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The Activation of Fe by Deuterons at Energies up to 20 MeV

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The proton and deuteron induced activation reactions have a great interest for the assessment of induced radioactivity of accelerator components. The IFMIF (International Fusion Materials Irradiation Facility) accelerator needs such a data for estimation of the potential radiation hazards from the accelerating cavities and beam transport elements (Al, Cu, Fe, Cr, Nb). The cross sections are needed in the energy range from the threshold (2 – 10 MeV) up to 40 MeV both for deuterons and protons.

Continuing deuteron activation measurements on Cu and Al, the activation cross-sections for production of ^{58,57,56,55}Co, ^{56,54,52}Mn and ^{59}Fe radioisotopes in deuteron induced reactions on Fe (natural isotope abundance) were measured from the respective thresholds up to 20 MeV. The irradiation experiment was carried out on the variable-energy cyclotron U-120M of the Nuclear Physics Institute Řež. The stacked-foil technique was utilized. The absolute values of cross sections were calculated from the induced activities measured by calibrated HPGe detectors and from total irradiation charge taking into account time profile of the current.

The comparison of present results with data of other authors and with the prediction of EAF-2007 library is discussed.

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I. INTRODUCTION

Charged particle induced activation measurements play an unsubstitutable role in obtaining extremely needful experimental cross section data. For many nuclear reactions there is presented only slight amount of results in databases (EXFOR *etc.*). however, For this reason two deuteron induced activation experiments on natural iron target have been carried out. Moreover, natural aluminium foils have been used as an additional beam monitor.

The variable-energy cyclotron U-120M of the NPI Řež provides deuterons in energy range 11 – 20 MeV. Thus, cross sections of deuteron induced reactions on Fe and Al from the appropriate threshold energy up to 20 MeV have been measured.

The absolute cross section values were calculated from the measured induced activities. Obtained results were compared not only with previously measured data presented in EXFOR database but also with EAF-2007 [1] and ACSELAM [2] data library. Measured activities were compared with FISPACT-2007 code [3] calculations.

II. EXPERIMENTAL ARRANGEMENT

The high purity Fe and Al disc foils (Goodfellow product) of natural isotopic abundance (^{54}Fe 5.8%, ^{56}Fe 91.72%, ^{57}Fe 2.2%, ^{58}Fe 0.28%; ^{27}Al 100%) were bombarded by deuteron beam from U-120M cyclotron working in the negative ion mode of acceleration [4]. The declared thickness of Fe and Al foils was 25 μm and 50 μm, respectively. The precise thickness of each foil was determined by measuring of respective mass and

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Table 1. Decay data of the studied isotopes [5].

Isotope	$T_{1/2}$	E_γ (keV)	I_γ (%)
^{52m}Mn	21.1 m	1434.068	98.3
^{52g}Mn	5.591 d	744.233	90.0
		935.538	94.5
		1434.068	100.0
^{54}Mn	312.3 d	834.848	99.976
^{56}Mn	2.5785 h	846.771	98.9
		1810.772	27.2
^{55}Co	17.53 h	477.2	20.2
		931.3	75.0
^{56}Co	77.27 d	846.771	100
		1037.840	13.99
		1238.282	67.6
^{57}Co	271.79 d	122.0614	85.6
		136.4743	10.68
^{58m}Co	9.04 h	24.889	0.0389
^{58g}Co	70.86 d	810.775	99.0
^{59}Fe	44.503 d	1099.251	56.5
		1291.596	1291.596
^{51}Cr	27.7025 d	320.0824	10.0
^{24}Na	14.959 h	1368.633	100.0
		2754.028	99.944

diameter.

Stacks of foils were placed in the target holder serving as a Faraday cup. The incident deuteron beam was completely stopped in the target.

The initial deuteron energy was 20.0 (±0.2) MeV for both experiments. The first stack of foils (EXP A) was bombarded by deuteron beam of mean current 0.20 μA in the time duration of 28 min. The irradiation time of the second stack (EXP B) was 30 min and the mean current 0.25 μA. Mean current of incident deuteron beam was calculated from the charge measurement (1 s record intervals). ^{27}Al(d,pα)^{24}Na activation reaction on Al foils was used as the additional monitor of beam current.

III. DATA MEASUREMENT

The mean energy of deuteron beam in each foil was calculated by the SRIM 2008 code [6].

The induced activities of irradiated foils were measured soon after irradiation to obtain results for the ^{52m}Mn isotope that is characterized by the short half-life (see Table 1). The measurements continued in the course of two months to get activities of long-lived isotopes.

Two calibrated HPGe detectors of 23% and 50% efficiency and of FWHM 1.8 keV at 1.3 MeV were used. The time synchronization between the PC recording beam current and the PC measuring sample activities was guaranteed. Measured gamma spectra were analyzed by the DEIMOS code [7]. Activated isotopes were identified on the basis of half-life $T_{1/2}$, gamma-ray energies E_γ and intensities I_γ, taking into account the correction for decay after and during the irradiation.

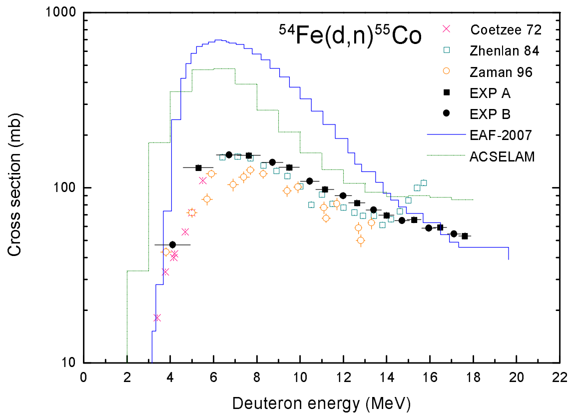

Fig. 1. (Color online) Cross section of the ^{54}Fe(d,n)^{55}Co reaction.

The estimation of systematic errors of measured cross section values consists of current uncertainty 5%, uncertainty of foil thickness 5% and initial energy determination 2%. 1 – 5% represent statistical errors in determination of the gamma peak areas.

IV. RESULTS AND DISCUSSION

The cross section values were calculated from the measured activities. Obtained cross sections were compared with earlier published experimental data and evaluated data of EAF-2007 and ACSELAM library. Several results are described.

1. Cross section of ^{54}Fe(d,n)^{55}Co reaction

Q-value of ^{56}Fe(d,3n)^{55}Co reaction is Q = -17.66 MeV [8]. Up to the corresponding threshold energy there is only one possible reaction how the ^{55}Co isotope can be produced, that is ^{54}Fe(d,n)^{55}Co, Q = +2.84 MeV. Cross sections of this reaction are presented in Fig. 1. Significant discrepancy between measured and evaluated data in the region of maximum of the excitation function can be seen.

2. Cross section of ^{54}Fe(d,α)$^{52m,52m+g}$Mn reactions

^{52}Mn can be only produced by the (d,α) reaction channel up to the threshold energy of the ^{56}Fe(d,2nα)^{52}Mn reaction (Q = -15.33 MeV). The activities of short lived ^{52m}Mn metastable state were measured soon after the end of irradiation. Long lived ^{52g}Mn ground state was measured after lapse of cooling time comparable to at least ten times the amount of the ^{52m}Mn half-life (after more than 5 h). ^{52m}Mn decays for 1.75% to the ground state, for 98.25% to the stable ^{52}Cr. Measured data of

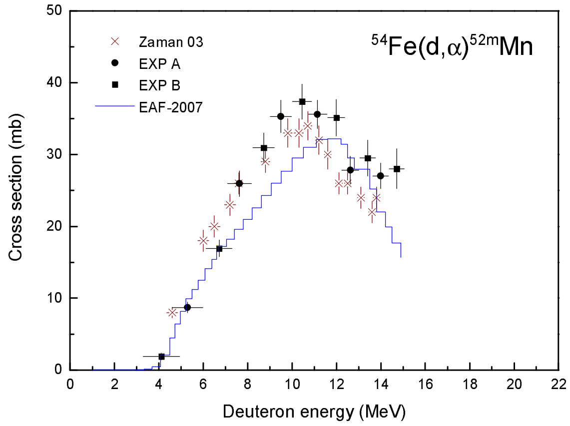

Fig. 2. (Color online) Cross section of the ^{54}Fe(d,α)^{52m}Mn reaction.

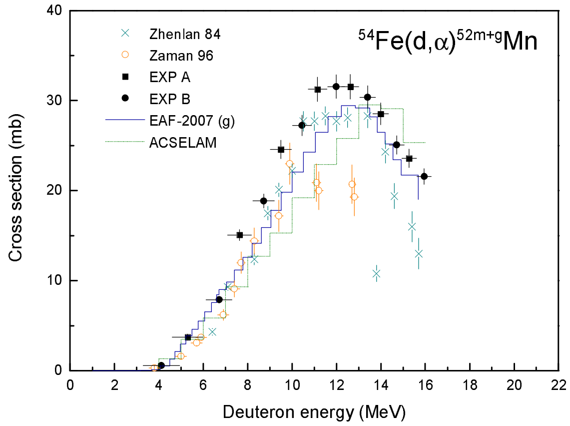

Fig. 3. (Color online) Cross section of the ^{54}Fe(d,α)$^{52m+g}$Mn reaction.

the ^{54}Fe(d,α)^{52m}Mn reaction are shown in Fig. 2. Cumulative cross sections of the ^{54}Fe(d,α)$^{52m+g}$Mn reaction are presented in Fig. 3. Good agreement with the evaluated data can be observed.

3. Cross section of ^{58}Fe(d,p)^{59}Fe reaction

Only the ^{58}Fe(d,p)^{59}Fe reaction leads to the ^{59}Fe production. A comparison with earlier published data and evaluated cross sections is shown in Fig. 4. Disagreement between measured and evaluated data can be evidently seen.

4. Cross section of ^{nat}Fe(d,x)^{56}Co reaction

In the energy interval up to 20 MeV the ^{56}Co isotope can be produced by the following reactions: ^{54}Fe(d,γ), ^{56}Fe(d,2n), ^{57}Fe(d,3n). Figure 5 shows comparison with other experimental data. There is good agreement in most cases between this work and other authors.

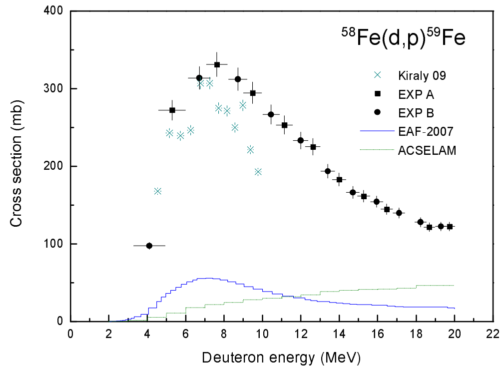

Fig. 4. (Color online) Cross section of the ^{58}Fe(d,p)^{59}Fe reaction.

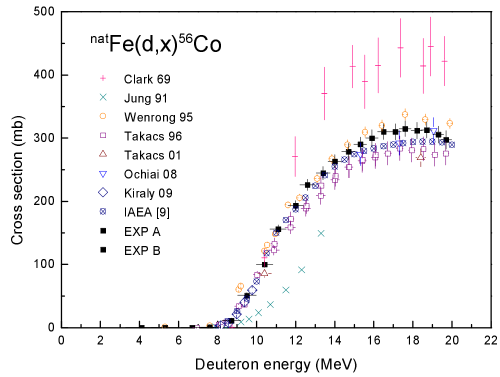

Fig. 5. (Color online) Cross section of the ^{nat}Fe(d,x)^{56}Co reaction.

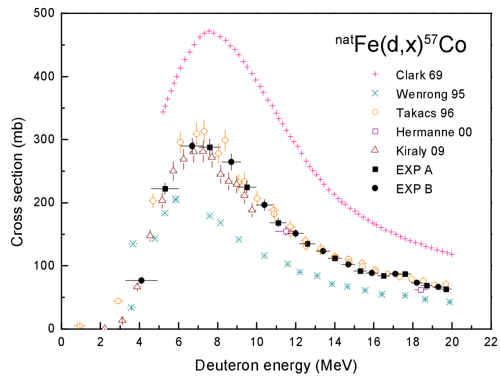

Fig. 6. (Color online) Cross section of the ^{nat}Fe(d,x)^{57}Co reaction.

5. Cross section of ^{nat}Fe(d,x)^{57}Co reaction

Three reactions as a whole can lead to the production of the ^{57}Co isotope in the energy range up to 20 MeV, namely: ^{56}Fe(d,n), ^{57}Fe(d,2n) and ^{58}Fe(d,3n). The comparison of experimental data is shown in Fig. 6. Good agreement with some earlier published data can be seen.

6. Cross section of ^{nat}Fe(d,x)$^{58m+g}$Co reaction

The activity of long lived ^{58g}Co isotope was measured after the cooling time comparable to the period

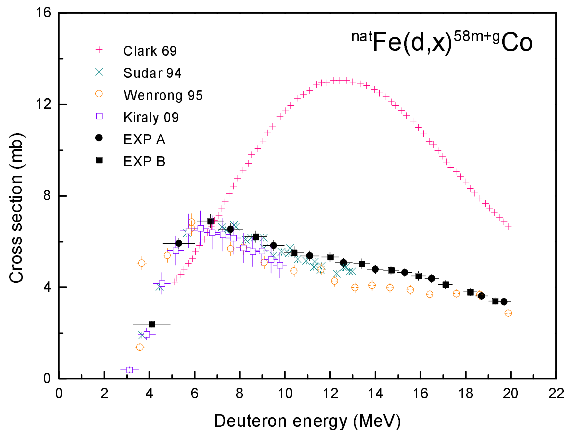

Fig. 7. (Color online) Cross section of the ^{nat}Fe(d,x)$^{58m+g}$Co reaction.

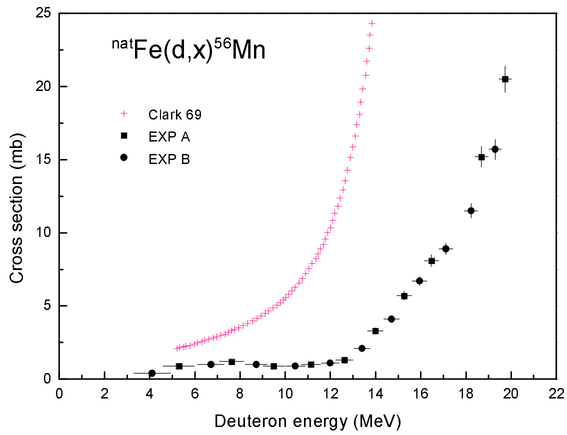

Fig. 8. (Color online) Cross section of the ^{nat}Fe(d,x)^{56}Mn reaction.

of ^{58m}Co complete decay. The metastable state of the ^{58}Co isotope is directly non-measurable with regard to low energy and weak intensity of only the one value of gamma-ray energy. In Fig. 7 there are presented and compared cumulative cross sections of ^{nat}Fe(d,x)$^{58m+g}$Co reaction.

7. Cross section of ^{nat}Fe(d,x)^{56}Mn reaction

The ^{56}Mn radioisotope can be produced by deuteron collisions with each isotope of Fe natural abundance in the range up to 20 MeV. Cross sections of the ^{nat}Fe(d,x)^{56}Mn reaction are presented in Fig. 8. EXFOR database contains only one file with comparable values.

V. ACTIVITY COMPARISON

The induced activity of each foil was calculated using the FISPACT-2007 code. A comparison of calculated and measured values is presented in C/E form in Fig. 9.

Phenomenal disagreement especially in the region of lower energies can be observed. In particular, it is caused

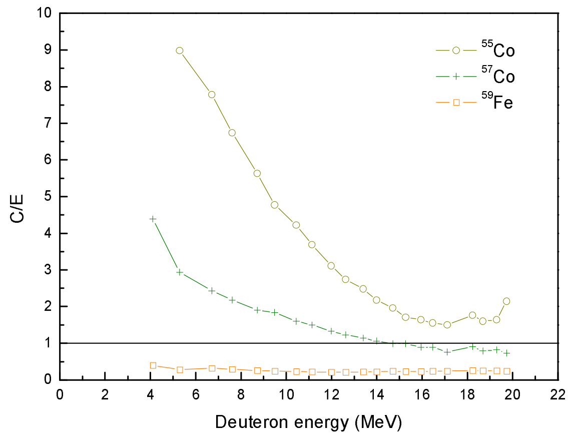

Fig. 9. (Color online) Comparison of measured and calculated activities.

by considerably different cross section values presented in EAF-2007 library in comparison with experimentally measured data (see Figs. 1 and 4).

VI. SUMMARY

Cross section values of several deuteron induced activation reactions on Fe and Al thin foils were measured and compared with EXFOR database, EAF-2007 and ACSELAM data libraries.

The comparison of obtained experimental activities with results of the FISPACT-2007 code was presented. Significant disagreement between measured and calculated data can be caused by insufficient description of deuteron breakup mechanism in calculation model.

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