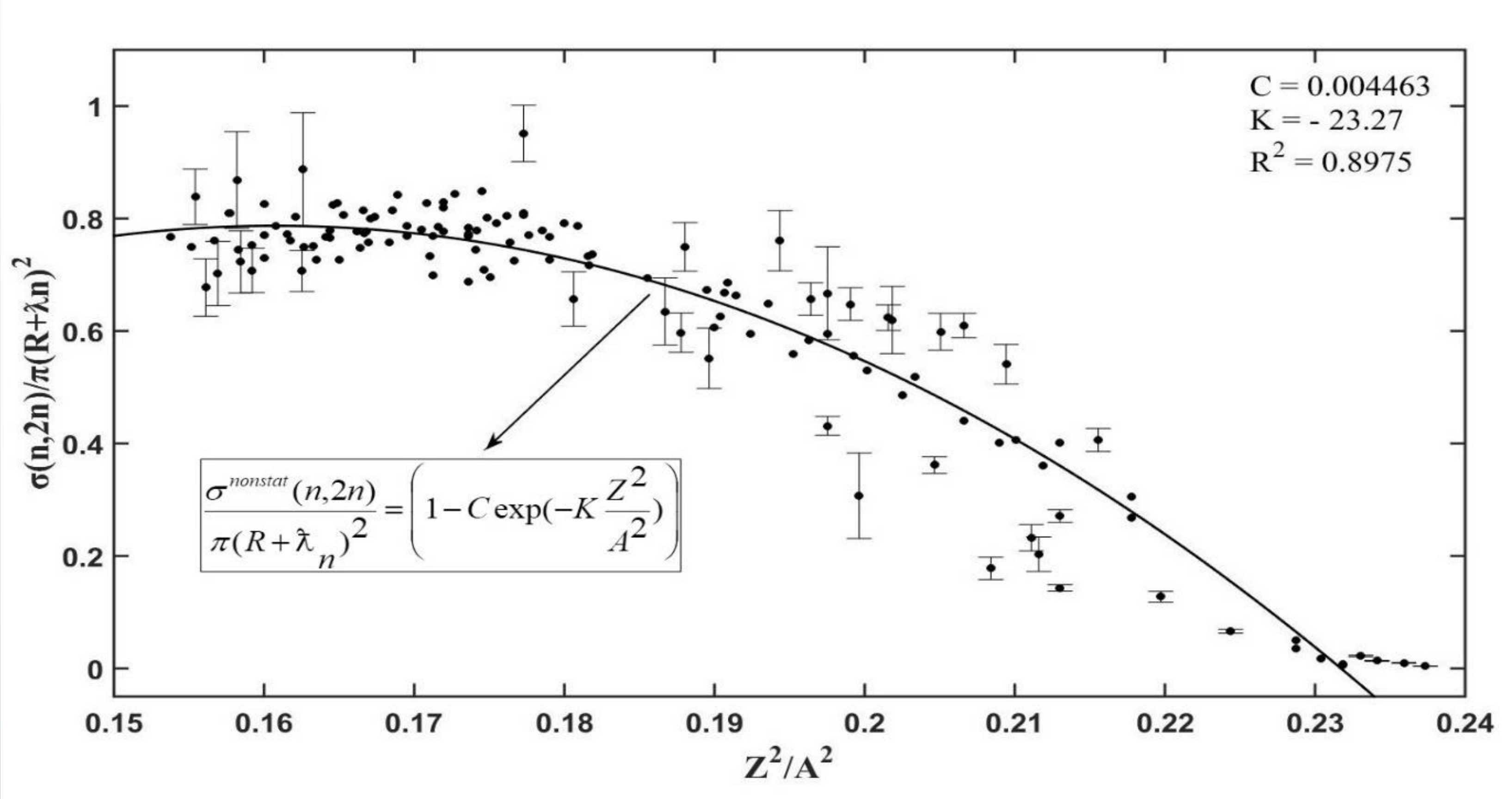

Figure 2. The dependence of the reduced (n,2n) cross sections on parameter Z^2/A^2

The very heavy nuclei such as ^{238}U, ^{232}Th and very light nuclei ^{6,7}Li, ^{9}Be, ^{11}B, ^{12}C, ^{14}N are excluded from the consideration. Also, double magic nucleus ^{40}Ca is not considered.

Conclusions

1. In the framework of the statistical model a theoretical formula for the (n,2n) reaction cross section was deduced. In addition, a non-statistical share of the total neutron cross section was obtained.

2. Known experimental data of the (n,2n) cross sections for 14 – 15 MeV neutrons were analyzed using the obtained formulae. It was shown that the non-statistical share of the total cross section is in agreement with experimental data.

Thank you for your attention