EUROPEAN FUSION DEVELOPMENT AGREEMENT

EFDA–JET–PR(05)25

G. Bonheure, M. Hult, J. Gasparro, S. Popovichev, L. Bertalot,
A. Murari and JET EFDA contributors

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G. Bonheure[1], M. Hult[5], J. Gasparro[5], S. Popovichev[2], L. Bertalot[4], A. Murari[3]
and JET EFDA contributors

[1]Partners in the Trilateral Euregio Cluster, ERM - KMS, B 1000 Brussels, Belgium
[2]EURATOM/UKAEA Fusion Association, Culham Science Centre, Abingdon, OX14 3DB, UK
[3]Consorzio RFX, Euratom/ENEA Association, Padova, Italy
[4]Euratom/ENEA Association, Frascati, Italy
[5]EC-JRC-IRMM, Institute for Reference materials and Measurements , Geel, Belgium
** See annex of J. Pamela et al, "Overview of JET Results ",*
(Proc.20 [th] IAEA Fusion Energy Conference, Vilamoura, Portugal (2004).

Preprint of Paper to be submitted for publication in
Review and Scientific Instruments

ABSTRACT

A new instrument has been developed at JET to measure losses of fast particles in the MeV energy range. Neutron fluxes are recorded as well. The measurement technique is based on activation of in vessel samples. These samples are used as flux monitors. They are installed on a specifically designed holder, into six slots at different angular positions with respect to the magnetic field. This important design feature allows 1) a measurement of the local pitch angle distribution of fast particles and 2) a strong discrimination between neutron-induced and charge particle induced activation because neutron-induced activation is independent on the magnetic field direction. A special technique for low level activation, 'Ultra low-level gamma ray spectroscopy', was used to investigate the JET samples with enhanced sensitivity. First application of the instrument in helium plasmas experiments [1] on JET is reported. Some measured activation products are a result of neutroninduced activation. A neutron spectrum was inferred from these measurements in agreement with the results of another neutron spectrometer. ^{7}Be, an activation product involving mostly high energy protons and deuterons was measured in signi cant amount. Two nuclear reactions possibly due to alpha particles were registered, though at a level close to the detection limit.

1. INTRODUCTION

Measurements of both slowing down and escaping alpha particles remain one of the difficult issues in reactor grade plasmas. The lack of established techniques to measure these particles has been recognized as one of the diagnostic weakness of the tokamak community, requiring further R&D in the perspective of the ITER project. Collecting data for the 'non-activated' phase of ITER is also needed for regulatory purposes. In JET a series of methods are being developed to measure the slowing down of alpha particles [2, 3]. These approaches involve different experimental techniques, ranging from neutron spectrometry and γ-ray and Extreme Ultraviolet spectroscopy to Neutral particle Analysis. On the contrary, at the moment no diagnostic is available to measure the alpha particle and fast ion losses. There is also need for regulatory purposes to collect activation data on the so-called 'non-activated' phase of ITER. The present article describes the application in JET of a technique to measure losses of fast ions in the MeV energy range based on the activation technique[4, 5]. The idea is to insert an activation probe into the vacuum chamber. Carefully selected samples are activated from reactions of type (X, p),(X,n), (X, γ), etc ... where X is a light charged particle p,t,d,^{3}He and α. After exposure, samples are extracted and their activation products are measured using e.g gamma-ray spectrometry. Particles with energy falling below the threshold energy are not recorded and this implies that: 1) The application of the activation technique is limited to the MeV energy range 2)In case of a strong flux of low energy events, there is no saturation effect compared to other detection techniques.

2. IN-VESSEL ACTIVATION PROBE

The new activation probe is shown in figure 1. Samples are installed into six slots at different angular positions with respect to the magnetic field. This allows to measure the local pitch angle

distribution of incident energetic particles. Each slot can be filled with several samples of different material composition. Multiple nuclear reactions are simultaneously used in order to discriminate between different ion species and to record some spectral information. In the case of the measurements reported here, 18 samples were used with size indicated in the table below. Each slot was filled with the same composition of samples: (i) Pure Ti near the tip of the probe (ii) MgF_2 located just above the Ti and (iii) an alloy of Ti(90% by mass), Al(6%)and V(4%) located above the MgF_2. Six additional samples were installed at the back of the probe head in a shielded location for background-check.

Material	*Number of samples*	*Size*	*Thickness*	*Mass*
Natural Ti	*6*	*10mm × 10mm*	*1mm*	*0.45g*
M gF_2	*6*	*10mm × 10mm*	*1mm*	*0.315g*
Ti(90%)AI(6%)V(4%)	*6*	*30mm × 10mm*	*1mm*	*1.35g*

2.1. PROBE LOCATION

The activation probe is installed at the lower end of a manipulator arm. The probe shaft has an access vertically downwards inside JET vacuum vessel through a 'slit shaped' port. Angular position of the samples is shown in the figure 2. Local losses of fast ions are expected to be highly anisotropic. Trajectory calculations for typical fast ion velocity distributions show non-uniform angular distributions of the activation products.

3. MEASUREMENTS

After exposure, samples are extracted from the vacuum vessel and activation products are measured with high purity germanium detectors. This detector is suitable for high energy resolution gammaray spectrometry. A first gamma-ray spectrometry analysis was conducted on the JET site, 48 hours after the end of experiments. It is shown in figure 3. This spectrum includes the gamma-ray sum emission of all samples and sample holder together. Main activation products detected in this first analysis were Scandium isotopes, ^{46}Sc, ^{47}Sc, ^{48}Sc, ^{7}Be, ^{24}Na and various background radionuclides. As intensities of gamma-ray lines from each individual sample were rather weak, more advanced technique were necessary, including Ultra Low-Level Gamma-ray Spectroscopy (ULLGS), a special low background technique.

3.1. ULTRA LOW-LEVEL GAMMA-RAY SPECTROSCOPY TECHNIQUE

The main features of this technique are

- Underground laboratory
- Highly efficient detectors
- Detector system and shielding made of selected radiopure elements

To detect very weak activity requires an underground set-up. Measurements above ground suffer

from the fact that highly energetic radiation interferes with detectors and create non-desirable background. The samples were analyzed at a nuclear metrology institute which operates several high purity Germanium detectors in a special underground laboratory facility called HADES. It is located 223m below sea level at Belgian Nuclear Research site. Figure 4 shows the gain of 3 order of magnitude which is achieved in the background reduction. The ULLGS spectra confirmed the presence of activation products cited above and revealed further ones: ^{54}Mn, ^{56}Co, ^{57}Co, ^{58}Co. ^{51}Cr was also found in trace amount but at a level under the decision threshold. The main contribution to the uncertainty comes from counting statistics. There is also a signi cant contribution from uncertainties due to geometry because of the short distance between the +ample and the detector. For more details about our ULLGS analysis see in [6].

3.2. SURFACE ANALYSIS OF SAMPLES

In order to investigate the contamination of sample surfaces, standard Secondary Ion Mass Spectroscopy (SIMS) measurements were performed as well. The following 'contaminating' elements were detected with SIMS measurements on the surface layer of the TiAlV samples :

- Boron
- Beryllium
- Carbon
- Iron

Boron, likely, comes from the sputtering of the Boron Nitride sample holder. Carbon and Beryllium are relatively important impurity elements inside the vacuum vessel. Beryllium evaporation was also applied before experiment. Iron is sputtered from the vacuum vessel walls. These elements are found on all samples and they are not distributed uniformly between the samples as shown in figure 5 for the case of Boron.

4. DISCUSSION OF EXPERIMENTAL RESULTS

Figure 6 shows activation measurements data plotted versus the angular position. The activation product found with the highest activity is the 7Be. In order of decreasing activity, Scandium products come in a second group. In contrast with other radionuclides , the Scandium radionuclides are distributed uniformly over the samples, within measurement uncertainty. The last group includes activation products found in very weak amount, under the level of 10 milliBq per gram. The angular pattern is not uniform. Natural titanium samples (T) are located slightly closer (10mm) to the plasma edge than the TiAlV (V) samples. Figure 6 shows for most activation products a higher activity measured on Natural titanium samples (T) than on (V) samples, that is a decrease of the activation with the distance from the plasma edge. The main processes which are the sources for these activation products are the following:

- Charged particle induced reactions
- Neutron induced reactions
- Contamination of sample surfaces

By contamination of sample surfaces, it is meant activation products which are transported materials from the holder and from the vacuum vessel walls on the sample surfaces. Particularly important in view of monitoring charged particle fluxes, activation products induced by neutron and charged particles must be clearly separated. The angular dependence of the measured activity presented in the above figure helps strongly to discriminate between the different processes. Scandium isotopes are produced primarily through neutron induced nuclear reactions with Titanium. The neutron source in a tokamak plasma is mostly nearly isotropic. That explains why the angular distribution of scandium isotopes is uniform. Scandium isotopes are also found on titanium samples placed at the back of the probe in a location well-shielded from charged particles. In these experimental results shown in figure 6, it is important to note that contrary to usual deuterium plasmas operation of the JET tokamak, neutron-induced activation products are not the dominant activation products measured.

4.1. NEUTRON-INDUCED ACTIVATION

Neutron-induced reactions are shown in figure 3 and are also listed in the table below with the energy threshold and main gamma-ray line energy:

Reaction string	***Energy threshold (MeV)***	***γ (MeV)***
$^{46}Ti(n, p)^{46}Sc$	*3*	*0.889*
$^{47}Ti(n, p)^{47}Sc$	*1*	*0.159*
$^{48}Ti(n, p)^{48}Sc$	*5*	*0.983, 1.037, 1.312*
$^{24}Mg(n, p)^{24}Na$	*5.5*	*1.368*
$^{27}Al(n, \alpha)^{24}Na$	*5.4*	*1.368*

Cross sections for these reactions from [7] are shown in figure 7. ^{46}Sc is produced mainly from the reaction ^{46}Ti(n; p)^{46}Sc. The measured count rate for the ^{46}Sc gamma-ray line is compatible with the calculated rate expected from the total neutron fluence on the samples. ^{47}Sc is produced mainly from the reaction ^{47}Ti(n; p)^{47}Sc. The count rate is similarly compatible with the expected rate from neutron fluence. ^{48}Sc is produced primarily from reaction ^{48}Ti(n; p)^{48}Sc. In usual deuterium operation of the JET tokamak, most of neutrons are emitted at an energy near 2.45MeV. In these Helium plasma experiments in which the activation probe was operated, a signi cant flux of neutrons with energy above 5MeV was observed as seen from the detection of ^{24}Na and ^{48}Sc activation products.

4.1.1. UNFOLDING OF NEUTRON ACTIVATION DATA

The neutron spectrum was determined with a simple unfolding procedure. Each of the above listed nuclear reactions have a particular energy response to the neutron flux, given by the cross section. Multiple $Y_{1...n}$ activation products result from the sample being exposed to the incident neutron flux ϕ (E)

$$Y_{1...n} = \int R_{1...n}(E)\phi(E)dE$$

where $R_{1...n}$(E) is the response to the incident neutron flux. Let us discretize the energy axis in p intervals(p≤n). The above set of integrals is then solved by using the inverse response function to find ϕ (E).

$$\phi_p = \sum_k^n R_{p,k}^{-1} Y_k$$

The spectrum is time-integrated over the total duration of the sample exposure. The spectrum plotted in figure 8 shows the neutron energy distribution typical from these Helium plasma experiments. Neutrons with energy 1MeV < E_n < 3MeV make up for about 55-60% of the neutron fluence, neutrons with energy En > 3MeV about 35-40%, while at energy above 5MeV , the spectrum falls at a few percent. Neutrons with energy above 5MeV represent at most 5% of the total measured fluence. The error in the spectrum comes mainly from statistics and is about 20% at the maximum.

During these Helium plasma experiments, a compact neutron spectrometer (NE213)[9] was available to measure neutron spectra. For the first time, this innovative technique was used simultaneously with the activation probe. The spectrum measured with the NE213 spectrometer is shown in figure 9. The main features found in the activation probe spectrum are similar to the compact neutron spectrometer (NE213) spectrum.

The neutron yield measured with the set of fission chambers [10] was close to 8.5×10^{15} neutrons, time-integrated over all the discharges. In the case of helium plasma experiments with signi cant beryllium impurity content , the following nuclear reactions may contribute to the neutron source [8]:

- Deuterons: D(d,n)^{3}He (Q = 3.3MeV), ^{9}Be(d, nγ)^{10}B (Q = 4.36MeV)
- Helium 4: ^{9}Be(^{4}He, nγ) ^{12}C (Q = 5.7MeV)

Measured neutron spectra indicate most of neutrons (~95%) were found at an energy below 5MeV which indicates that they are mostly produced through the deuterons induced reactions. ^{4}He produced neutrons through the ^{9}Be(^{4}He, nγ)^{12}C reactions account for about 5% of neutron production which is close to previous findings [8]. The fast ^{4}He particle production is estimated in the range of 10^{17}–10^{18}.

4.2. CHARGED PARTICLE INDUCED REACTIONS

A relatively large amount of ^{7}Be activation product was detected on the samples. ^{7}Be is primarily produced with the following nuclear reactions: ^{10}B(p, α),^{10}B(d, αn) which involve ^{10}B. Boron is a

component of the sample holder but it is also an intrinsic impurity always present in the plasma chamber. It is likely that Boron originated mainly from self-sputtering of the sample holder.

Mainly 3 nuclear reactions were used to monitor the flux of escaping α particles at detector location. These reactions are indicated below together with approximate incident fluence threshold and energy threshold for alpha particles.

Reaction	***γ (MeV)***	***Fluence thershold (cm^{-2})***	***α energy threshold (MeV)***
$^{19}_{9}F(\alpha, n)^{22}_{11}Na$	*1.274*	*≤ 1.e+11*	*≥ 2.6*
$^{48}_{22}Ti(\alpha, n)^{51}_{24}Cr$	*0.320*	*≤ 1.e+12*	*≥ 4*
$^{51}_{23}V(\alpha, n)^{54}_{25}Mn$	*0.834*	*≤ 1.e+11*	*≥ 4*

$^{54}_{25}$Mn was detected on both natural titanium and TiAlV samples at a very weak level. $^{22}_{11}$Nawas not observed and it is below the detection limit. Traces of $^{51}_{24}$Cr have been observed. The signal from $^{51}_{24}$Cr is however below the desicion threshold [6]. The main indications from these measurements are: 1) the alpha particle losses at detector location and with energy above the threshold for the above reactions are below the upper limit for detectable flux 2) At very low level of activation, background sources of activation interfere with the measurements: 1) deposition of material is a non negligible contribution and 2) neutron activation of sample impurities can also play a role. Some activation products are not found on MgF_2 samples, e.g Mn-54, which mean that they are not essentially deposited.

SUMMARY

In recent experiments in JET aimed at studying fast ions in Helium plasmas, in-vessel samples were used as flux monitors to measure losses of particles in the MeV energy range. Several activation products were found in the samples as a result of various nuclear reactions. Some activation products are produced as a result of neutron-induced activation. A neutron spectrum is inferred from the measurements and shows that neutron spectrum emitted from these plasmas has a large neutron emission above 2.5MeV. This result is in agreement with another independent measurement of the neutron spectrum. For the first time, a special technique for low level activation 'Ultra low-level gamma-ray spectroscopy' was used to investigate activation of JET samples induced by fast ions and to resolve the angular distribution of fast ion losses. During these experiments , the detector was located in a region of low losses. Two nuclear reactions possibly due to alpha particles were registered, though at a level close to the detection limit. ^{7}Be activation product is measured in significant amount and it is mostly produced in the sample holder as a result of nuclear reactions involving high energy protons and deuterons. Quantitative flux measurements based on the ^{7}Be activation product are currently limited due to uncertainties associated with the transport of material (activated and non activated) on the sample surfaces.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the support and contribution made directly and indirectly by members of plasma boundary group, including M. Stamp, G. Matthews, J. Vince and G. Kaveney. This work was carried out under the European Fusion Development Agreement.

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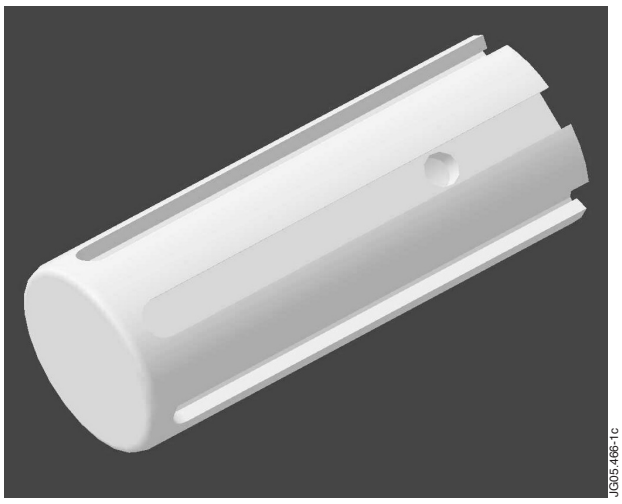

Figure 1: Sketch of the fast particle in-vessel activation probe: the six samples containing slots are regularly spaced and are 60 degree apart

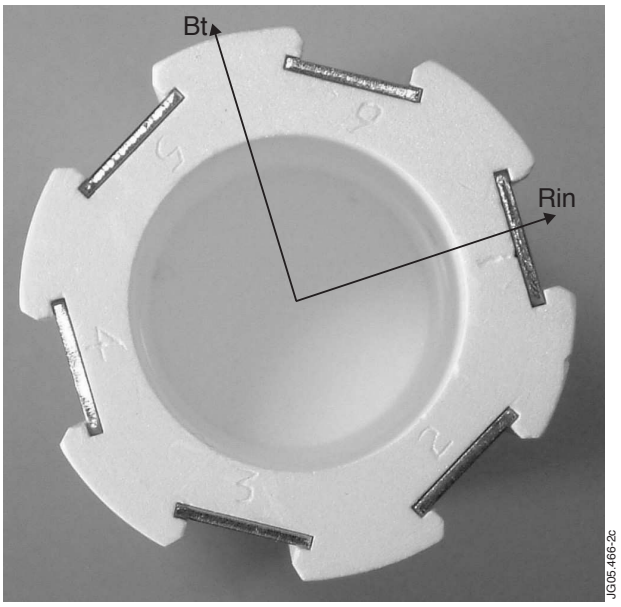

Figure 2: Sample orientations: the six samples containing slots are regularly spaced and are 60 degree apart. Slot numbers are visible on the picture. R_{in} indicates the direction along the major radius and pointing radially inward while B_t indicates the standard direction of the toroidal magnetic field. The orientation angle is counted clockwise from the direction of the toroidal magnetic field, i.e the angle between the toroidal field and slot 1 (R_{in}) is 90 degree.

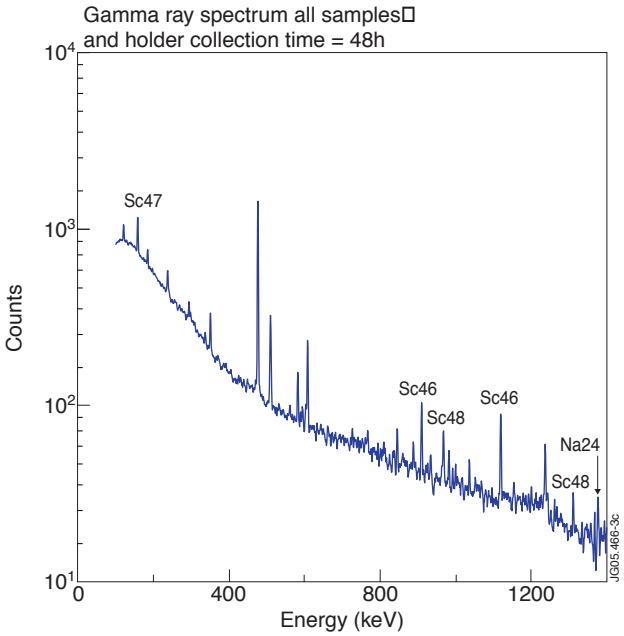

Figure 3: Gamma-ray spectrum of all samples and holder: first spectrum collected after experiment.

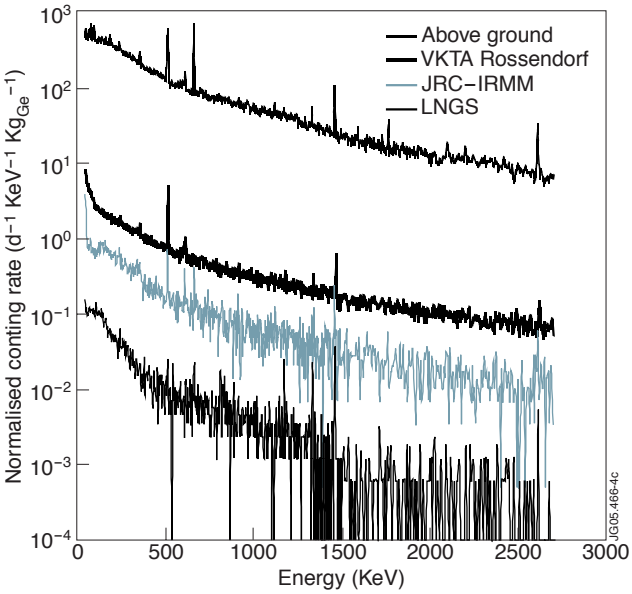

Figure 4: Comparison of normalized background counting rates at sea level and various underground facilities.

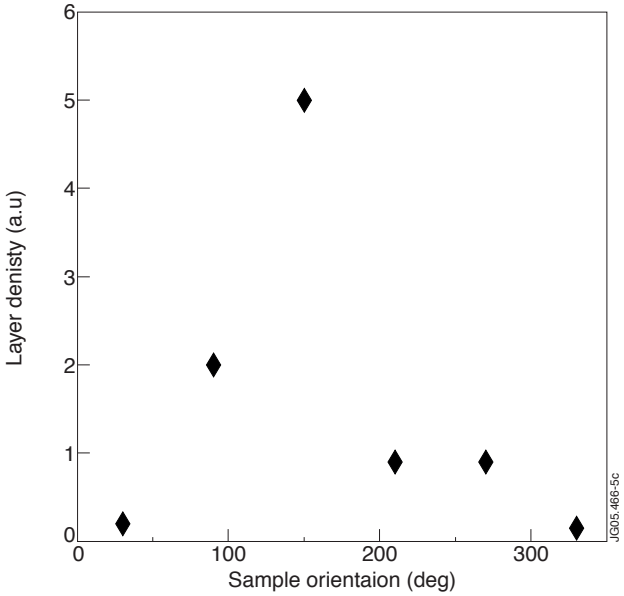

Figure 5: Relative distribution of Boron 10 deposition on the 6 TiAlV samples.

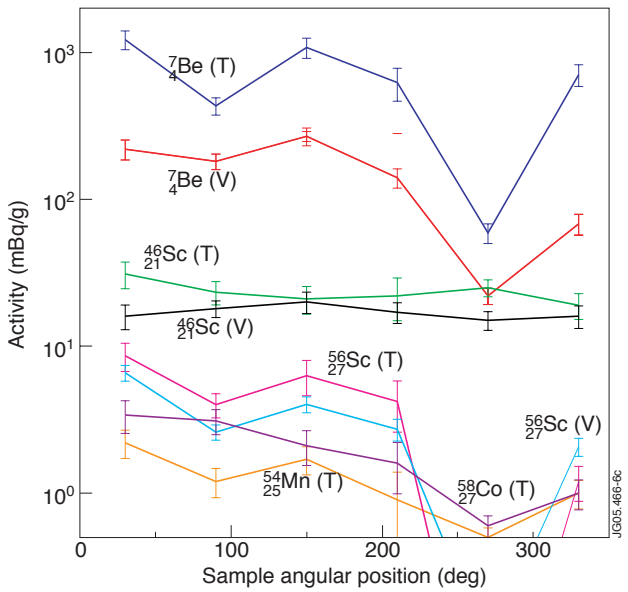

Figure 6: Angular distribution of measured radionuclides for Ti and TiAlV samples.

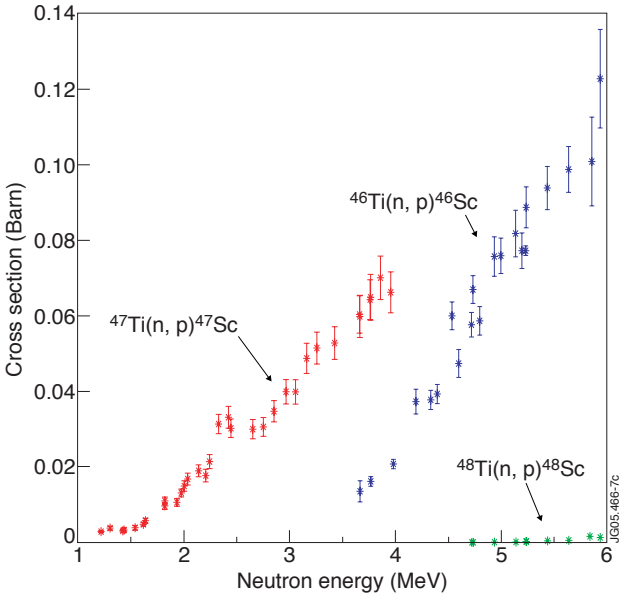

Figure 7: Cross sections of n-p nuclear reactions induced on some Titanium isotopes by fast neutrons.

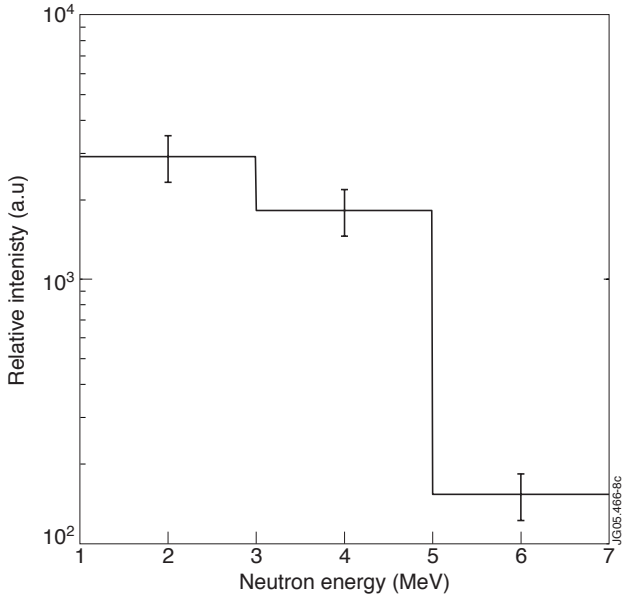

Figure 8: Neutron spectrum from unfolding of activation data.

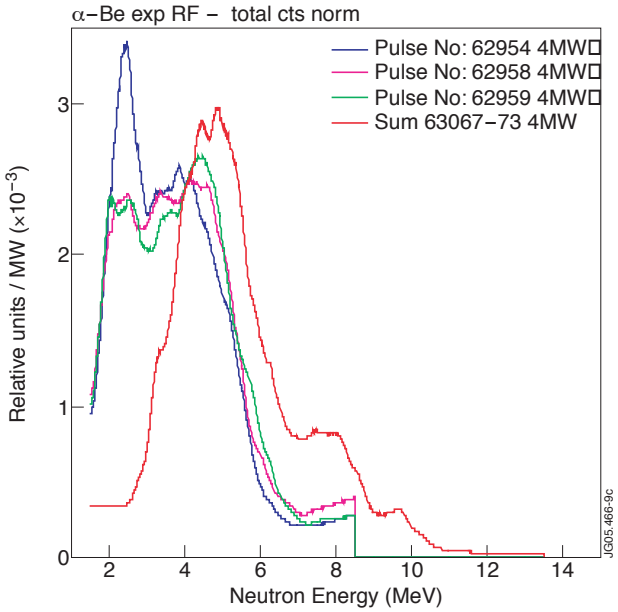

Figure 9: Neutron spectrum from unfolding of NE213 spectrometer measurement.