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# Measurement of Energy Spectra of Recoil Nuclides Induced by 14.9 MeV Neutrons*

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**Abstract** The energy spectra of radioactive recoil nuclides sputtered from metallic target induced by 14.9 MeV neutrons are measured. The activation measurement technique is used to measure the change of sputtered activities with the distances between targets and collectors. The energy loss of the sputtered particles in the air is calculated by a formula of universal nuclear stopping power. The energy distributions are deduced from the sputtered activities and the energy loss in the different distances. In this method the energy spectra of recoil nuclides for thick target from seven samples of Mg, Al, Cr, Fe, Co, Nb and type 316 stainless steel with 8 reactions have been presented in the first time.

**Key words** energy spectrum, recoil nuclide, activation technique

## 1 Introduction

Sputtering is the removal of material from the surface of a solid through the impact of energetic particles. Bombarding energies can vary from a few tens of electronvolts to 100 MeV. Usually, ions are for bombardment as they can readily be accelerated to a defined energy and mass selected. The sputtered particles from the surface of a solid are emitted with a broad distribution in energy and exit angles. Energy distributions of sputtered particles are, however, of greater importance for a better and more detailed understanding of the sputtering process. Early energy distribution measurements by Thompson, Weher, Kopitzki, and their coworkers[1—3] clearly showed the epithermal nature of sputtered particles. Most results of measurements comfirmed the theoretically predicted $E^{-2}$ high-energy tail, thus again providing strong support for random collision cascades in sputtering[4—5].

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Up till now, most measurements of energy distributions of sputtering particles were limited by ions. No results have been reported in the literature induced by the fast neutron. With the application of intense neutron fluxes in science, technology and power generation, the effects of high energy neutron bombardment, not only in the bulk material, but also at the surface become important. To know the energy distribution of the sputtered particles induced by the fast neutrons is very important for the basic material damage studies and the engineering design of fission and fusion reactors.

In this paper, we report a new experimental method for measuring the recoil activities of sputtered particles. The present measurement was performed in air. For each sample, some target-collector assemblies were prepared with different target-collector distances. For each target-collector assembly, the sputtered activity was measured by the activation method and the energy loss of the sputtered particle passing through the air was calculated by using the universal nuclear stopping powers. The energy distributions were deduced from the sputtered activities and energy loss. Though the present results are rough, it is a signficanct attempt in the case of lacking any experimental result and is of reference value for design fusion reactor.

## 2 Experimental measurements

Because the sputtering yields are very low, it is very important to select suitable materials and reactions. In the present experiments, seven kinds of materials, magnesium, aluminum, chromium, iron, cobalt, niobium and type 316 stainless steel with eight reactions were chosen for the measurement of the sputtering yields.

The present measurement was performed in air. The collectors for the sputtering materials were made from plastic film. Most of the collectors were first cut into a 2.5 cm × 2.5 cm. The thickness of each collector is 0.013 mm. A plastic ring was made specially as the holder to fix the collector and target. Each target-collector assembly consists of one target, two collectors and two plastic holders as shown in Fig. 1. The thickness of the holder was 0.2, 0.5, 1.0, 2.0, 3.0 and 5.0 mm which separated the target from the collectors. For each material studied, 4 to 6 target-collector assemblies were prepared and loaded into a cylinderical plastic tube as a target-collector stack.

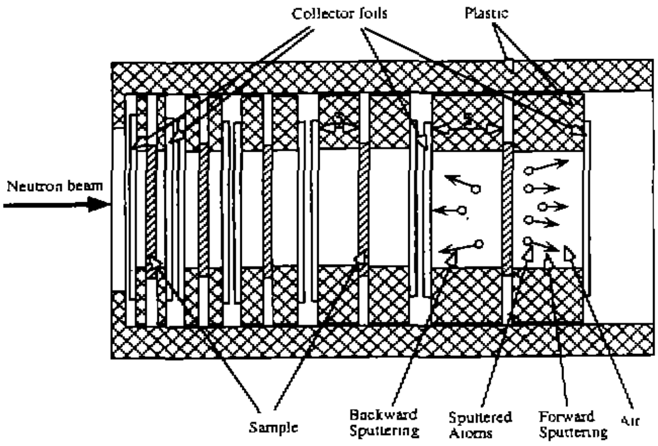

**Fig.1** The experimental target-collector stack

The 14.9 MeV neutrons were produced by T(d, n) reaction at the neutron generator of Fusion

Neutronics Source (FNS), Japan Atomic Energy Research Institute (JAERI). The target-collector stack was placed at the distances of 10 mm to 50 mm from the neutron source in direction of 0° with respect to $d^+$ beam. The irradiation time was varied according to the half life-time of recoil nuclide from 10 minutes to two days.

After the irradiation, gamma-rays from the irradiated samples and the sputtered materials deposited in the collectors were measured using five germanium detectors. One of the germanium detectors was used as the standard detector in which the detection efficiency has been calibrated carefully. The other detectors were used to measure relative gamma-ray yields. The efficiencies of the relative detectors were calibrated for each gamma-ray by measuring the same sample in both the relative and the standard detectors.

The amount of sputtering is measured by the sputtering yield ($S_n$) which is defined as the mean number of atoms removed from the surface of a solid per neutron passing through this surface. In nearly all neutron sputtering measurements, a sticking probability of one was assumed. We have

$$S_n = \frac{C_2 \varepsilon_1 \sigma W N_A \mu}{C_1 \varepsilon_2 A S_2} e^{\lambda(t_{c2} - t_{c1})} \frac{(1 - e^{-\lambda t_{m1}})}{(1 - e^{-\lambda t_{m2}})}, \tag{1}$$

where,

$C_1$: γ-ray peak counts at the sample foil,

$C_2$: γ-ray peak counts at the collector foil,

$\lambda$: decay constant of radioactivity produced,

$\varepsilon_i$: the detector efficiency,

$\sigma$: the cross section of reaction studied,

$t_c$: duration of cooling,

$t_m$: duration of γ-ray counting,

$\mu$: gamma-ray self-absorption correction factor.

$S_2$: the area of the collector foil measured,

$W$: the weight of the sample,

$A$: the atomic weight of the target nuclide,

$N_A$: the Avogadro's number.

The neutron sputtering yields were obtained from the collectors for different positions for each sample. In order to obtain the sputtering yields at 0 mm distance (surface of sample), for each sample the neutron sputtering yields were deduced by extrapolating the data at different distances to 0 mm distance.

## 3 Energy distributions

In order to deduce the energy distribution of the sputtered particles, it is necessary to know the energy loss of the sputtered particles in the air. In sputtering experiments with neutrons, the primary knockon atoms can be produced in a nuclear reaction such as (n, p), (n, α), (n, 2n), etc. For a reaction C(n, b) D, according to the mechanics of nuclear reaction, the kinetic energy of the recoil nuclide, T, in the laboratory coordinate system, is

$$T = \left\{ \frac{(A_D E_n)^{1/2}}{(A_D + A_b)} \cos\theta \pm \left( \frac{A_D E_n}{(A_D + A_b)^2} \cos^2\theta + \frac{A_b Q + (A_b - 1) E_n}{(A_D + A_b)} \right)^{1/2} \right\}^2, \tag{2}$$

where $A_D$ and $A_b$ are the mass numbers of the recoil nuclide and the light ejected particle. $E_n$ is the energy of incident neutron, $Q$ is the reaction $Q$ -value, and $\theta$ is the recoil nuclide scattering angle in the laboratory frame of reference.

The radioactive primary knockon atoms starting with an energy $T$ in the direction $\theta$ of the neutron were sputtered from the surface of the target to the air. The energy loss by the particle per unit path length, $\frac{dE}{dx}$, is related to the nuclear stopping cross section. In general, a reduced energy is often introduced to describe the nuclear stopping power,

$$\varepsilon = \frac{32.53 M_2 T(\mathrm{keV})}{Z_1 Z_2 (M_1 + M_2)(Z_1^{0.23} + Z_2^{0.23})}, \tag{3}$$

where $M_1$, $Z_1$ and $M_2$, $Z_2$ are the mass and atomic number of the sputtered particle and the air, respectively. For the air, as a result of average, the mass number $M_2 = 14$ and the atomic number $Z_2 = 7$. For practical calculations, the universal nuclear stopping power[6] is

$$\frac{dE}{dx}(T) = \frac{8.462 \times 10^{-15} Z_1 Z_2 M_1}{(M_1 + M_2)(Z_1^{0.23} + Z_2^{0.23})} \frac{d\varepsilon}{dx}, \tag{4}$$

where the unit of $\frac{d\varepsilon}{dx}$ is $\frac{\mathrm{eV}}{(\mathrm{atoms/cm^2})}$ and the reduced nuclear stopping $\frac{d\varepsilon}{dx}$ is calculated as:

For $\varepsilon \leq 30$:

$$\frac{d\varepsilon}{dx}(\varepsilon) = \frac{\ln(1 + 1.1383\varepsilon)}{2(\varepsilon + 0.01321\varepsilon^{0.21226} + 0.19593\varepsilon^{0.5})}. \tag{5}$$

For $\varepsilon > 30$:

$$\frac{d\varepsilon}{dx}(\varepsilon) = \frac{\ln\varepsilon}{2\varepsilon}. \tag{6}$$

In all calculation, the sputtered particles with the average transferable energy was assumed. The energy loss of the sputtered particles passing through the air with $\Delta x_i$ distance was obtained as the following:

$$\Delta E_i = \frac{dE}{dx} \frac{\Delta x_i}{1.967 \times 10^{-13}}, \tag{7}$$

where the unit of $\Delta E_i$ is MeV. The energy distributions of the sputtered particles can be calculated by

$$\frac{dS_n}{dE} = \frac{S_{n,i} - S_{n,i+1}}{\Delta E_{i+1} - \Delta E_i}. \tag{8}$$

The energy distributions of the sputtered particles for all reactions were deduced from the formula (8) and plotted in Fig.2 ~ Fig.6. For all reaction, because the sputtering yields were measured only for 4 ~ 6 collectors, the energy distributions in present work were very rough.

For $^{24}$Na emitted from two reactions $^{27}$Al(n,α)$^{24}$Na and $^{24}$Mg(n,p)$^{24}$Na, there are a great difference in the energy distributions as shown in Fig.2. For $^{56}$Mn and $^{51}$Cr particles, they also are produced by two different reactions, the results are in agreement with each other. For the same reaction $^{93}$Nb(n,2n)$^{92m}$Nb, two measurements were made and the results agree in the range of errors. The present recoil energy spectra represent the thick target results. In principle, the recoil energy spectra of the thin target can be obtained by unfolding that of the thick target. For most recoil energy spectra in the present measurements, the spectra fall off approximately with $E^{-m}$ where $0.5 \leq m \leq 1$. As an example, recoil energy spectra of the $^{27}$Mg with a high energy tail $m = 0.5$. Because the present recoil energy spectra represent the thick target results, so it is difficult to make a comparison with the theoretical calculation.

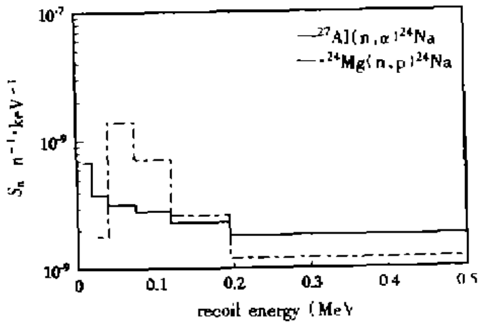

**Fig.2** Energy spectra of $^{34}$Na sputtered by 14.9 MeV neutrons

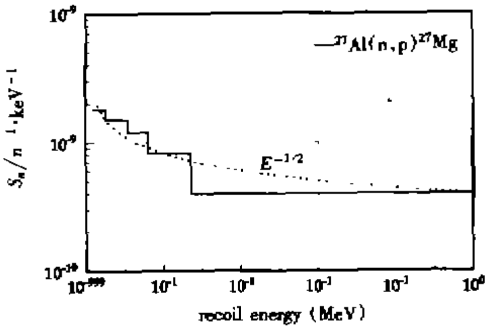

**Fig.3** Energy spectra of $^{27}$Mg sputtered by 14.9 MeV neutrons

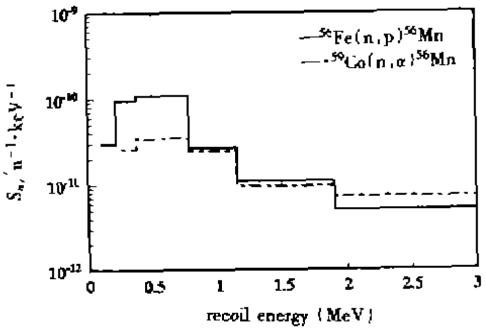

**Fig.4** Energy spectra of $^{56}$Mn sputtered by 14.9 MeV neutrons

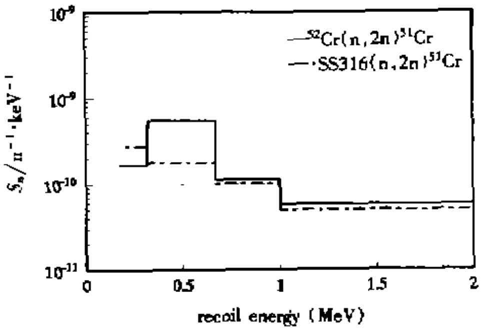

**Fig.5** Energy spectra of $^{51}$Cr sputtered by 14.9 MeV neutrons

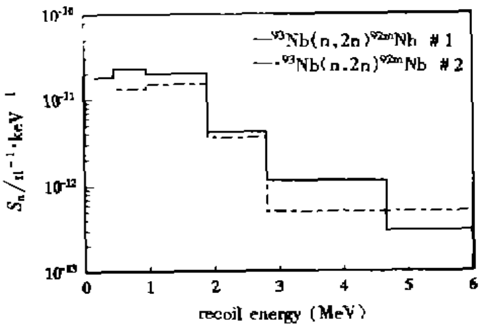

**Fig.6** Energy spectra of $^{92m}$Nb sputtered by 14.9 MeV neutrons

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# 对 14.9 MeV 中子核反应产生的反冲核能谱的测量

O571.421
O571.523

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池田裕二郎$^{+}$　杜江峰　周先意
翁惠民　韩荣典

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**摘要**　测量了由 14.9 MeV 中子入射金属产生的反冲核的能谱.用活化技术测量溅射产额随靶与收集器之间距离的变化,用统一的原子阻止本领公式来计算溅射粒子在空气中的能量损失.溅射粒子的能量分布可由不同距离的溅射产额和能量损失导出.用这种方法第一次测量了 Mg、Al、Cr、Fe、Co、Nb 和 316 型不锈钢等 7 种样品的 8 种核反应所产生的反冲核的能谱.

**关键词**　能谱,反冲核,活化技术

**中图法分类号**　O571.421, O571.523

中子　核反应　测量