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Cross sections for fast-neutron interaction with ytterbium isotopes

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ABSTRACT

Measurements of (n,2n), (n,p), and (n,d*) (The expression (n,d*) cross section used in this work includes a sum of (n,d), (n,np) and (n,pn) cross sections.) reaction cross-sections on ytterbium isotopes have been carried out in the range of 13.5–14.8 MeV using the activation technique. The monoenergetic neutron beams were produced via the $^{3}H(d,n)^{3}He$ reaction. The neutron energies of different directions were determined using the Nb/Zr method. Samples were activated along with along with Nb and Al monitor foils to determine the incident neutron flux. Data are reported for the following reactions: $^{168}Yb(n,2n)^{167}Yb$, $^{170}Yb(n,2n)^{169m+g}Yb$, $^{176}Yb(n,2n)^{175m+g}Yb$, $^{172}Yb(n,p)^{172}Tm$, $^{173}Yb(n,p)^{173}Tm$, $^{176}Yb(n,d^{*})^{175}Tm$, $^{174}Yb(n,p)^{174}Tm$, and $^{176}Yb(n,p)^{176}Tm$. The experimentally deduced cross-sections are compared with the existing experimental data. Furthermore, theoretical statistical model, based on the Hauser–Feshbach formalism, have been carried out using the HFTT.

1. Introduction

Studies of excitation functions of neutron threshold reactions on medium and heavy mass nuclei are of considerable significance for testing nuclear models and for practical applications. A large number of experimental data on neutron induced cross sections for fusion reactor technology applications have been reported and great efforts have been devoted to compilations and evaluations (CINDA-A, 2000; Mclane et al., 1988). We chose to study the neutron-induced reaction cross sections of the ytterbium isotopes mainly for three reasons. First, the ytterbium is an important rare-earth metal for the nuclear technology and material science. Second, in the energy range around 13.5–14.8 MeV, the cross sections of $^{172}Yb(n,p)^{172}Tm$ and $^{176}Yb(n,d^{*})^{175}Tm$ reactions of the ytterbium isotopes have not been reported, and the $^{173}Yb(n,p)^{173}Tm$ reaction was only measured by two laboratories. Third, for $^{168}Yb(n,2n)^{167}Yb$, $^{170}Yb(n,2n)^{169m+g}Yb$, $^{176}Yb(n,2n)^{175m+g}Yb$, $^{174}Yb(n,p)^{174}Tm$, and $^{176}Yb(n,p)^{176}Tm$ reactions of the ytterbium isotopes, the cross sections around 14 MeV have been measured by several groups, but most of them were obtained before 1990, furthermore, there was disagreement in those data. Thus it is necessary to make further precision measurements for the cross section of the ytterbium isotopes.

In the present work three (n,2n), four (n,p), and one (n,d*) reaction cross sections on ytterbium isotopes have been studied at neutron energies of 13.5–14.8 MeV and a gamma-ray counting technique was applied using high-resolution gamma-ray spectrometer and data acquisition system. The present results of $^{168}Yb(n,2n)^{167}Yb$, $^{170}Yb(n,2n)^{169m+g}Yb$, $^{176}Yb(n,2n)^{175m+g}Yb$, $^{172}Yb(n,p)^{172}Tm$, $^{173}Yb(n,p)^{173}Tm$, $^{176}Yb(n,d^{*})^{175}Tm$, $^{174}Yb(n,p)^{174}Tm$, and $^{176}Yb(n,p)^{176}Tm$ reactions were compared with the previous works and evaluation data.

2. Experimental

2.1. Samples and irradiations

About 8 g of Yb_2O_3 powder of natural isotopic composition (>99.99% pure) was pressed at 10 ton/cm^2, and 2.0 cm in diameter was obtained. Two such pellets were prepared. The thickness of samples was 3.320 mm and 3.680 mm. Monitor foils of Nb (99.99% pure, 0.20 mm thick) and Al (99.999% pure, 0.04 mm thick) of the same diameter as the pellets were then attached in front and at the back of each sample.

Irradiation of the samples was carried out at the Pd-300 Neutron Generator at Chinese Academy of Engineering Physics (CAEP) and lasted about 2 h with a yield $\sim 3–4 \times 10^{10}$ n/(4πs). The groups of samples were wrapped in cadmium foil and placed at 0° and 135° angle relative to the beam direction and centered about the T–Ti target at distances of ~3–5 cm. Neutrons were produced by the $T(d,n)^{4}He$ reaction with an effective deuteron beam energy of 125 keV and beam current of 200 μA. The tritium-titanium (T–Ti) target used in the generator was 2.38 mg/cm^2 thick. The neutron

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flux was monitored by a uranium fission chamber so that corrections could be made for small variations in the yield.

2.2. Determination of the incident neutron energy

The neutron energies in the measurements were determined by the cross-section ratio for the ^{93}Nb(n,2n)^{92m}Nb and ^{90}Zr(n,2n)$^{89m+g}$Zr reactions and were also calculated by the following formula (Luo et al., 2010; Nethaway 1978; Pavlik et al., 1982):

$$(E_n)^{\frac{1}{2}} = \frac{(M_d M_n E_d)^{\frac{1}{2}} \cos\theta + (M_d M_n E_d \cos^2\theta + \{M_\alpha + M_n\}[M_\alpha Q + E_d(M_\alpha - M_n)])^{\frac{1}{2}}}{M_\alpha + M_n} \quad (1)$$

where E_d is deuteron beam energy, E_n is the kinetic energy of the neutrons emitted at angle θ, M_d, M_n and M_α are the masses of deuteron, neutron and alpha particle, respectively. The result was shown in Fig. 1. The uncertainty in the neutron energy at ~3–5 cm was estimated to be 0.2 MeV from a consideration of the sample sizes, d^+ beam diameter of about 3–4 mm, and the uncertainty in the Nb/Zr method (Lewis and Zieba, 1980).

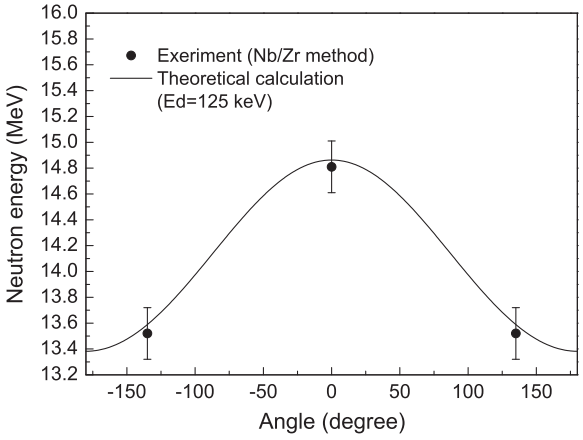

Fig. 1. Angular dependence of d–T neutron energy. The neutron energies were calculated by choosing the incident deuteron energy Ed = 125 keV. The solid circles show experimental data determined by the Nb/Zr method (Lewis and Zieba, 1980).

2.3. Measurement of radioactivity

After the irradiation, a period of ~1 min-3 days elapsed before starting the gamma-ray activity measurements. The gamma ray of ^{167}Yb, $^{169m+g}$Yb, $^{175m+g}$Yb, ^{172}Tm, ^{173}Tm, ^{175}Tm, ^{174}Tm, ^{176}Tm, ^{92m}Nb, ^{24}Na and $^{89m+g}$Zr was determined by a high-purity germanium (HPGe) detector with a relative efficiency of 68% and an energy resolution of 1.69 keV at 1332 keV for ^{60}Co (Luo et al., 2010). Fig. 2 shows typical spectra acquired from the Yb_2O_3 samples during the measurement, where the γ-rays of interest have been marked. The distance between the sample and the detector is ~3–9 cm. The efficiency calibration was determined by using point-like calibrated gamma-ray sources (Luo et al., 2010). The decay characteristics of the product radioisotopes and the natural abundances of the target isotopes under investigation are summarized in Table 1 (Browne and Firestone, 1996).

2.4. Calculation of cross sections and their uncertainties

The reaction cross-sections were calculated by the following formula (cf. Luo et al., 2009):

$$\sigma_x = \frac{[S\varepsilon I_\gamma \eta KMD]_0}{[S\varepsilon I_\gamma \eta KMD]_x} \frac{[\lambda AFC]_x}{[\lambda AFC]_0} \sigma_0 \quad (2)$$

where the subscript 0 represents the term corresponding to the monitor reaction and subscript x corresponds to the measured reactionε is the full-energy peak efficiency of the measured characteristic gamma-ray; $I\gamma$ the gamma-ray intensity; η the abundance of the target nuclide; M the mass of sample; $D = e^{-\lambda t_1} - e^{-\lambda t_2}$ the counting collection factor; $S = 1 - e^{-\lambda T}$ the growth factor of the product nuclide; T the total irradiation time; t_1,t_2 the time intervals from the end of the irradiation to the start and end of counting, respectively; A the atomic weight; C the measured full energy peak area; λ the decay constant and F is the total correction factor of the activity:

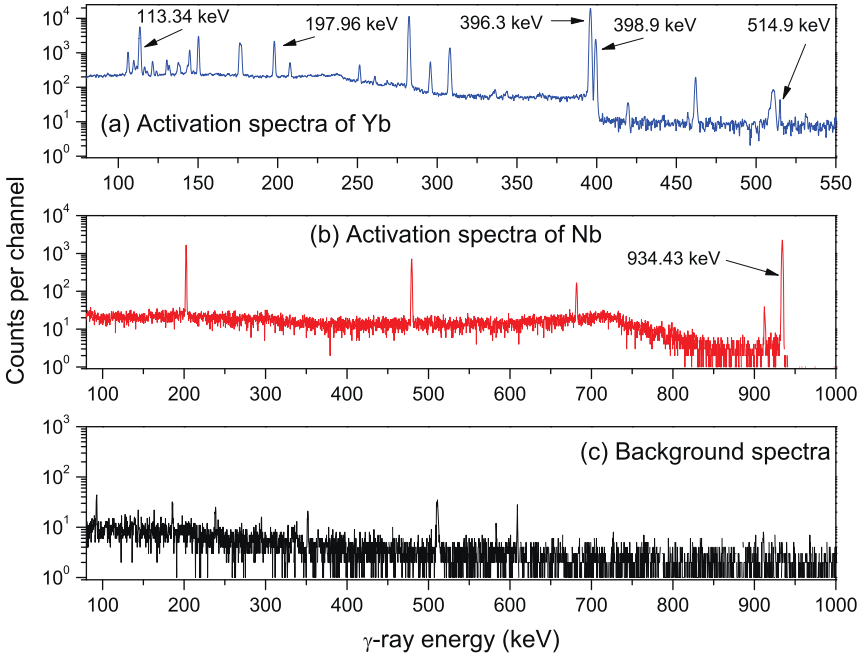

Fig. 2. (a) The γ-ray spectra of ytterbium about 40 min after the end of irradiation; (b) The γ-ray spectra of niobium about 5 h after the end of irradiation and (c) Background spectra.