Cross-section studies of important neutron and relativistic deuteron reactions

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Abstract. The cross-sections of relativistic deuteron reactions on natural copper were studied by the means of activation method. The deuteron beams produced by JINR Nuclotron (Russia) with energies from 1 GeV up to 8 GeV were used. Lack of such cross-sections prevents the usage of copper foils for beam integral monitoring. The copper monitors will help us to improve the beam integral determination during ADS studies. The yttrium samples are very suitable activation detectors for monitoring of neutron fields not only in the ADS studies. But experimental cross-section data for higher energy threshold neutron reactions are still missing. This situation is the reason why we have started to study neutron reactions on yttrium by the means of quasi mono-energetic neutron source based on NPI Řež cyclotron (Czech Republic).

1. Introduction

Suitable activation detectors are necessary for monitoring of proton and deuteron beams and also neutron fields in accelerator driven system (ADS) studies. One example is the study of the international collaboration "Energy and Transmutation of Radioactive Waste" (E&T RAW) at Joint Institute for Nuclear Research Dubna, Russia [1,2,3]. The results of the experiments with activation detectors that were carried out with the spallation setup QUINTA [2] are presented also in these proceedings. This contribution is focused on two subjects.

We use aluminium foils and ^{24}Na reaction for beam monitoring. Large distance from irradiated set-up is necessary in this case due to production of ^{24}Na by neutrons. On the other hand, the determination of the deuteron production of radionuclides on copper monitor is not influenced by neutron reactions and such monitor can be placed near set-up. Therefore we measured cross-sections of different radionuclides production by deuterons on copper.

We made also extensive studies of neutron reaction cross-sections by the means of quasi mono-energetic neutron sources at Nuclear Physics Institute (NPI) in Řež, Czech Republic and at The Svedberg Laboratory (TSL) in Uppsala, Sweden. These studies are described by J. Vrzalová in further

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contribution in these proceedings. The preliminary results of studies of neutron reactions on yttrium will be presented in this contribution.

2. Relativistic deuteron reactions on copper

Cross-sections of relativistic proton reactions on aluminium and copper are mostly known. Situation is very different for relativistic deuterons. Experimental cross-sections for ^{24}Na production by deuteron reaction on aluminium are very scarce for energies higher than 200 MeV and experimental cross-sections for deuteron reactions on copper are completely missing. For this reason, we have started a set of studies of these relativistic deuteron reactions.

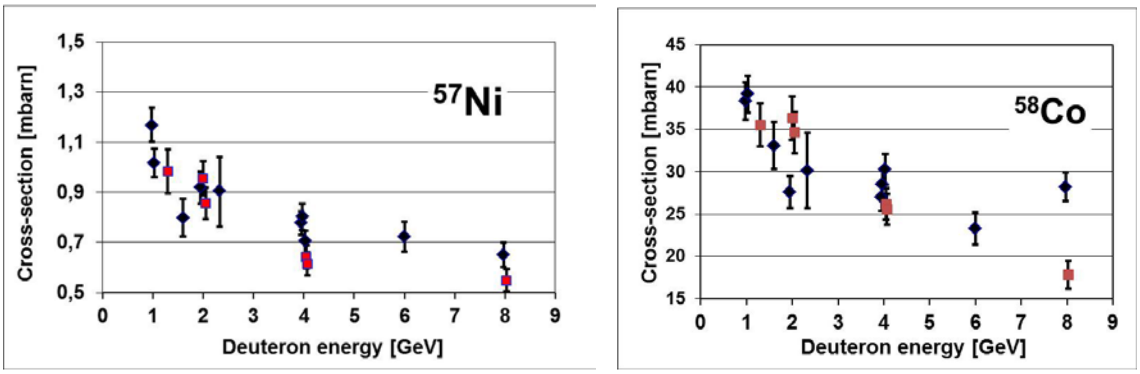

Figure 1. (a) Cross-section of ^{nat}Cu(d,x)^{57}Ni reaction (b) Cross-section of ^{nat}Cu(d,x)^{58}Co reaction.

The measurements were performed in the frame of E&T RAW collaboration during irradiations of QUINTA and GAMMA-3 set-ups with deuterons from Nuclotron accelerator at JINR Dubna. Sixteen irradiations were performed during five sets of experiments realized from 2011 up to 2013. The deuteron beam integrals were determined by production of ^{24}Na in aluminium foil. The aluminium and copper foils had the same sizes (10×10 cm) and thicknesses of copper and aluminium were 0.0128 cm and 0.0196 cm, respectively. Both foils were placed in the same position. The distance from set-up was sufficient to neglect the possible influence of neutrons and other particles produced to the direction of the beam monitors. The deuteron reaction cross-sections on copper were determined relatively to ^{27}Al(d,3p2n)^{24}Na in principle. The used copper foils have natural isotope composition (69.15 % of ^{63}Cu and 30.85 % of ^{65}Cu).

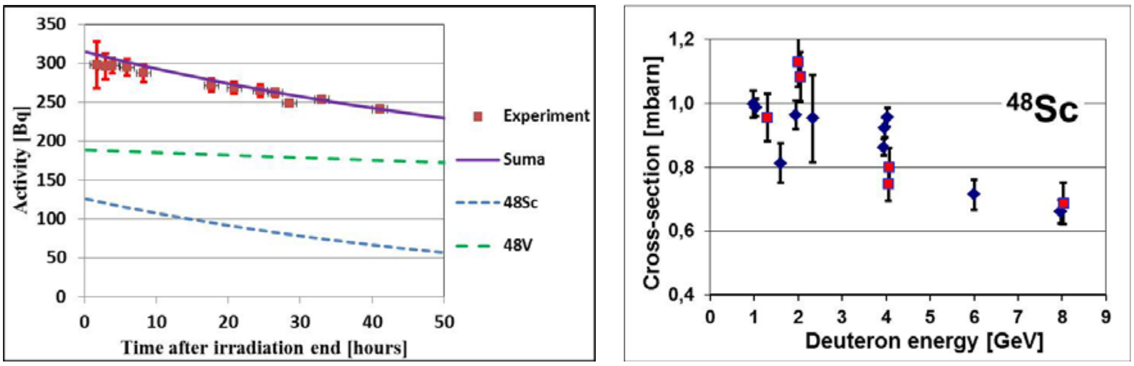

Figure 2. (a) Gamma decay curve of ^{48}Ti gamma lines (4 GeV deuteron irradiation in December 2012) (b) Cross-section of ^{nat}Cu(d,x)^{48}Sc reaction (results of last two set of irradiations are signed by red).

The activation method and gamma-ray spectrometry were used for the cross-section determination. Measured gamma spectra were analyzed by the DEIMOS code. After identification of the isotope by the means of gamma peaks the yield of activated material was calculated. All necessary spectroscopic corrections were taken into account. The detailed description is in [4].The foil was packed from original size to a smaller one with dimensions 2.5×2.5×0.3 cm^3 for the spectroscopy measurement. Activated foils were measured by two or more detectors and also in more different geometries which were in the range from 4 cm up to 10 cm far from detector. More measurements were done to detect and identify short lived and long lived radioisotopes. The cross-sections were determined taking into account the number of atoms in a sample and deuteron beam integral, see [5] for details.

Gamma lines of more than seventeen different radioisotopes (for example ^{24}Na, ^{42}K, ^{43}K, ^{43}Sc, ^{44}Sc+ ^{44m}Sc, ^{46}Sc, ^{47}Sc, ^{48}Sc, ^{48}V, ^{48}Cr, ^{52}Mn, ^{56}Mn, ^{55}Co, ^{56}Co, ^{57}Co, ^{58}Co + ^{58m}Co and ^{57}Ni) were identified in the obtained gamma spectra, for some examples see Fig. 1. Radioisotopes ^{48}Sc (43.7 hours) and ^{48}V (383.4 hours) decay both to the same daughter nucleus ^{48}Ti. The analysis of the A=48 isobars is complicated also by the sequence of the decays ^{48}Cr → ^{48}V → ^{48}Ti, see Fig. 2.

Similar case is decay of radionuclides ^{43}K (22.3 hours) and ^{43}Sc (3.9 hours) which decay both to the same daughter nucleus ^{43}Ca. The gamma line with energy 617.49 keV is produced only by ^{43}K decay and it is possible to use its intensity as norm to suppress contribution of ^{43}K to gamma line with energy 372.8 keV during first few hours after end of irradiation. We will obtain yield of ^{43}Sc decay using 372 keV line after subtraction of ^{43}K contribution, see Fig. 3.

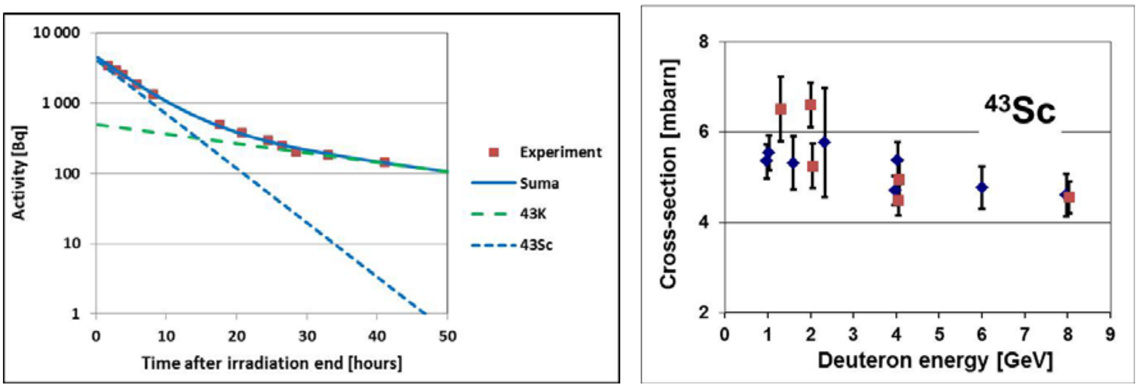

Figure 3. (a) Gamma decay curve of ^{43}Ca gamma line (b) Cross-section of ^{nat}Cu(d,x)^{43}Sc reaction.

The ground state ^{44g}Sc with half-life 3.9 hour and isomeric state ^{44m}Sc with energy 271.13 keV and halftime 58.6 hours are populated in the case of isotope ^{44}Sc, see Fig 4. The isomeric state decays by gamma transition to the ground state with probability 98.2 %. The beta decay of this state is within our accuracy negligible. Half-life of ground state beta decay is much shorter than half-life of isomeric state which is dominantly decaying by gamma decay to ground state of the same isotope. The number of ^{44g}Sc nuclei is very early done only by isomeric state decay.

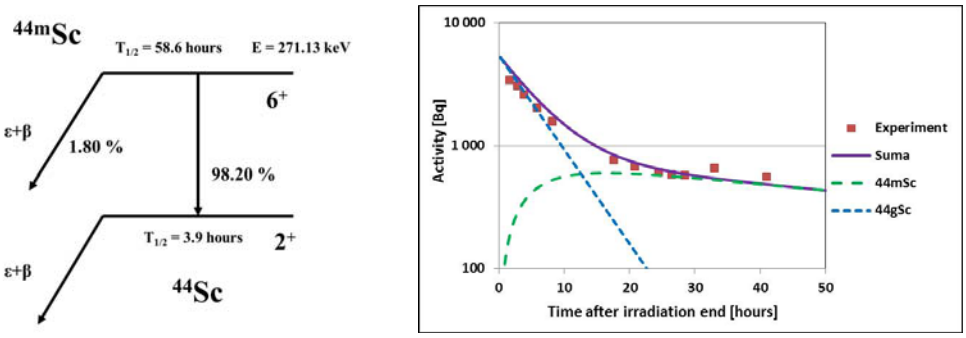

Figure 4. (a) Decay scheme of ^{44m}Sc and ^{44}Sc (the Lund/LBNL Nuclear Data Search web) (b) Activity of ^{44g}Sc produced by ^{44g}Sc states populated directly and through isomeric state ^{44m}Sc.

3. Neutron threshold reactions on yttrium

We have made extensive studies of (n,xn) reactions on materials used as activation detectors [4]. The two quasi mono-energetic neutron sources have been used. We are studying threshold (n,xn) reactions on yttrium just now. Preliminary results of first test experiment were shown during last Varna school [6]. We have six new irradiations with different energies on NPI neutron source for energies from 17.4 MeV up to 33.5 MeV. We analyse two accessible reactions ^{89}Y(n,2n)^{88}Y and ^{89}Y(n,3n)^{87}Y. The second reaction is similar to mentioned reaction of ^{44}Sc production. The ground state has half-life 79.8 hours much longer than half-life (13.38 hours) of isomeric state with energy 380.79 keV. The beta decay of the isomeric state is again within our accuracy negligible, see more detailed description in [6].

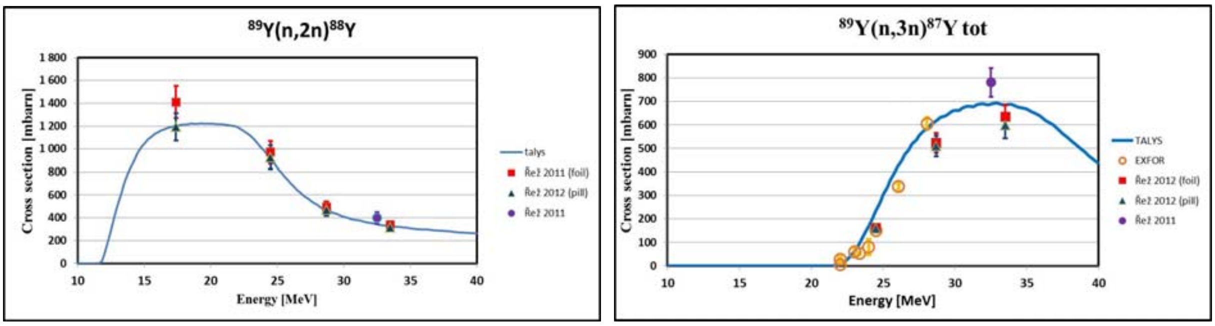

Figure 5. Excitation function of ^{89}Y(n,2n)^{88}Y and ^{89}Y(n,3n)^{87}Y (total production). Two types of samples (circular pill with diameter 10 mm and thickness 1.5 mm and square foil 25×25×0.64 mm) were used.

4. Conclusion

We present measurements of different radionuclide production on natural copper by relativistic deuterons. The excitation functions of more than seventeen different radionuclides production were obtained within energy range from 1 GeV up to 8 GeV. The excitation functions of reactions ^{89}Y(n,3n)^{87g}Y and ^{89}Y(n,3n)^{87m}Y were measured for the first time. Shape of excitation functions for all measured reactions is in good agreement with TALYS 1.4 code. Certain differences are for absolute magnitude of cross-sections.

Acknowledgements

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