Measurement of Deuteron-Induced Activation Cross-Sections for Aluminum, Copper and Tungsten in 22-34 MeV Region

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Activation cross-sections for deuteron-induced reactions on aluminum, copper and tungsten were measured by using a stacked-foil technique at the AVF cyclotron in TIARA facility, JAERI. We irradiated three types of stacked-foil with 35 MeV deuteron beam and the activation cross sections for the ^{27}Al(d,x)^{27}Mg, ^{24}Na, ^{nat}Cu(d,x)$^{62,\ 63}$Zn, $^{61,\ 64}$Cu and ^{nat}W(d,x)$^{181\text{-}184,\ 186}$Re, ^{187}W reactions were obtained in 22-34 MeV region. The experimental cross sections were compared with other experimental ones and the data from ACSELAM library in the IRAC code system.

1. Introduction

International Fusion Materials Irradiation Facility (IFMIF) is an accelerator-based D-Li neutron source designed to produce an intense neutron field for testing fusion materials. The IFMIF is driven by two 40 MeV deuteron linear accelerators with 125 mA beam current. In the design of the IFMIF system, the long-term operation with a total facility availability of at least 70 % by hands-on maintenance is planned [1]. However, beam loss would activate the structure materials along the beam transport lines and make hands-on maintenance more difficult. Therefore, the accurate estimation of the activities produced in accelerator components and the selection of structure materials are important issues in order to determine the beam loss criteria for achieving the overall availability.

Aluminum is the main component of the beam tube and chamber. Copper is used in the cavity wall, electrodes and magnetic conductor. For beam slits and coating to protect the beam facing materials, high-Z elements are so useful that gold, tantalum and tungsten are candidate materials.

In this work, we focused on main twelve radioactive nuclei produced in Al, Cu and W by the irradiation with deuteron beam. Since those nuclei have half-lives longer than ten minutes, it would give effects on considering the cooling time for starting hands-on maintenance.

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2. Experimental Procedure and Data Processing

Activation cross sections were measured by using a stacked-foil technique. In order to cross-check the obtained cross sections, three different types of stack consisting of natural composition aluminum, copper and tungsten foils with chemical purity more than 99.95 % were prepared as shown in fig. 1. Every stack was wrapped in an aluminum foil of 10 μm in thickness. The thickness of the foil was 200 μm for Al, 25 μm for Cu and 20 μm for W. The stacks were irradiated with a 35 MeV deuteron beam at the AVF cyclotron in TIARA facility, JAERI. Each irradiation was performed with a 0.1 μA beam for 5 minutes. After suitable cooling time, the decayed gamma-rays emitted from the irradiated foils were measured by a calibrated Ge detector and the induced activities were obtained for the following nuclei as ^{27}Mg, ^{24}Na, $^{61, 64}$Cu. $^{62, 63}$Zn, $^{181\text{-}184}$, ^{186}Re, ^{187}W and ^{65}Zn.

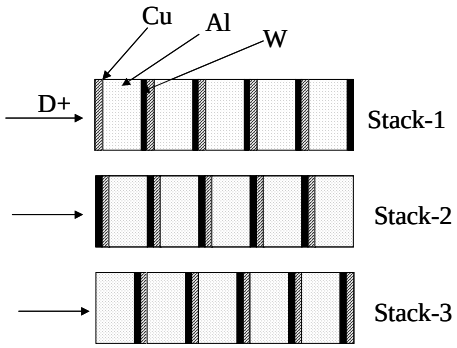

Fig. 1 Schematic view of the irradiated stacks

The energy degradation along the stack and the effective deuteron energy at the middle position of each foil were estimated by using the IRACM code[2]. The number of incident deuteron on each stack was determined from the ^{nat}Cu(d,x)^{65}Zn reaction cross section data reported by Takács *et al.*[3] and the observed ^{65}Zn activities. The elemental cross-sections were derived from the induced activities and the number of incident deuteron. The following errors were taken into account as well as statistical error (1-40 %) in the error estimation of the present results: the errors in the determination of continuous background for obtaining net counts of the decayed gamma-ray (1-30 %), the standard cross sections for the ^{nat}Cu(d,x)^{65}Zn reaction (12 %), the full energy efficiency of the Ge detector (3 %) and the foil thickness (1 %). Finally, the total uncertainty on cross section values was estimated as 13-50 %.

3. Results and Discussion

We have measured the elemental cross sections for producing the twelve radioactive nuclei and compared those with previous ones by other groups and the data from ACSELAM library calculated by using the ALICE-F code[4]. As the cross sections in ACSELAM library are given for each isotope target, we normalized the values to elemental cross sections by weighting with natural abundance in order to compare with the present results in figures.

3-1. Aluminum

The activities of three nuclei, ^{22}Na($T_{1/2}$=2.6y), ^{24}Na($T_{1/2}$=15.0h) and ^{27}Mg($T_{1/2}$=10m), are expected to be important from the viewpoint of hands-on maintenance. However, the ^{27}Al(d,αp2n)^{22}Na reaction has high threshold energy around 25 MeV and the ^{22}Na activity is very weak in 22-34 MeV region, so that the ^{22}Na production was not considered in this work.

The comparison of the present cross sections with other experimental ones and the data in ACSELAM library for producing ^{27}Mg and ^{24}Na are shown in figs. 2 and 3. For ^{27}Mg, there is only one experimental data reported by Wilson *et al.*[5] in low energy region. The present results are

larger than the data of ACSELAM by a factor of 1.3-2.0. Though the cross sections of the $^{27}Al(d,x)^{24}Na$ reaction were reported by many authors, the present results are in agreement with the data by Takács *et al.*[3], Martens *et al.*[6], and Michel *et al.*[7]. within experimental error. This work show that the data in ACSELAM for the $^{27}Al(d,x)^{22}Na$ reaction are about 1 order lower than the experimental ones.

3-2. Copper

Figures 4-7 show the present results for the $^{nat}Cu(d,x)^{61}Cu(T_{1/2}=3.33h)$, $^{64}Cu(T_{1/2}=12.7h)$, $^{62}Zn(T_{1/2}=9.19h)$ and $^{63}Zn(T_{1/2}=38m)$ reactions with other experimental ones and the data in ACSELAM library. In the energy region of 22-34 MeV, there exist only two experimental data reported by Bartell *et al.*[14] and Fulmer *et al.*[15] on those reactions. There are lots of differences between the two experimental data. In the case of ^{64}Cu, the present results are in agreement with their values within experimental error. For other nuclei, the present results support the shape of cross sections reported by Fulmer. However, their data become systematically higher than the present ones by a factor of 1.5-4.

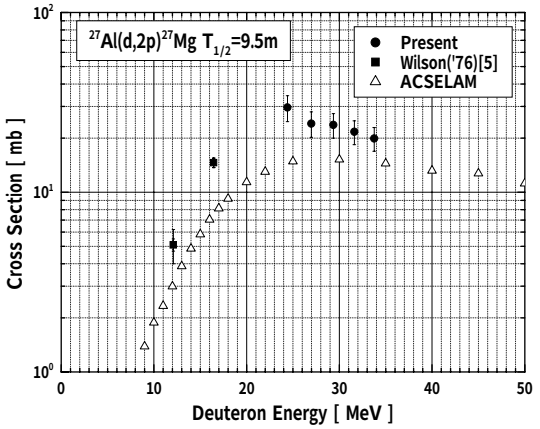

Fig. 2 Cross sections for the $^{27}Al(d,2p)^{27}Mg$ reaction

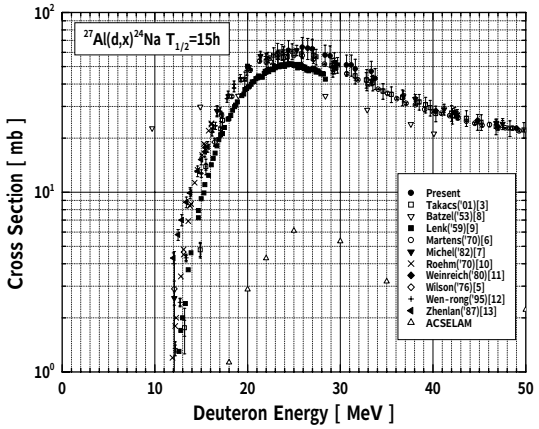

Fig. 3 Cross sections for the $^{27}Al(d,x)^{24}Na$ reaction

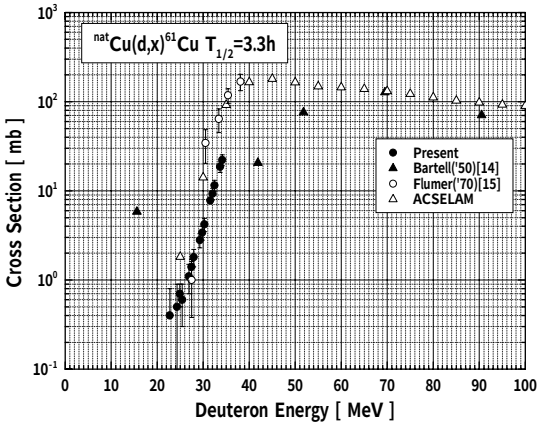

Fig. 4 Cross sections for the $^{nat}Cu(d,x)^{61}Cu$ reaction

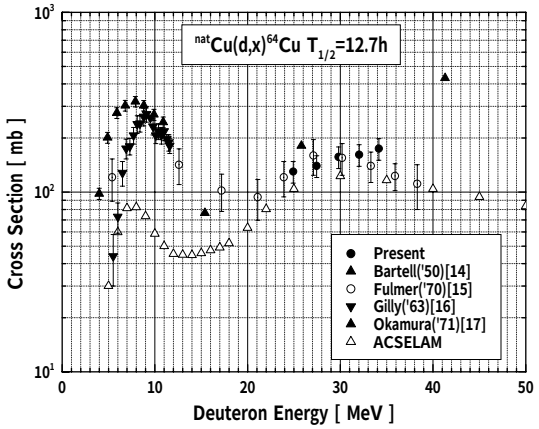

Fig. 5 Cross sections for the $^{nat}Cu(d,x)^{64}Cu$ reaction

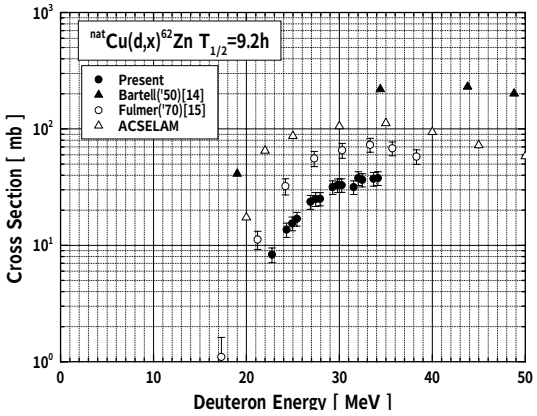

Fig. 6 Cross sections for the $^{nat}Cu(d,x)^{62}Zn$ reaction

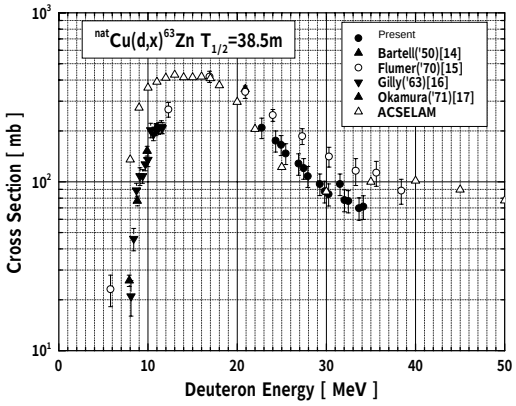

Fig. 7 Cross sections for the $^{nat}Cu(d,x)^{63}Zn$ reaction

The present results are in agreements with the data of ACSELAM except for the $^{nat}Cu(d,x)^{61}Cu$ and ^{62}Zn reactions. In the case of ^{64}Cu, large discrepancy between experimental and ACSELAM data was observed around 10 MeV as shown in fig. 5. It should be noted that the ^{64}Cu activity would be produced by not only $^{63}Cu(d,p)$ but also $^{63}Cu(n,\gamma)$ reaction. The latter reaction could be induced by secondary neutron, so that the experimental results would include the contribution.

3-3. Tungsten

Figures 8-13 show the present results for the $^{nat}W(d,x)^{181}Re(T_{1/2}=19.9h)$, $^{182g}Re(T_{1/2}=2.67d)$, $^{182m}Re(T_{1/2}=12.7h)$, $^{183}Re(T_{1/2}=70d)$, $^{184g}Re(T_{1/2}=38d)$, $^{184m}Re(T_{1/2}=169d)$, $^{186}Re(T_{1/2}=3.78d)$ and $^{187}W(T_{1/2}=23.72h)$ reactions with other experimental ones and the data in ACSELAM library.

In the energy region of 22-34 MeV, there are no experimental data. The present data are in fairly good agreement with the data in ACSELAM of ^{181}Re, $^{182m+g}Re$ and ^{183}Re. The valleys of cross section curves are also reproduced well in ACSELAM library. In the case of ^{186}Re, the present results show decreasing tendency above 24 MeV. For the $^{184m+g}Re$ and ^{187}W production reactions, this work shows that the bumps exist around 30 and 10 MeV, respectively. It should be noted that the ^{187}W could be produced by not only $^{186}W(d,p)$ but also $^{186}W(n,\gamma)$ reaction. The latter reaction is

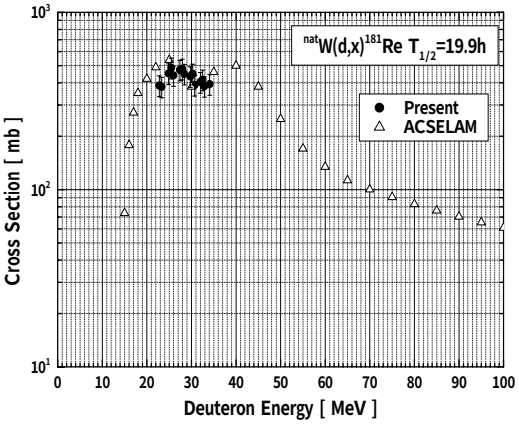

Fig. 8 Cross sections for the $^{nat}W(d,x)^{181}Re$ reaction

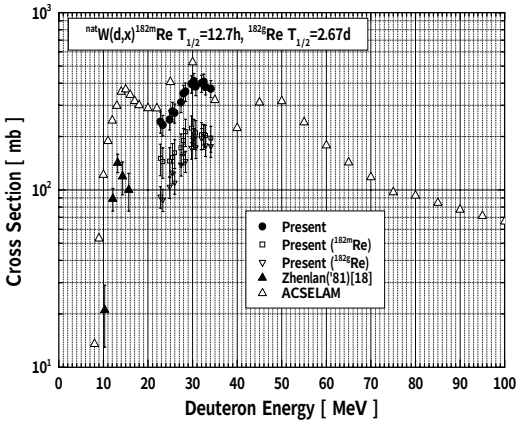

Fig. 9 Cross sections for the $^{nat}W(d,x)^{182}Re$ reaction

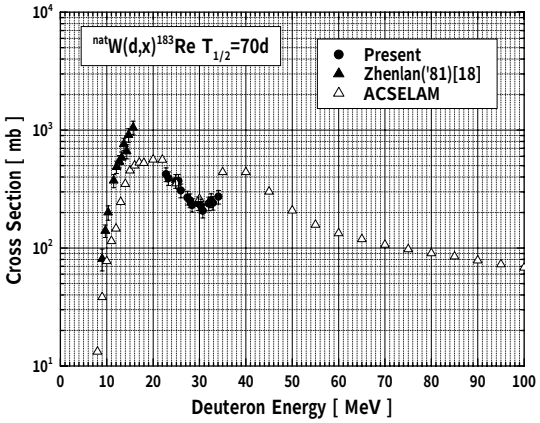

Fig. 10 Cross sections for the $^{nat}W(d,x)^{183}Re$ reaction

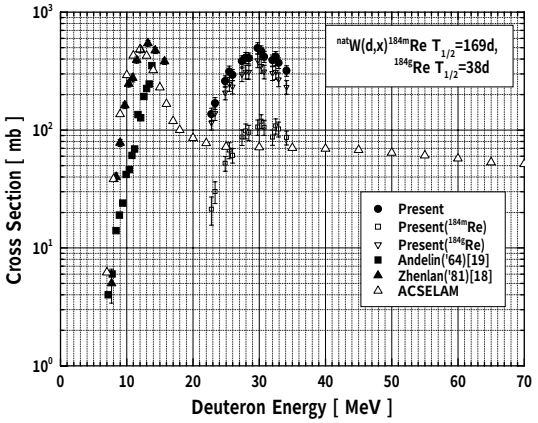

Fig. 11 Cross sections for the $^{nat}W(d,x)^{184}Re$ reaction

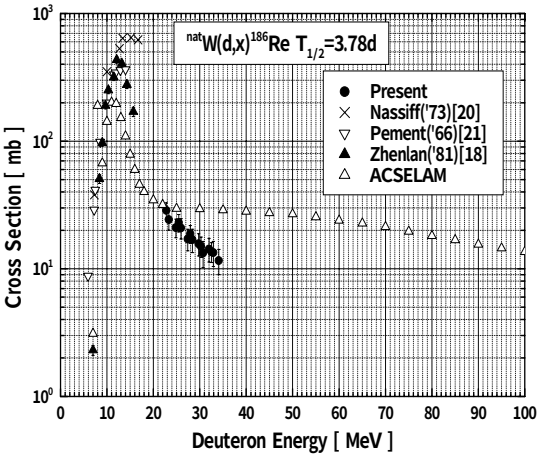

Fig. 12 Cross sections for the $^{nat}W(d,x)^{186}Re$ reaction

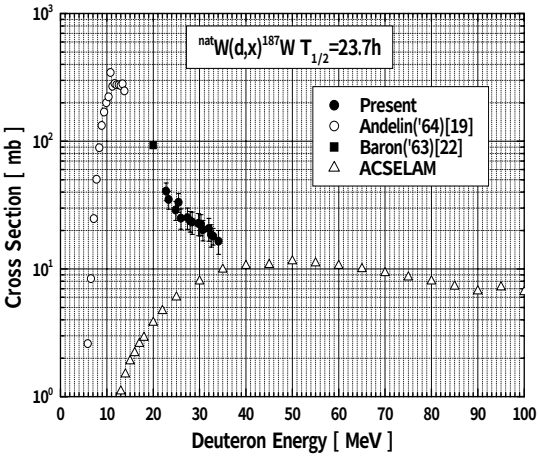

Fig. 13 Cross sections for the $^{nat}W(d,x)^{187}W$ reaction

induced by secondary low-energy neutron. The experimental results obtained by adopting an activation method include the component via the (n,γ) reaction. On the other hands, the values in ACSELAM were calculated for only (d,p) reaction. Previous experimental data by Andelin *et al.*[19] and Baron *et al.*[22] also show higher values than the data in ACSELAM about 1-2 order below 20 MeV.

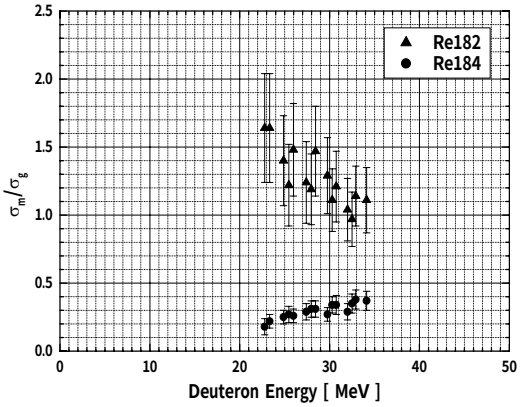

Fig. 14 The ratio of cross sections for producing the ground and meta-stable states of ^{182}Re and ^{184}Re

Moreover, we have obtained the activation cross sections corresponding to producing the ground and meta-stable states for ^{182}Re and ^{184}Re as shown in figs. 9 and 11. The obtained branching ratios (σ_m/σ_g) were also shown in Fig. 14.

4. Conclusion

The activation cross-sections for the deuteron-induced reactions have been obtained for Al, Cu and W in 22-34 MeV region. Present results were compared with previous experimental ones and the values in ACSELAM library. For $^{nat}Al(d,x)^{24}Na$, it was pointed out that the values of ACSELAM are obviously lower than experimental ones by about 1 order. Present results show good agreements with ACSELAM library for the $^{nat}Cu(d,x)^{64}Cu$, ^{63}Zn and $^{nat}W(d,x)^{181-183}Re$ reactions. For the $^{27}Al(d,p)^{27}Mg$, $^{nat}Cu(d,x)^{61}Cu$, $^{62,63}Zn$, $^{nat}W(d,x)^{186}Re$ reactions, the discrepancy is shown between the present results and the data in ACSELAM by a factor of 1.3-4. This work showed that the bumps existed around 30 and 10 MeV for producing ^{184}Re and ^{187}W, respectively. Moreover, we obtained the ratio of cross sections for producing the ground and meta-stable states of ^{182}Re and ^{184}Re.

Acknowledgments

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