Reduced Sputtering Yields Induced by Fast Neutrons

1999 Chinese Phys. Lett. 16 844

(http://iopscience.iop.org/0256-307X/16/11/024)

Reduced Sputtering Yields Induced by Fast Neutrons *

YE Bang-jiao(叶邦角)[1], FAN Yang-mei(范扬眉)[1], Yoshimi KASUGAI[2], Yujiro IKEDA[2], ZHOU Xian-yi(周先意)[1,3], HAN Rong-dian(韩荣典)[1]
[1]Department of Modern Physics, University of Science and Technology of China, Hefei 230026
[2]Center of Neutron Science, Japan Atomic Energy Research Institute, Tokai-mura, Naka-gun, Ibaraki-ken 319-11, Japan
[3]International Centre for Materials Physics, Chinese Academy of Sciences, Shenyang 110015

(Received 5 April 1999)

The reduced sputtering yield (Y_n^R) of materials induced by fast neutron is presented. Based on the experimental Y_n^R results for (n, 2n), (n, p), (n, α) and (n, np) reactions, the value of Y_n^R for (n, non-elastic) reaction is deduced by using data of cross sections in JENDL-3.2 and ENDF/B-VI. The value of Y_n^R for (n, n) reaction is predicted by relation between Y_n^R and the mean projected ranges of recoil nuclides. Combining both Y_n^R for (n, n) and (n, non-elastic) reactions, the total Y_n^R is obtained. Systematics of Y_n^R for (n, non-elastic), (n, n) and (n, total) reactions have been demonstrated.

PACS: 79.20.−m, 25.40.−h, 28.52.Fa, 24.90.+d

When energetic particles bombard a solid and the energy is transferred to a surface or a near-surface atom, sputtering can occur. Neutron sputtering, i.e., the removal of atoms (or clusters and microsize particles) from the surfaces during neutron bombardment, is connected to radiation damage mechanism and ranges of energetic ions in solid. In a fusion reactor, very high neutron fluxes on first wall/blanket materials are expected during normal operations. An accurate calculation of first wall/blanket sputtering induced by neutrons is very important for design of fusion reactor and its maintenance.

Unfortunately, the neutron sputtering yields are still poorly investigated. The experimental data on the neutron sputtering yield are very scarce and contradictory. Different measurements on Nb, for example, had different results widely varying in the sputtering yields[1−3] and had a big difference from the results predicted by theory. Usually, the experimental data were much higher than those of the theoretical predictions.[4] The highest reported sputtering yields have been associated with the observation of micron sized "chunks" of target material.[5,6]

In order to get a basic understanding of neutron sputtering, the authors have made a systematic study on the sputtering yields (Y_n) for 24 materials: F, Mg, Al, Sc, Ti, V, Cr, Fe, Co, Ni, Cu, Zr, Nb, Mo, Pd, Ag, Cd, In, Ta, Re, Pt, Au, Pb, and SS316 at the Fusion Neutron Facility, Japan Atomic Energy Research Institute.[7] The sputtered radioactive materials deposited on the collectors were investigated by the neutron activation analysis. The values of Y_n for 57 reactions belonging to (n, 2n), (n, α), (n, p) and (n, np) have been measured. A reduced sputtering yield (Y_n^R), that is, Y_n divided by the value of cross section, was introduced to specialize the sputtering process. The systematics for Y_n^R as a function of the atomic number (Z_C) of target materials have been found for (n, 2n), (n, p), (n, α) and (n, np) reactions. A simple power function $Y_n^R = aZ_C^b$ was very good for describing the systematics, where a and b are fitting parameters depending on the type of reactions, respectively. Most of the deviations between measured values and systematic results are within the range of 25%.

When the nuclear excitation is high enough, more than one particle may evaporate from the compound nucleus. Such reaction is termed non-elastic, that is, (n, non.) reaction. The typical of Y_n^R (n, non.) reactions include (n, n′), (n, 2n), (n, p), (n, α), (n, np) and so on. The value of Y_n^R for (n, non.) reaction can be deduced from (n, 2n), (n, p), (n, α), and (n, np) reactions due to the domination of 4 reactions in the non-elastic process, especially for high Z_C materials. We introduce a sign σ_4 to represent the sum of cross sections of these 4 reactions, that is,

$$\sigma_4 = \sigma_{(n,2n)} + \sigma_{(n,p)} + \sigma_{(n,\alpha)} + \sigma_{(n,np)}. \quad (1)$$

Let σ (n, non.) represents total cross section of non-elastic reaction. The ratio between σ_4 and $\sigma_{(n,non.)}$ varies with the atomic number Z_C as shown in Fig. 1. The values of the cross sections in Fig. 1 are taken from JENDL-3.2 and ENDF/B-VI.[8] It shows that ratio $\sigma_4/\sigma_{(n,non.)}$ increases with increase of Z value. When $Z > 13$ the ratio $\sigma_4/\sigma_{(n,non.)}$ is larger than 0.5. As an approximate consideration, the value Y_n^R for (n, non.) reaction can be obtained as follows,

$$Y^R_{n(n,non.)} = \frac{\sum_b^{all} Y^R_{n,(n,b)}\sigma_{(n,b)}}{\sigma_{(n,non.)}} \approx \frac{\sum_b^{4} Y^R_{n,(n,b)}\sigma_{(n,b)}}{\sigma_4}, \quad (2)$$

*Supported by the Returned Scientists' Foundation of Chinese Academy of Sciences.

Table 1. Fitting parameters a and b of Y_n^R systematics for different reactions.

	(n, 2n)	(n, p)	(n, α)	(n, np)	(n, non.)	(n, n)	(n, total)
a	0.02938	0.02667	0.01198	0.17481	0.10773	0.12187	0.08811
b	−3.5526	−3.3889	−2.9149	−3.9485	−3.8749	−3.5998	−3.6162

where the summation over all means for all (n, non.) reactions and over 4 means for the (n, 2n), (n, p), (n, α) and (n, np) reactions, respectively. Except for very low Z_C value, this approximation does not bring a great deviation for the sputtering process of (n, non.) reaction. The Y_n^R values of (n, non.) reactions for 42 materials have been calculated as shown in Fig. 2. The systematics of the Y_n^R for (n, non.) reaction can be deduced by fitting the Y_n^R values with Z_C of the materials. The values of the experimental Y_n^R for (n, 2n) and (n, α) reactions are also shown in Fig. 2. The fitting parameters a and b are given in Table 1.

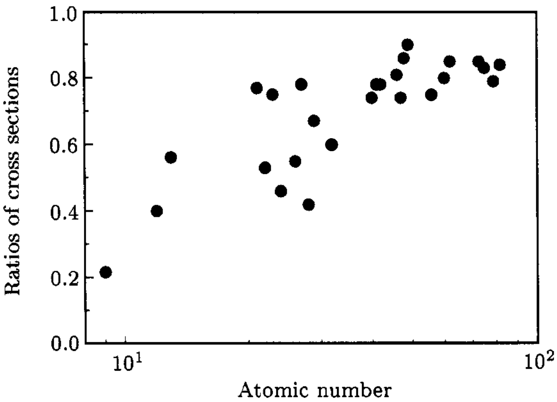

Fig. 1. Ratios of cross sections between 4 main reactions and total non-elastic reaction. The 4 main reactions are (n, 2n), (n, p), (n, α) and (n, np). The data take from JENDL-3.2 and ENDF/B-VI.

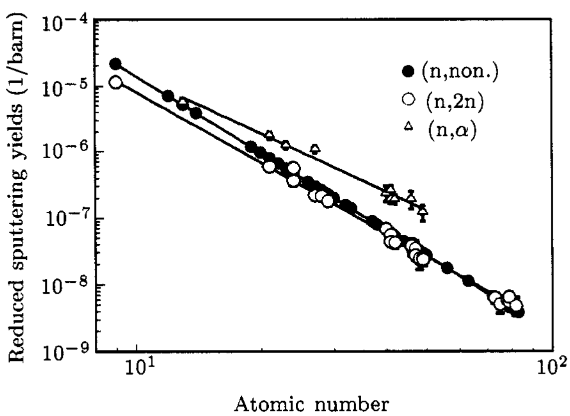

Fig. 2. Experimental Y_n^R for (n, 2n) and (n, α) reactions and deduced Y_n^R for (n, non.) reactions.

Sputtering process can generally be described by using the concepts developed for describing radiation damage in bulk of a material.[9] Based on the theoretical consideration, the forward sputtering yield is given as follows:[10]

$$Y_n = N\sigma(E_n)\langle R(\overline{T})\rangle, \tag{3}$$

where $\sigma(E_n)$ is the cross section of reaction between the incident neutron and the atoms in the solid, N is the density of atoms in the solid, $\langle R(\overline{T})\rangle$ is the mean projected range of a primary knockon atom starting with a mean kinetic energy $\overline{T}$.

For an elastic scattering process induced by fast neutrons which may be regarded as (n, n) reaction, the maximum transferred energy is

$$T_{\max} = \frac{4A_D E_n}{(1+A_D)^2}, \tag{4}$$

where E_n is the incident neutron energy and A_D is the mass number of recoil atom. The mean kinetic energy in the elastic scattering process is about $\overline{T}_{(n,n)} = T_{\max}/2$. For a nuclear reaction C (n, b)D, where C, D and b are the target atom, the product atom, and the light particles which are emitted in the reaction, where for a short time a compound nucleus is formed, the mean transferred energy is about $\overline{T}_{(n,b)}$, where b = 2n, p, α, etc. According to nuclear reaction dynamics, $\overline{T}_{(n,b)}$ is calculated by average scattering angle θ,

$$\overline{T}_{(n,b)} = \frac{A_D E_n}{(A_D + A_b)^2} + \frac{A_b Q + (A_b - 1)E_n}{A_D + A_b}, \tag{5}$$

where A_C, A_D and A_b are the mass numbers of the target atom, the recoil atom and the emitted light particles. Q is the Q-value of a nuclear reaction process. The Y_n^R of elastic process can be deduced by the following relation:

$$\frac{Y^R_{n(n,n)}}{Y^R_{n,(n,p)}} = \frac{\langle R(\overline{T}_{(n,n)})\rangle}{\langle R(\overline{T}_{(n,p)})\rangle}. \tag{6}$$

The theoretical mean ranges have been calculated by using the results of Schiott[11] for the low and intermediate energy ranges.

$$\langle R(T)\rangle\left(\frac{\mu g}{\text{cm}^2}\right) = \begin{cases} C_l A_D\left(\dfrac{Z_C^{2/3}+Z_D^{2/3}}{Z_C Z_D}\overline{T}(\text{keV})\right)^{2/3}, \\ \varepsilon < 0.1, \\ C_i A_D \dfrac{Z_C^{2/3}+Z_D^{2/3}}{Z_C Z_D}\overline{T}(\text{keV}), \\ 0.5 < \varepsilon < 10, \end{cases} \tag{7}$$

where ε is defined as a reduced energy

$$\varepsilon = \frac{32.5 A_D}{(A_C + A_D)Z_C Z_D (Z_C^{2/3} + Z_D^{2/3})^{1/2}} T(\text{keV}), \tag{8}$$

with Z_C and Z_D being the atomic numbers of the target and the recoil atoms, respectively. C_l and C_i are obtained from the results of Schiott.

For most of the targets, the $\langle R(\overline{T})\rangle$ for (n, n) reaction is approximately two times larger than that of (n, p) reaction. In the calculation, 30 materials for Z from 12 to 74 are selected. The values of Y_n^R for elastic process are shown in Fig. 3. Systematics of the Y_n^R for elastic process can be obtained by fitting Y_n^R to Z_C. The fitting parameters a and b for (n, n) reaction is 0.12187 and −3.5998, respectively.

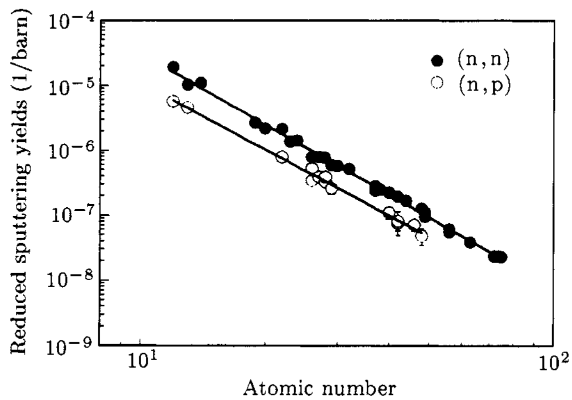

Fig. 3. Systematics of Y_n^R for (n, p) and (n, n) reactions.

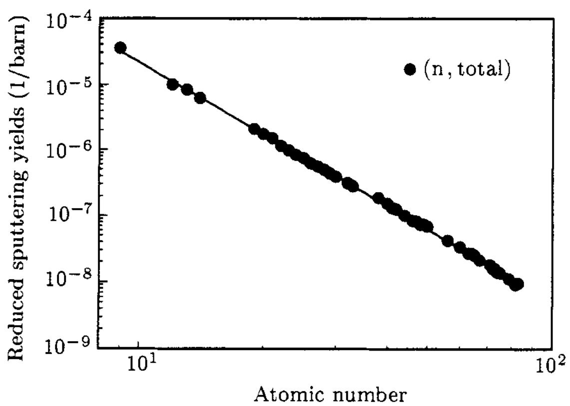

Fig. 4. Systematics of total Y_n^R for 42 materials induced by fast neutrons.

Usually, to measure the total Y_n^R is very difficult in experiment. Reaction induced by fast neutron can be divided into two processes, non-elastic and elastic. Based on above results, the Y_n^R for (n, total) reaction can be obtained by combining the values of Y_n^R for (n, non.) and (n, n) reactions.

$$Y^R_{n,(n,total)} = \frac{Y^R_{n,(n,n)}\sigma_{n,n} + Y^R_{n,(n,non.)}\sigma_{(n,non.)}}{\sigma_{(n,total)}}. \quad (9)$$

The values of Y_n^R for 42 reactions for Z_C from 9 to 82 are calculated according to the formula (9), where values of cross section are taken from JENDL-3.2 and ENDF/B-VI. The result shows a strong systematics depending on Z_C as shown in Fig. 4. The fitting parameters of systematics are also listed in Table 1. Present result for sputtering yield induced by fast neutrons is applicable to materials with $Z_C > 9$. In the case of lack of any experimental data, the present systematic result is very convenient in estimating the sputtering yield. The present result is very useful for design of fusion reactor, for example, to estimate the surface erosion of the first wall and radioactivity productions sputtering from the cooling system of the fusion reactor.

REFERENCES

1. M. Kaminsky and S. K. Das, J. Nucl. Mater. 53 (1974) 162.
2. R. Behrisch, R. Gahler and J. Kalus, J. Nucl. Mater. 53 (1974) 183.
3. L. H. Jenkins *et al.*, J. Nucl. Mater. 63 (1976) 438.
4. M. T. Robinson, J. Nucl. Mater. 53 (1974) 201.
5. O. K. Harling *et al.*, Phys. Rev. Lett. 34 (1975) 1340.
6. M. Kaminsky *et al.*, Phys. Rev. Lett. 32 (1974) 599.
7. B. J. Ye, Y. Kasugai and Y. Ikeda, JAERI-Research, 97-082, (1997).
8. JEF Report 14, *Table of simple integral neutron cross section data from JEF-2.2, ENDF/B-VI, JENDL-3.2, Brond-2 and CENDL-2*, 1994, France.
9. P. Sigmund, Phys. Rev. 184 (1969) 383.
10. R. Behrisch, *Sputtering by Particle Bombardment II, Topics in Applied Physics.* (Springer-Verlag, Berlin, 1983) Vol. 52.
11. H. E. Schiott, Radiation Effects, 6 (1970) 107.