

International Atomic Energy Agency

INDC(ARG)-012

Distr.: G

IN DC

INTERNATIONAL NUCLEAR DATA COMMITTEE

**INTEGRAL ACTIVATION CROSS SECTION RATIOS OF
Ti(n,x)Sc-46, Ti(n,x)Sc-47, Ti-48(n,p)Sc-48, Ti-50(n, α)Ca-47
RELATIVE TO Al-27(n, α)Na-24 IN THE NEUTRON SPECTRUM
PRODUCED BY 23.2 MeV DEUTERONS INCIDENT ON A
THICK Be METAL TARGET**

M.D. Bovisio de Ricabarra, D. Waisman and G.H. Ricabarra
Argentine National Atomic Energy Commission
Avda. Libertador 8250, Buenos Aires, Argentina

May 1993

Reproduced by the IAEA in Austria
May 1993

INDC(ARG)-012

Distr.: G

INTEGRAL ACTIVATION CROSS SECTION RATIOS OF
Ti(n,x)Sc-46, Ti(n,x)Sc-47, Ti-48(n,p)Sc-48, Ti-50(n, α)Ca-47
RELATIVE TO Al-27(n, α)Na-24 IN THE NEUTRON SPECTRUM
PRODUCED BY 23.2 MeV DEUTERONS INCIDENT ON A
THICK Be METAL TARGET

M.D. Bovisio de Ricabarra, D. Waisman and G.H. Ricabarra
Argentine National Atomic Energy Commission
— Avda. Libertador 8250, Buenos Aires, Argentina

May 1993

INTEGRAL ACTIVATION CROSS SECTION RATIOS OF $Ti(n,x)Sc46$,
 $Ti(n,x)Sc47$, $Ti48(n,p)Sc48$, $Ti50(n,\alpha)Ca47$ RELATIVE TO
 $Al27(n,\alpha)Na24$ IN THE NEUTRON SPECTRUM PRODUCED BY 23.2 MeV
DEUTERONS INCIDENT ON A THICK Be METAL TARGET

M. D. Bovisio de Ricabarra, D. Waisman and G. H. Ricabarra

División de Física Nuclear, Centro Atómico Bariloche, Comisión Nacional de Energía Atómica, Avda. Bustillo 9500, Bariloche, Argentina. National Atomic Energy Commission, Avda. 9 de Julio 369, 1200 Buenos Aires, Argentina.

Received 20 May 1993; accepted 9 November 1993. This work was partially funded by the Argentine Ministry of Education and Culture and by the CNEA (Comisión Nacional de Energía Atómica).

ABSTRACT - In this paper we report the results of new measurements of the integral activation cross section ratios have been made and measured for $Ti(n,x)Sc46$, $Ti(n,x)Sc47$, $Ti48(n,p)Sc48$, and $Ti50(n,\alpha)Ca47$ relative to $Al27(n,\alpha)Na24$, in the neutron spectrum produced by 23.2 MeV deuterons incident on a thick metal Be target. Validation of these cross sections in a high energy neutron continuum and a spectrum bias the object of this work. The neutron spectrum in the irradiation site has been obtained in a previous work and tested by the excellent agreement obtained (1-3%) between experimental and ENDF/B-V or VI calculated fission ratios to U235. Evaluated activation and cross section libraries have been used to calculate the titanium integral activation cross sections in the irradiation spectrum. In addition a new group of experimental differential data, non evaluated, published established from 1990 to 1992 (Jülich, Geel, ANL) was also taken into account to calculate the integral cross sections. A comparison of the Ti isotopes' experimental integral activation cross section with the calculated values shows an excellent agreement with the new set of non evaluated differential data and poor agreement with the evaluated libraries.

In the Cf252 spectrum averaged cross section shows similar behaviour: $\sigma_{Ti46} = 2.0(1) \times 10^{-2}$, $\sigma_{Ti47} = 2.0(1) \times 10^{-2}$, $\sigma_{Ti48} = 2.0(1) \times 10^{-2}$, $\sigma_{Ti50} = 2.0(1) \times 10^{-2}$ and $\sigma_{Ti48} = 2.0(1) \times 10^{-2}$ barns at 23.2 MeV. The $Ti48$ and $Ti50$ cross sections are in good agreement with the calculated values.

Introduction - We will review some known data on the activation cross sections of the Ti isotopes. Titanium (n,p) and (n,α) activation cross sections, reactions, are important in neutron dosimetry and fusion reactor technology. The first measurements of the Ti isotopes were made by

several researchers, in a Cf252 fission-neutron spectrum, in the U235 fission spectrum produced thermal neutrons, and one measurement made recently by the Jülich group, in neutron spectra induced by 20 and 25 MeV deuterons incident on a Be metal target. In this work we present our results obtained at 23.2 MeV. The objective of this work is the validation and testing of the titanium activation cross sections in the high energy spectrum produced by 23.2 MeV deuterons impinging in a thick beryllium target at the Tandar Accelerator of CNEA (Cátedra de Física). Previous measurements^{1,2} of Th232, U236 and U238 integral activation cross sections relative to U235 fission cross section, in the same facility and spectrum showed an excellent agreement (2-1-3%) with the calculated ratios using ENDF/B-V or VI libraries and the unfolded spectrum. This is a stringent test of the technique used and the unfolded neutron spectrum ob-

tailed, and to add new isotopes around the Na24 isotope. Unfortunatly, the available time was limited, so we had to make some assumptions about the reaction rates of the other isotopes.

II. IRRADIATION AND NEUTRON FLUX MONITORING

Experiments were made at the tandem accelerator of the CNEA, with deuterons of 20.2 MeV and $\approx 2.35 \mu\text{A}$ average beam current. The detectors were placed at 4 cm from the beam spot in the Be target at approximately 0 degree. Two irradiations (TAN8 and TAN9) of about 48 hours were made.

An activation stack composed of metal foils wrapped with thin aluminum was irradiated together with a SSNTD stack as described in ref. [1], to assure exactly the same spectrum as in the unfolding spectrum measurement. The Na24 activity distribution of Aluminum foils intercalated in the stacks was used to check geometrical reproducibility and normalize the results to the same flux at the back of the stack ($\approx 9.5 \times 10^7 \text{n/sec/cm}^2$). The various foil thicknesses are:

The titanium foil was measured to obtain the titanium reactions. Al27(n, α)Na24 was used as flux monitor, Au and Nb were used as secondary monitors. The values:

The titanium, niobium and aluminum foils in the activation stack were 1.25, 1.0 and 0.18 mm thick respectively and have 0.75 mm diameter, and the gold foil was 0.07 mm thick and 1 cm diameter. The total sample length is 1.5 cm.

The thicknesses of aluminum foil are not yet known.

III. ACTIVATION MEASUREMENTS

Al(n, α)Sc46, Ti(n, α)Sc47, Ti48(n,p)Sc48, Ti50(n, α)Ca47 integral cross sections were measured by activation technique. Flux monitoring and spectrum verification was made by measuring the activity of Al27(n, α)Na24, Au197(n,2n)Au196 and Nb93(n,2n)Nb92m monitor reactions.

The neutrals induced photopeaks activities in Ti of Sc47 (34422 days; 99.987% 159.4 keV), Sc46 (83.83 days; 99.984% 899.3 keV and 99.987% 1120.5 keV), Sc48 (1.821 days, 100% 983.5) and 1312.0 keV, and 97.5% 1037.5 keV) and Ca47 (4.153 days; 74.9% 1297.1 keV) were measured in a 20% reverse HP-Ge diode with a thin Be window.

The activities of the first run (TAN8) were measured at 18 cm and 22.5 cm distance from the diode. The activities corrected for efficiency in both geometries agree within 1%, except 2% for the 1297.1 keV photo-peak that have poor statistics at 22.5 cm. The activity of each peak was weighted averaged.

The second run (TAN9) was only measured at 18 cm. The activity of each gamma ray from the two runs, corrected for time of irradiation and beam current fluctuations, agree 1-2%. These activities were weighted averaged and reduced for photopeak gamma intensity, gamma self-absorption in the sample and differences in flux due to the foil position in the sample stack. True coincidences summing-up, calculated with Andreev et al.² formalism neglecting angular correlation³ was negligible.

Titanium reaction rates were measured relative to Al27(n, α)Na24 reaction rate, Table 1. Reaction rates are expressed per atom of isotope, Ti(n, α)Sc47 per atom of Ti47, Ti48, Ti(n, α)Sc46 per atom of Ti48, Ti(n, α)Sc48 per atom of Ti48. The reaction rates of the secondary standards, Au197(n,2n) and Nb93(n,2n), were also measured and their ratio relative to Na24 agree 0.6% or better with the same ratios obtained in the

unfolding experience described in ref. 21. In this work we used the same set of UNF-90 evaluated differential cross section data as those given in Table 1. Experimental Results

Reaction	Rate ^a (d/s/atom)	Ratio to Na24	Ratio $\times \langle \sigma \rangle$ (mbarn)
A127(n, α)Na24	3.85E-16±2.2%	15.15	40.54±4.1%
Au197(n,2n)Au196	5.83E-15±3.5%	15.15	614.2±4.1%
Nb93(n,2n)Nb92m	1.15E-15±2.5%	2.988	121.1±3.4%
Ti(n,x)Sc46	1.40E-15±2.5%	3.635	147.4±3.3%
Ti(n,x)Sc47 ^b	1.32E-16±4.7%	0.344	13.93±5.2%
Ti48(n,p)Sc48	1.86E-16±2.6%	0.484	19.60±3.4%
Ti50(n, α)Ca47	2.42E-17±4.8%	0.0628	2.548±5.2%

^a Rate per atom of Ti46, ^b Rate per atom of Ti47+Ti48
 $\langle \sigma \rangle$ A127(n, α) calculated using unfolded spectrum ITER1 and differential data from IRDF90

The errors in the correction factors are ±10%. The error in gamma efficiency determination is less than 1% in most cases (except 2% for the low energy ~159.4 keV photopeak of Sc47) plus 2% error from the intensity uncertainty of calibration sources.²² Extrapolation and saturation calculations errors due to half life uncertainties were always negligible. 3) Self-absorption in the sample was calculated assuming exponential approximation and photonic absorption coefficients from Shirley²³, amounts to 1 or 2% in all cases, except 5% for the Sc47 photopeak. Errors were assumed to be equal to half the corrections. 4) The relative error in the normalization factors to the back stack flux was estimated between 0.2% and 0.6% according to foil location in the stack. 5) A +4.6% correction was applied to gold because the foil diameter (1cm) was lower than the standard diameter of 0.5". The error is 0.5% as discussed in a previous work².

4. Cross Sections Calculation

4.1. Differential Cross Sections Used in The Calculations

Several cross sections libraries have been used for titanium isotopes:²⁴ 1) ENDF/B-VI evaluated neutron dosimetry file; 2) IAEA evaluation by Manokhin et al.²⁵, which is mainly based on BOSPOR-80 Machine Library of evaluated Threshold Reaction Cross Sections and its testing by means of Integral Experiments²⁶; 3) The evaluation made by Zhao Wenrong et al²⁷; 4) International Reactor Dosimetry File^{28,29}; IRDF90. 5) The JENDL Dosimetry File with data from graphs of ref. 12. The ENDF/B-VI titanium threshold activation cross sections have been evaluated in Jan. 1977 by C. Philis, O. Bersillon and D. Smith and the distribution was made in Jan. 90 (ENDF/B-VI Dosimetry File). The Japanese evaluation was made in 1977 by Manokhin (ENDF/B-VI), IRDF90 and Manokhin et al. supply (n,np) cross section data, that are basically the same as those from the 1977 evaluation of C. Philis, O. Bersillon and D. Smith. The Japanese evaluation also supplies (n,np) cross section data in JENDL Dosimetry File^{28,29}. The JENDL

Zhao Wenrong et al. evaluation includes implicitly (n,np)

(n,nd) and (n,nt) reactions, see fig. 6, 7, 8 in ref. 9.

New differential data published from 1990 to 1992 has not been used in ENDF/B-VI, Manokhin et al., Zhao et al. and IRDF90 evaluations.

A new measurement of Ti47(n,p)Sc47 reaction cross section from 1.2 to 8 MeV was done at ANL to investigate a 25% discrepancy between the differential and the averaged data for Cf252 neutron spectrum¹³.

Excitation functions of natural Ti(n,x)Sc46,47,48 from 12.5 to 19.6 MeV, has been obtained at Geel Van de Graaf Accelerator¹⁴ and data from 5.4 to 10.5 MeV at the Jülich Compact Cyclotron^{15,16}.

This new group of experimental data (Jülich-Geel-ANL) from 1990 to 1992 was also used to calculate the integral cross sections and compared with the integral cross sections obtained in this work. The data has been taken from tables and in some cases from figures of the published papers^{13,14,15,16} and no evaluation was made.

IIB- Calculation of Titanium Isotopes Integral Cross Sections

Relative to A127(n,a)Na24

The titanium sample has been irradiated simultaneously with different standards. The main standard A127(n,a)Na24, and two secondary standards Nb93(n,2n)Nb92m and Au197(n,2n)Au196 which are added in the analysis to see the consistency of the experimental results. The data can be found at the following references and in the tables below and in the next section of this paper.

Table 2. Standards Integral Cross Section Calculation

	Reaction	IRDF90	Manokhin	ENDF/B-VI	Chinese
A127(n,a)Na24	40.54	41.14	41.12	40.81	
Au197(n,2n)Au196	602.3	602.7	592.5	584.0	
Nb93(n,2n)Nb92m	118.7	120.7		117.1	

$\langle \sigma \rangle$ averaged on unfolded neutron spectrum ITER1

As it is explained in the text the stack of foils used is the same as the one used to obtain the irradiation spectrum, ITER1, by unfolding techniques¹. The integral cross sections of A127(n,a)Na24 was calculated with the ENDF/B-VI, Manokhin et al., IRDF90, and Zhao et al. libraries. As shown in Table 2, the agreement is around 1.5%.

The integral cross sections of titanium isotopes on ITER1 spectrum were calculated for IRDF90, ENDF/B-VI, JENDL, Manokhin et al., the evaluated chinese library, and the new group of differential experimental data called Jülich-Geel-ANL.

The experimental integral cross section data was obtained from the ratio of Ti(n,x)Sc46, Ti(n,x)Sc47, Ti48(n,p)Sc48 and Ti50(n,a)Ca47 reaction rates relative to the standard reaction rate (A127(n,a)Na24) of Table 1 and $\langle \sigma \rangle$ of the standard calculated with IRDF90. The experimental and calculated values are compared in Tables 8 and 9; a brief table 10 is reported only

Table 3. Experimental Integral Cross Sections and
Calculated with Jülich-Geel-ANL Data

Reaction	Experimental $\langle\sigma\rangle$ (mbarn)	Calculated $\langle\sigma\rangle$ (mbarn)	(C/E-1) %
Ti(n,x)Sc46 ^a	147.4±3.3%	149.0	+1.1
Ti(n,x)Sc47 ^b	13.93±5.2%	14.98 ^c	+7.6
Ti48(n,p)Sc48	19.60±3.4%	19.80	+1.0
Ti50(n, α)Ca47	2.548±5.2%	2.572	+0.9

^a $\langle\sigma\rangle$ averaged on unfolded neutron spectrum ITER1.

^b Ti(n,x)Sc46 per atom of Ti46(8.2%).

^c Ti(n,x)Sc47 per atom of Ti47+Ti48(81.2%).

$\alpha(E)$ for 3MeV<E<5.37MeV from ANL.

Table 4. Calculated Integral Cross Sections with Evaluated Libraries and Experimental Results

LIBRARY	Ti(n,x)Sc46 ^a	Ti(n,x)Sc47 ^b	Ti(n,x)Sc48 ^c
IRDF90	133.4 ± 9.5	9.628 ± 4.31	18.00 ± 8.2
MANOKHIN et al.	139.0 ± 10.0	9.995 ± 4.28	18.04 ± 8.0
ENDF/B-VI (Zhao Wenrong et al.)	189.4 ± 6.0	10.28 ± 4.26	18.85 ± 3.8
CHINESE	138.9 ± 6.3	9.62 ± 4.02	18.04 ± 8.0
JENDL (JENDL-3.2)	142.2 ± 4.1	12.45 ± 4.10	18.35 ± 6.4
Experimental ^d	147.4±3.3%	13.93±5.2%	19.60±3.4%

^a Per atom of Ti46, ^b Per atom of Ti47+Ti48, ^c Per atom of Ti48.

^d $\langle\sigma\rangle$ averaged on unfolded neutron spectrum ITER1.

^e Estimated with data from graphics of Ref. 12.

^f Measured Integral Cross Section (this paper).

III-Conclusions

The main comment is that the new set of differential data published between 1990 to 1992 called Jülich-Geel-ANL gives a much better agreement with the experimental integral cross sections of titanium isotopes than the evaluated libraries (Manokhin et.al., ENDF/B-VI, Zhao Wenrong et al., IRDF90 and JENDL).

This suggest that at least for Ti(n,x)Sc46 and Ti(n,x)Sc47 the contribution of (n,np) and (n,d) reactions are underestimated in the evaluated libraries.

On the other hand it is interesting to see how the cross section data used to calculate compares with integral cross sections measured in the fission spectrum of a Cf252 source. The experimental values are the recommended values given by Manhart¹⁷. Both values are compared in Table 5. The NBS Cf252 neutron spectrum¹⁸ was used for average cross section calcula-

tions, neutron spectra, spectra of various nuclides and other

physical quantities, and the code is available.

Table 5. Cf252 Spectrum Averaged Neutron Cross Sections.

LIBRARY	$\langle\sigma\rangle$ Ti(n,x)Sc46		$\langle\sigma\rangle$ Ti(n,x)Sc47		$\langle\sigma\rangle$ Ti(n,x)Sc48	
	C/E-1	%	C/E-1	%	C/E-1	%
IRDF90	12.62	-11	19.41	-0.1	3953	-7.5
Jülich-Geel-ANL	13.88	+2.2	19.63	+1.0	4364	+1.4
ENDF/B-VI	13.49	+5.0	24.10	+24.	4092	+4.2
JENDL	13.59	+4.3	20.76	+6.8	4028	+5.7
Mannhart ^a	14.20 ± 0.24		19.43 ± 0.31		4275 ± 0.078	

$\langle\sigma\rangle$ of Ti(n,x)Sc46,Sc47,Sc48 expressed per atom of Ti46,Ti47,Ti48

^a Calculated value on Cf252 spectrum (NRS) from ref. 12.

^b Recommended experimental values from ref. 17.

For the neutron spectrum of Cf252 the new set of data (Jülich-Geel-ANL) gives an excellent agreement.

For the Cf252 spectrum average neutron cross section of Ti(n,x)Sc47 calculated with ENDF/B-VI data (C/E-1)=+24%. This discrepancy reverse in sign for the d(Be) breakup neutron spectrum (ITER1 spectrum). (C/E-1)=-31%.

IRDF90 evaluation for Ti(n,x)Sc47 agrees with Mannhart recommended value in Cf252 spectrum, however in the d(Be) breakup neutron spectrum (C/E-1)=-31%.

In Fig. 1 we compare the non evaluated experimental data of Jülich-Geel-ANL with several evaluated libraries for Ti

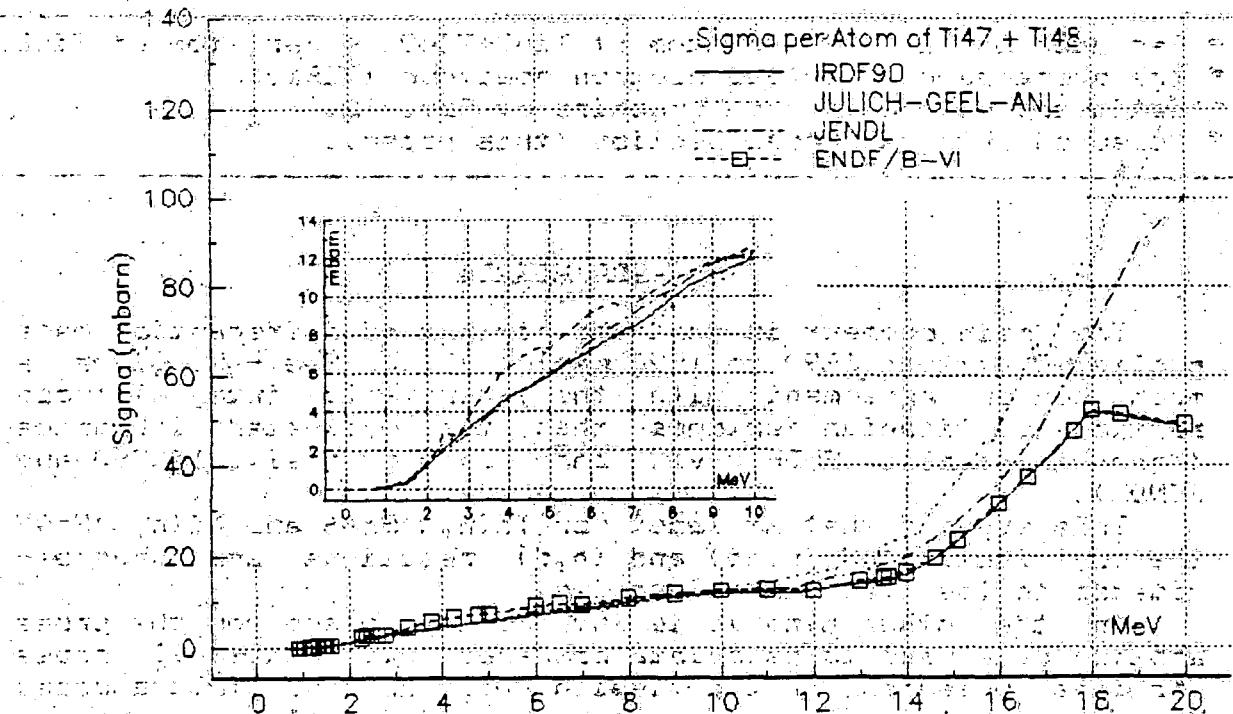


Fig. 1. Comparison of Ti(n,x)Sc47 Differential Sigma Cross Sections on evaluated libraries and experimental data (not been point fitted to the data).

$(n,x)Sc47$. It is quite clear the different behaviour above and below 12 MeV, suggesting the underestimation of (n,np) cross section in the evaluated libraries and also ENDF/B-VI overestimation of (n,p) cross section below 10 MeV.

We may conclude emphasizing the importance of the validation of the differential activation cross sections at higher energy neutron spectrum ($E \approx 7.5$ MeV) in addition to the validation at lower energy ($E \approx 2$ MeV) as has been used in the past.

References

1. M. D. Bovisio de Ricabarra, D. Waisman, L. Cohen de Porto, G. H. Ricabarra, "Integral Fis. Cross Sec. Ratios of Th232, U236, U238 Relative to U235 in the Neutron Spec. Produced by 23.2MeV Deuterons on a Thick Be Metal Target", INDC(ARG)-010 (1992).
2. D.S. Andreev et al., Izv. Akad. Nauk. SSSR, Ser. Fiz., 37, 1609 (1973).
3. G.J. McCallum, G.E. Coote, Nucl. Instr. Meth., 130, 189 (1975).
4. V.S. Shirley, 'Table of Radioactive Isotopes', J. Wiley and Sons, New York (1986).
5. H.D. Lemmel, IAEA-NDS-100 (1990).
6. V.N. Manokhin et al., 'Handbook on Nucl. Activation Data', Tech. Rep. Series № 273, IAEA (1987). (Part 2-3, 305-309).
7. V.M. Bychkov, K.J. Zolotarev, A.B. Plashchenko, V.I. Plyaskin, INDC(CCP)-183/L, (1982).
8. V.M. Bychkov, K.J. Zolotarev, A.B. Plashchenko, V.I. Plyaskin, INDC(CCP)-146/LJ, (1980).
9. Zhao Wentong et al., 'Compilation of Measurements and Evaluation of Nuclear Activation Cross Sections for Nuclear Data Applications', INDC(CPR)-16 (1989).
10. H.P. Kocherov, P.K. McLaughlin, IAEA-NDS- 141 (1990).
11. M. Wagner, H. Vonach, A. Pavlik, B. Ströhmaier, S. Tagesen, J. Martinez-Rico, Physics Data, № 13-5 (1990) (Karlsruhe).
12. Masaharu Nakazawa, Katsuhei Kobayashi, Shin Iwasaki, Tetsuo Iguchi, Kiyoshi Sakurai, Yujiro Ikeda and Tsuneo Nakagaya, 'JENDL Dosimetry File', JAERI 1325 (march 1992).
13. W. Mannhart, D. L. Smith, J. W. Meadows, Proc. Specialist Meeting on Neutron Activation Cross Sections for Fission and Fusion Energy Applications, Sep. 1989, Argonne, USA (Ed. M. Wagner, H. Vonach), pp 121-134, OECD, Paris (1990).
14. N. I. Molla, S. M. Qaim, S. M. Liskiev, R. Widera, Appl. Radiat. Isot., 42, pp 337-339 (1991).
15. N.I. Molla, S.M. Qaim, M. Uhl, Physics Rev. C, 42, pp 1540-1543 (1990).
16. S.M. Qaim, N.I. Molla, R. Wölflle, G. Stöckling, 'Nuclear Data for Science and Technology', 297-300(1992), Springer-Verlag, Proc. Int. Conf. ,13-17 May 1991, Jülich, Fed. Rep. of Germany (Ed. S.M. Qaim).
17. W. Mannhart, 'Handbook on Nuclear Activation Data', Tech. Rep. Series № 273, IAEA (1987). (Part 2-4, p. 416).
18. J. Grundl and C. Efsenhauer, 'Neutron Cross Sections for Reactor Dosimetry', Vol. I,(Review paper), IAEA-280, p. 66, (1978).