Measurements of cross-sections of producing short-lived nuclei with 14 MeV neutrons
- ^{27}Al(n, α)^{24m}Na, ^{144}Sm(n, 2n)^{143m}Sm, ^{206}Pb(n, 2n)^{205m}Pb, ^{208}Pb(n, 2n)^{207m}Pb -

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The activation cross-sections producing short-lived nuclei whose half-lives are shorter than a second were measured by the in-beam method. The neutron collimator installed in Fusion Neutronics Source (FNS) at the Japan Atomic Energy Agency (JAEA) was used. The scattering of the collimated neutron was calculated by the Monte-carlo simulation code MCNP-4C, and an appropriately geometrical condition for the in-beam method was considered. The cross-sections of ^{27}Al(n, α)^{24m}Na ($T_{1/2}$=20.20 ms), ^{144}Sm(n, 2n)^{143m1}Sm ($T_{1/2}$=66 s), ^{144}Sm(n, 2n)^{143m2}Sm ($T_{1/2}$=30 ms), ^{206}Pb(n, 2n)^{205m}Pb ($T_{1/2}$=5.54 ms) and ^{208}Pb(n, 2n)^{207m}Pb ($T_{1/2}$=806 ms) reactions were measured with uncertainties of 4.4 to 23%. The ^{144}Sm(n, 2n)^{143m2}Sm reaction was measured for the first time. The systematics for isomer ratios for 14.2 MeV neutrons, that is the ratio between the cross-section for the isomeric state (σ_m) and that for the ground state (σ_g) were proposed within accuracies a half to two times the ratio itself.

1. Introduction

There are a lot of data of activation cross-sections with 14 MeV neutrons from a viewpoint of the DT fusion reactor design. In general, most of data are long-lived nuclei whose half-lives are longer than several minutes. However, there are few data for short-lived nuclei whose half-lives are equal to or shorter than a few seconds. These data are also important for the nuclear database and improvement of accuracies for the evaluation value. Hence, we aimed to measure the cross-sections producing the short-lived nuclei with 14 MeV neutrons by using the in-beam method [1]. The systematics for the isomer ratio was studied by using the present and the previous results (e.g. [2,3]).

2. Experiment

The d-T neutrons were generated by bombarding a tritiated titanium (Ti-T) target with a 350 keV d^+-beam at the 0 degree beam line of the FNS at the JAEA. The induced activities were measured with a 36% HPGe detector. Samples were ^{27}Al, ^{144}Sm and ^{206,208}Pb, these were 1 mm thick rectangular (10 mm × 20 mm) or disk-shape (15 mm$^{\phi}$), and weights were 0.045 to 0.95 g. In Table1, the chemical form, the isotopic abundance and the weight of samples are listed.

In order to reduce the background at the measuring position, the neutron collimator at the 0 degree beam line was used (Fig.1). The angle between the d^+-beam and the axis of the collimated neutron beam was 80 degree, which resulted in a 14.2 MeV neutron energy [4]. The diameter of the collimator was 2 cm. The experimental arrangement is shown in Fig.2. The distance between an exit of the collimator and the sample was 15 cm. And the distance between the sample and the HPGe detector surface was 5 cm. The typical neutron fluence rates at the irradiation positions were measured with the standard reaction of ^{27}Al(n, α)^{24}Na [5]. The typical value at the sample position was 6.5×10^5 n·cm^{-2}·s^{-1}. The fast neutron does not damage the HPGe detector by the neutron collimator. However the effect of the scattered neutron from the sample, the sample folder and the atmosphere has to be taken into account. The amount of the scattered neutron was calculated by the MCNP-4C [6]. The result of the calculation is shown in Fig.3. It was found that the neutron fluence rate at the HPGe detector surface was 4.0×10^{-4} times against the sample position.

3. Result

The spectrum for the ^{144}Sm(n, 2n)^{143m2}Sm which were measured by the in-beam method are shown in Fig.4. The cross-sections of ^{27}Al(n, α)^{24m}Na, ^{144}Sm(n, 2n)^{143m1}Sm, ^{144}Sm(n, 2n)^{143m2}Sm, ^{206}Pb(n, 2n)^{205m}Pb and ^{208}Pb(n, 2n)^{207m}Pb reactions were obtained. The results are shown in Fig.5. Uncertainties which are 4.4 to 23% are mainly caused by statistics.

(1) ^{144}Sm(n, 2n) ^{143m2}Sm ($T_{1/2}$ = 30 ms, E_γ = 208 keV); The cross-section was measured for the first time.

(2) ^{144}Sm(n, 2n) ^{143m1}Sm ($T_{1/2}$ = 66 s, E_γ = 754 keV); The cross-sections had been measured with other methods [7,8] for comparison, the present are agreement with those value.

(3) ^{27}Al(n, α)^{24m}Na ($T_{1/2}$ = 20.20 ms, E_γ = 472 keV); Because the scattered neutron reacts the Al housing of the HPGe detector, the γ-rays from the ^{27}Al(n, α)^{24m}Na reaction become a background. Hence, it was found that the counting rate of the 472 keV γ-ray as the background was 0.5 cps, the effect were corrected properly (Fig.6). The evaluated data for this reaction listed in FENDL/A-2.0 [9] were underestimated 0.63 times as small as the present result, approximately.

(4) ^{206}Pb(n, 2n) ^{205m}Pb ($T_{1/2}$ = 5.54 ms, E_γ = 988 keV); The broken line shows the evaluated data of FENDL/A-2.0 for the ground state. It was found that σ_m is half σ_g.

(5) ^{208}Pb(n, 2n)^{207m}Pb ($T_{1/2}$ = 806 ms, E_γ = 1064 keV); The evaluated data for this reaction listed in FENDL/A-2.0 were overestimated 1.37 times as large as the present result, approximately. Re-evaluations except for the ^{144}Sm(n, 2n) ^{143m1}Sm reaction are strongly recommended.

4. Systematics

The isomer ratio was obtained by using the data set of the cross-section with 14.2 MeV neutrons, and the systematics was proposed. The value of (σ_{high} / σ_{low}) were plotted as a function of (J^m – J^0) as shown in Fig.7, where σ_{high} is the cross-section producing higher isomeric state and σ_{low} is the cross-section producing lower one, and (J^m – J^0) is the difference of spin between the isomeric state of the product nucleus and the ground state of the target one. In the case of Al shown in Fig.8, $(J^m - J^0) = 1 - 5/2 = -3/2$、$(\sigma_{high} / \sigma_{low}) = (\sigma_g / \sigma_m)$. The solid line was obtained by fitting the data, and it could predict the ratio within accuracies a half to two times the ratio itself.

5. Conclusion

We measured the cross-sections producing short-lived nuclei whose half-lives are between 5.54 and 806 ms by the in-beam method. We proposed the systematics for the isomer ratio for 14.2 MeV neutrons, which could predict the ratio within accuracies a half to two times the ratio itself.

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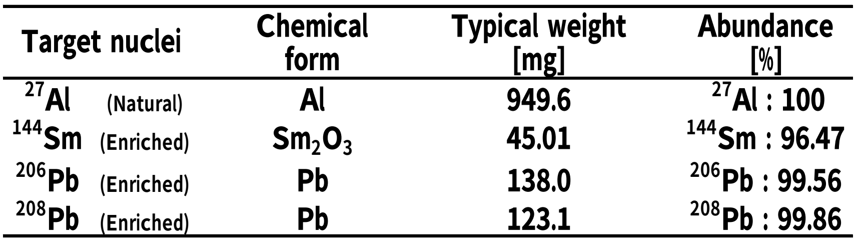
Table 1. Chemical form, weight and abundance of the samples.



Target nuclei		Chemical form	Typical weight [mg]	Abundance [%]
^{27}Al	(Natural)	Al	949.6	^{27}Al : 100
^{144}Sm	(Enriched)	Sm_2O_3	45.01	^{144}Sm : 96.47
^{206}Pb	(Enriched)	Pb	138.0	^{206}Pb : 99.56
^{208}Pb	(Enriched)	Pb	123.1	^{208}Pb : 99.86

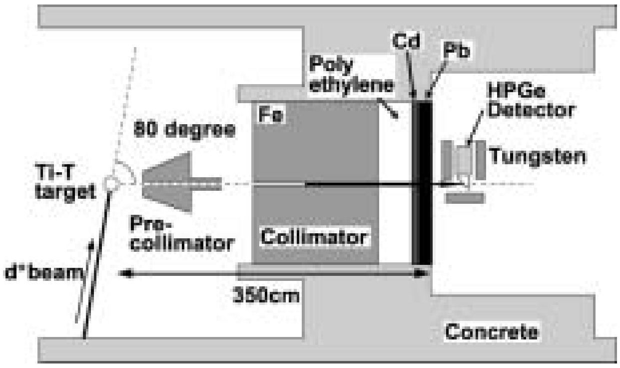


Fig.1. The schematic view of the 14 MeV neutron source and the neutron collimator system. The collimator is composed of Fe, Polyethylene, Cd and Pb.

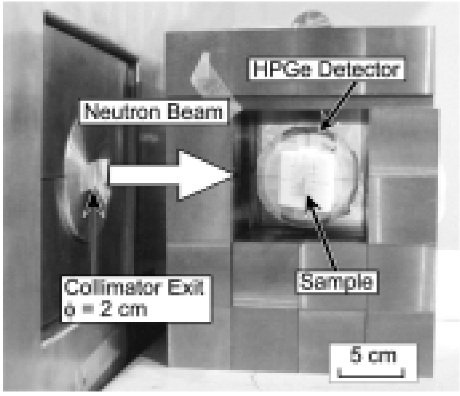


Fig.2. The schematic view of the experimental arrangement. Tungsten blocks are used to prevent the HPGe detector from the background γ-rays.

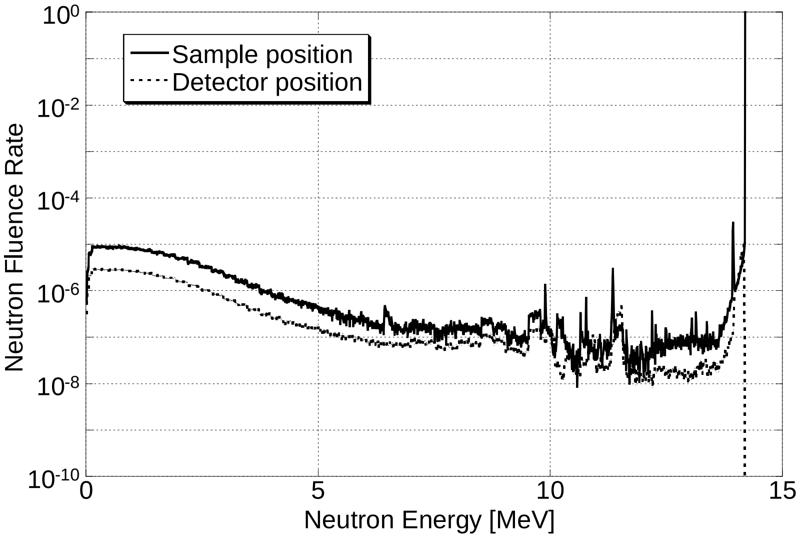


Fig.3. Neutron spectrum calculated by the MCNP-4C. The solid and broken lines indicate the neutron spectrum at the sample position and the detector position, respectively.

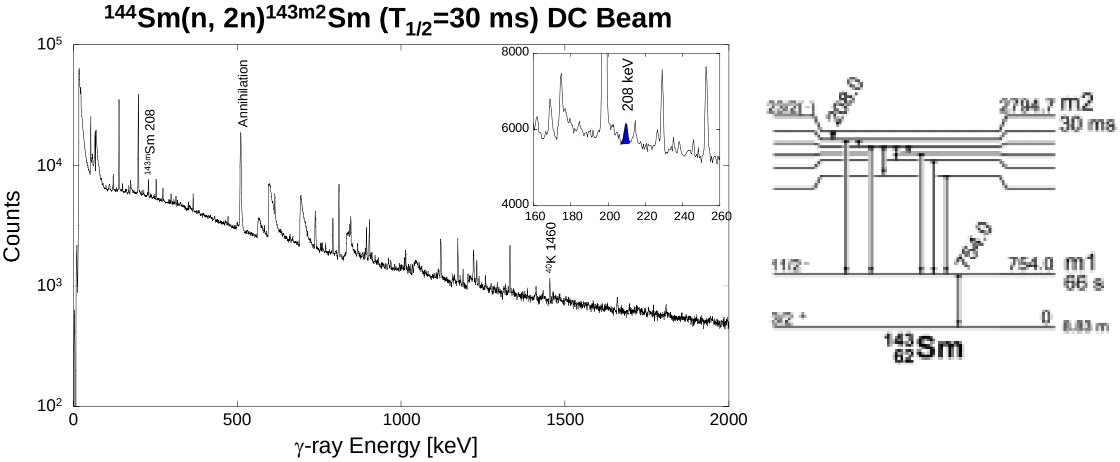


Fig.4. The measured HPGe spectrum for γ-rays from ^{144}Sm(n, 2n)^{143m2}Sm reaction with the in-beam method and a partial level scheme of the ^{143}Sm.

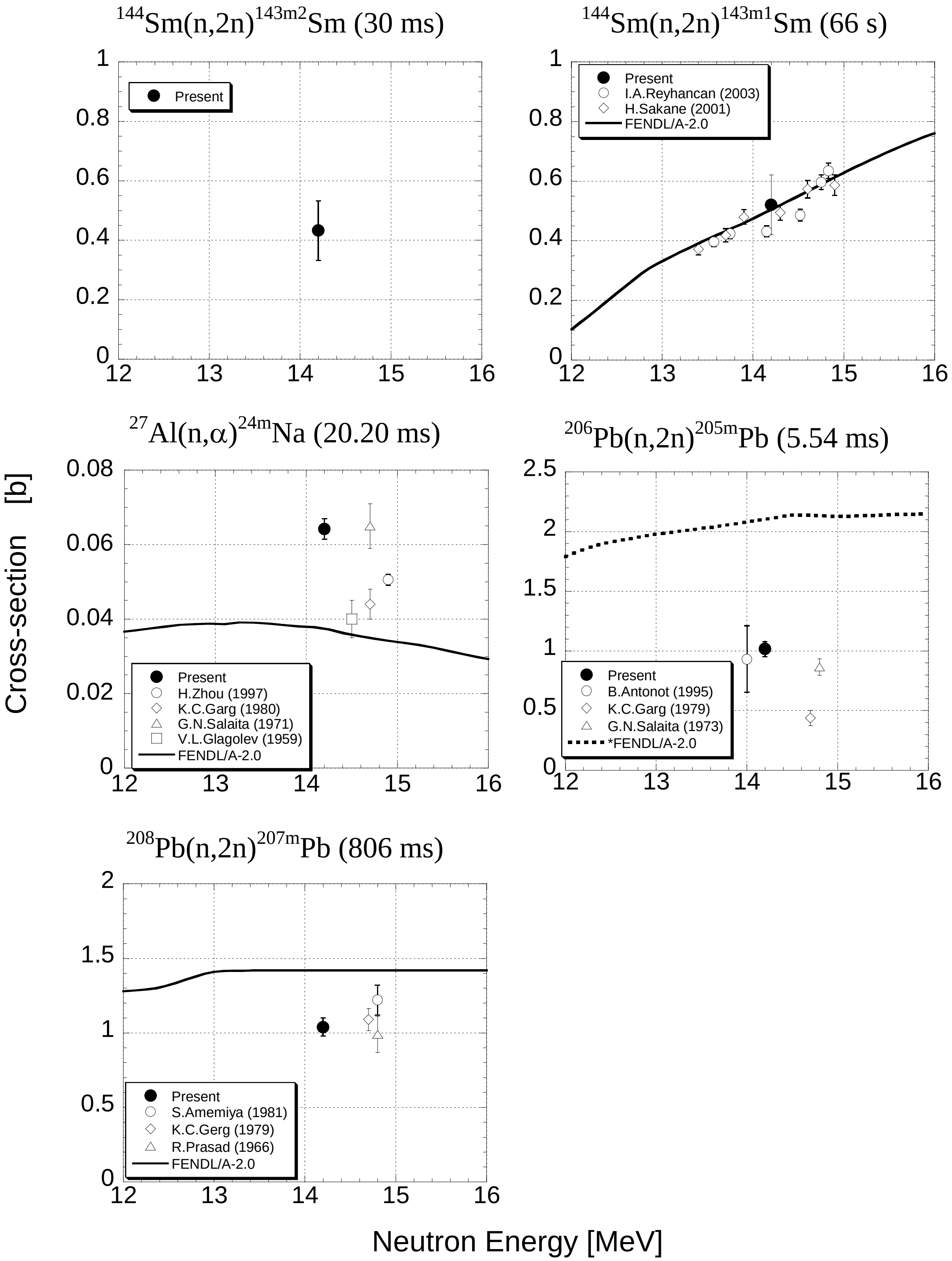


Fig.5. The experimental cross-section data compared with the previous ones and the evaluated data in FENDL/A-2.0.

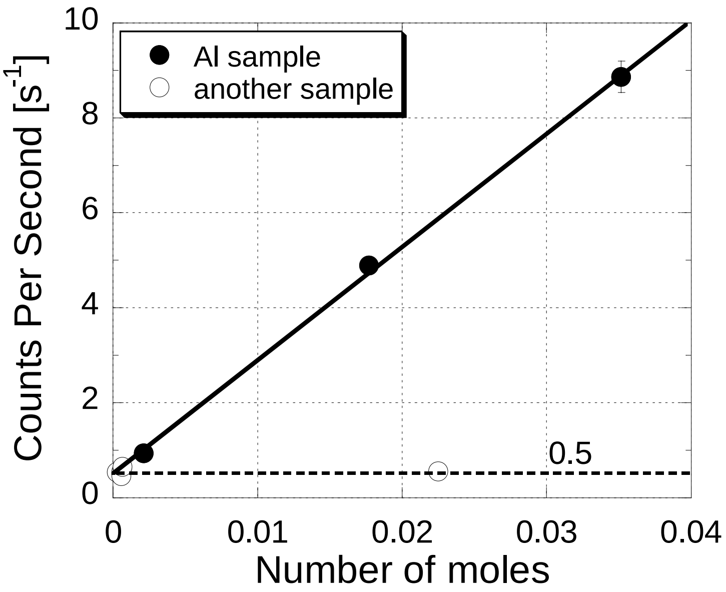


Fig.6. The relationship between the number of moles of the sample material and the background counting rate (cps). The solid and open circles indicate the cps of the 472 keV γ-ray from the Al samples and the other samples, respectively.

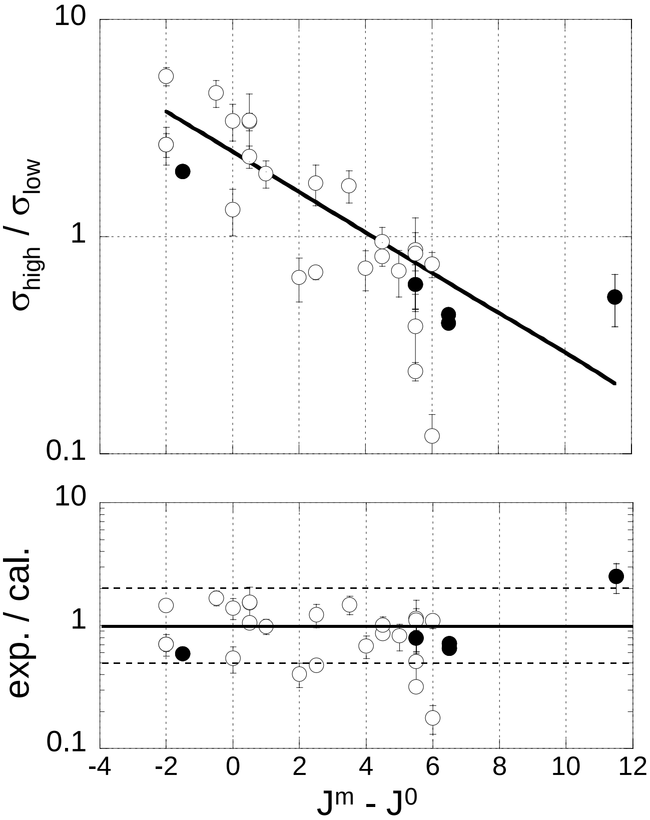


Fig.7. The relationship between (J^m - J^0) and ($\sigma_{high}/\sigma_{low}$). The solid line was obtained by fitting the data.

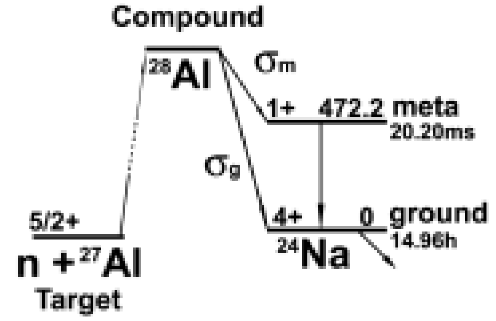


Fig.8. The schematic diagram for the isomer cross section of ^{27}Al (n,α) ^{24}Na reaction.