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^{65}Cu(d,p)^{66}Cu excitation function at deuteron energies up to 20 MeV

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Abstract. The proton and deuteron induced reactions have a great interest for the assessment of induced radioactivity of accelerator components. Such data are needed for estimation of the potential radiation hazard from the accelerating cavities and beam transport elements. Continuing previous irradiation experiments on copper, we provided two short run to obtain cross-section data for ^{65}Cu(d, p)^{66}Cu reaction. We carried out irradiation experiments with the variable-energy cyclotron U-120M of the Nuclear Physics Institute Řež. The stacked-foil technique was utilized. Because of a relatively short half life ($T_{1/2}$ = 5, 120 min) and a strong annihilation peak, we placed the 1 cm Pb plate between the irradiated sample and the gamma-ray detector to reduce the dead time. The absolute values of cross-sections were calculated from the induced activities measured by the calibrated HPGe detector. The comparison of present results with data of other authors and prediction of different libraries and model calculation is discussed.

1 Introduction

The proton and deuteron induced activation reactions have a great interest for the assessment of induced radioactivities in the accelerator components, targets and beam stoppers as well as isotope production for medicine. The IFMIF facility needs such data for estimation of the potential radiation hazards from the accelerating cavities and beam transport elements (Al, Fe, Cr, Cu, Nb) and metal and gaseous impurities of the Li loop (Be, C, O, N, Na, K, S, Ca, Fe, Cr, Ni). The cross sections are needed in the energy range from the threshold up to 40 MeV both for deuterons and protons.

Fispact is the inventory code included in the European Activation System (EASY), it has been developed for neutron-, deuteron-, and proton-induced activation calculations for material in fusion device and has been adopted by the ITER project as the reference activation code [1]. The FISPACT code uses external libraries (EAF-libraries) of reaction cross sections and decay data for all relevant nuclides to calculate an inventory of nuclides produced as a result of the irradiation of a starting material with a flux of neutrons, from FISPACT-2007 version with charged particles, too. The accuracy of the calculated inventory is depend on the quality of the input nuclear data (the European Activation File -EAF), so improved model calculations and further measurement are needed.

The natural cupper has two stable isotopes – 69.2% of ^{63}Cu and 30.8% of ^{65}Cu. Nevertheless, in the major part of a production of a radioisotope may be ascribed to the reaction on the specific isotope up to 20 MeV. Unfortunately, a lot of predicted radioisotopes decays through β^+. The strong annihilation peak accompanying β^+-decay of the irradiated Cu foils causes large dead time of the

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HPGe detector system in the investigation of the comparatively weaker gamma-lines under interest. That is very inconvenient especially in the case radionuclides of relatively small half life. Continuing previous activation experiments on copper [2], two short irradiation runs to obtain cross section data for $^{65}Cu(d,p)^{66}Cu$ reaction were performed.

2 Experimental arrangement

2.1 Irradiation

The variable energy NPI cyclotron (Fig. 1) provides protons and neutrons in energy range 11–37 MeV and 11–20 MeV, respectively. The neutron production target stations NG2 (for quasimonoenergetic neutrons, IFMIF like spectrum as well) were built up on the beam line of the cyclotron operated in negative ion mode of acceleration. At the same position the irradiation chamber for charge-particle induced activation experiments can be alternatively situted.

The reaction chamber was equipped by Faraday cup, foils were intensively cooled by alcohol. During an irradiation, the beam current was recorded with the uncertainty of 5% in a PC keeping time synchronization with the gamma-ray spectrometry device.

The cross-section for deuteron induced reaction on Al and Cu were measured by the stacked-foil technique and its absolute values were calculated from the measured induced activities. The high purity natural Cu and Al foils (Goodfellow product) were bombarded by deuterons at input energy of 20.4 ± 0.2 MeV. The thickness of Cu and Al foils was 25 and 50 μm, respectively. Foils were weighted (with the 2% uncertainty) to avoid relatively large uncertainties in the foil thickness declared by producer. The Cu and the two Al foils were placed by turns so as the Al foils served for additional monitoring of beam current and for appropriate reduction of deuteron energy as well. Two runs duration of 335 s and 300 s were carried out with mean beam current of 0.24 μA and 0.36 μA, respectively.

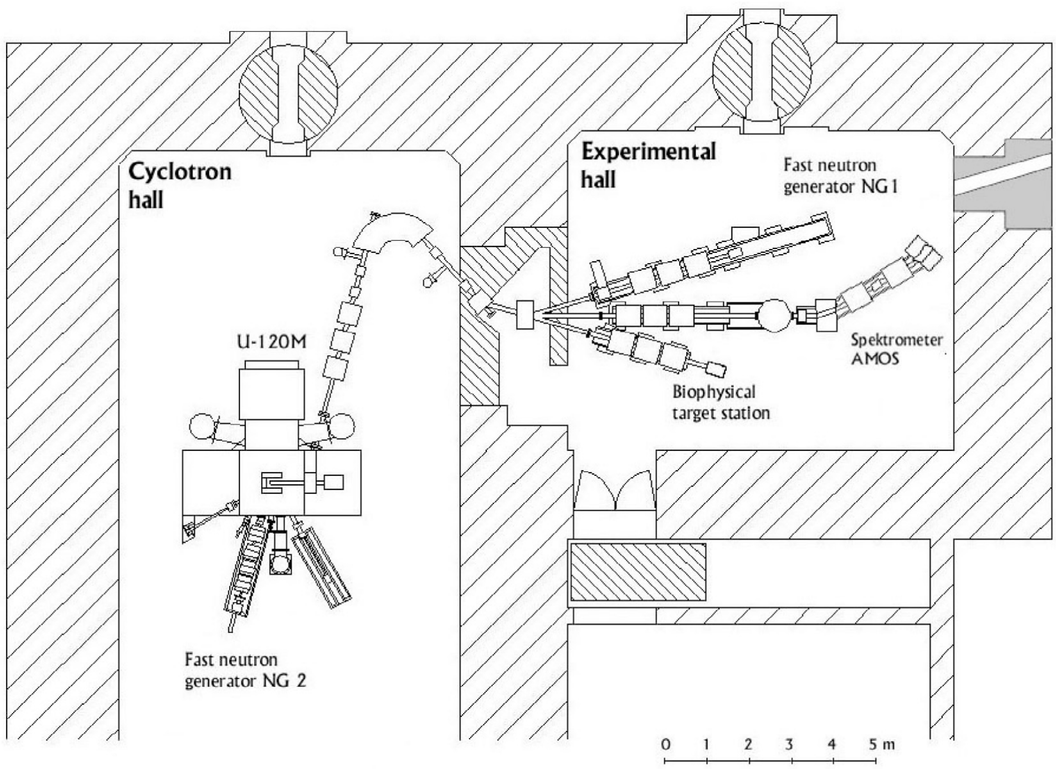

Fig. 1. NPI variable-energy cyclotron U-120M.

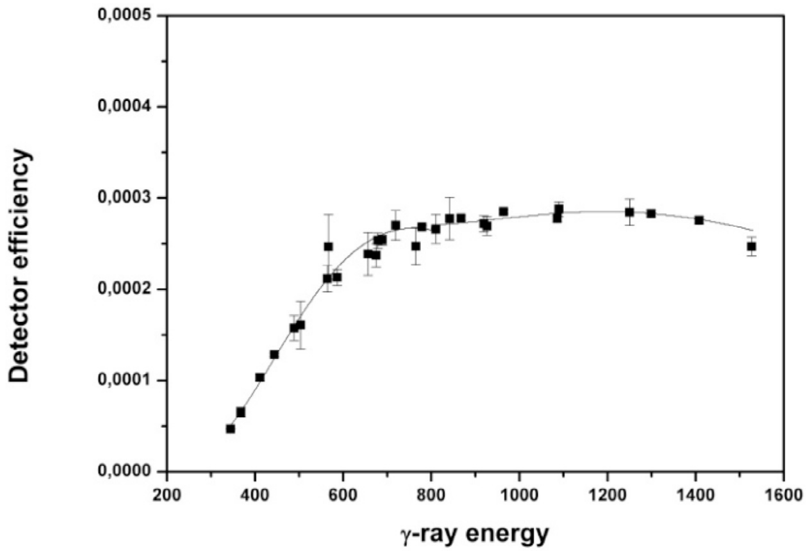

Fig. 2. The detector efficiency curve.

Table 1. Characteristic of isotopes observed from irradiated Cu foils.

Isotop	$T_{1/2}$	E_γ [keV]	I_γ[%]
66Cu	5,12 min	1039,2	9
63Zn	38,47 min	669,6	8
		962,1	6,5

2.2 Gamma-spectrometry

The irradiated Cu foils were immediately measured by HPGe detector of 50% efficiency and of FWHM 1.8 keV at 1.3 MeV. To reduce the dead time rate provoked by the strong annihilation peak accompanying β^+-decay, the observed Cu foil was situated within two iron slides of the 1 mm thickness and the lead plate of 10 mm thickness was placed between measured foil and HPGe detector. The detector efficiency (Fig. 2) was recalibrated according to the experimental condition using calibrated ^{152}Eu radioactive source.

3 Results

Activated isotopes were identified on the basis of $T_{1/2}$, γ-ray energies and intensities. The characteristic of the investigated isotopes are in Table 1. As it is seen from the table, the studied γ-rays come under well determined region of the detector efficiency, the calibration uncertainty is 3%.

The excitation function of the ^{65}Cu(d, p)^{66}Cu the only possible ^{66}Cu production reaction is shown in the Fig. 3. The previously determined cross section values for the ^{63}Cu(d, p)^{64}Cu, ^{65}Cu(d, 2n)^{65}Zn, together with the new values for the ^{63}Cu(d, 2n)^{63}Zn are also shown in Fig. 3.

4 Model analysis

The deuteron activation cross section calculations require the contributions from all reaction mechanisms involved in the deuteron-target nucleus interaction process, such as: direct reaction (DR) processes (breakup, stripping and pickup), preequilibrium emission (PE) and finally evaporation from the fully equilibrated compound nucleus (CN) [3–5].

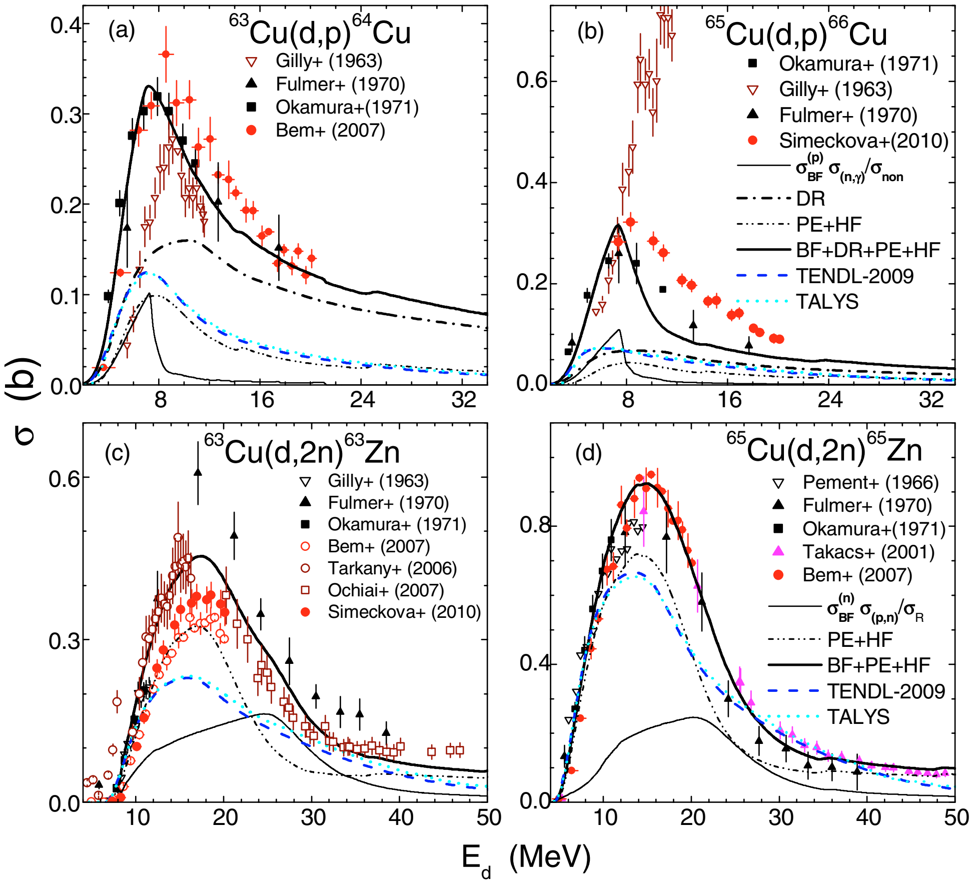

Fig. 3. (Color online) Comparison of measured (this work, solid circles, and Ref. [13]) and calculated activation cross sections for deuterons on ^{63,65}Cu, provided by the code TALYS (dotted curves), the library TENDL-2009 (dashed), and local analysis (thick solid) using the stripping (DR) contribution (dash-dotted) for the (d, p) reaction, the deuteron breakup (BF) (thin solid) for the (d, p) and $(d, 2n)$ reactions, and the PE+HF for components (dotted).

On the whole, the deuteron total breakup reaction cross section reduces the amount of the total reaction cross section that should be shared among different PE + CN outgoing channels. On the other hand, the inelastic or fusion breakup (BF) process where the deuteron constituents interacting with the target leads to a secondary composite nucleus brings contributions to different reaction channels and enhances the secondary-chance emission of particles from the original d-target interaction [3–5]. Therefore the absorbed nucleon following the deuteron breakup contributes to the enhancement of the (d, p) and (d, n) but mainly *(d,xp)* and *(d,xn)* reaction cross sections. In order to calculate this enhancement, the inelastic breakup cross section [4] has been multiplied by the corresponding fraction leading to the above-mentioned reactions, e.g. $\sigma(n, x)/\sigma_R$, or $\sigma(p, x)/\sigma_R$ where σ_R is the neutron and respectively proton reaction cross section, while x stands for γ, n, p, or α outgoing reaction channel [6].

The *(d,p) stripping* cross sections have been calculated by means of the code FRESCO [7] based on the Coupled-Reaction Channels (CRC) method. The neutron-proton interaction V_{np} was assumed to have a Gaussian shape [8], the transferred nucleon bound states were generated in a Woods-Saxon real potential with the global reduced radius of 1.25 fm, the diffuseness of 0.65 fm, while its depth has been adjusted to the nucleon binding energies in the residual nuclei. The spectroscopic factors used in calculations were those obtained experimentally from proton angular-distribution measurements [9].

The PE and CN cross sections, corrected for the breakup and stripping decrease of the total reaction cross section, have been analyzed in this work by using the default model parameters of the widely-used computer code TALYS-1.0 [10] as well as a local consistent parameter set within calculations with the PE + CN code STAPRE-H [11]. The local analysis results obviously have a higher accuracy while the global predictions may be useful for an understanding of unexpected differences between measured and calculated cross sections. The main PE + CN assumptions and parameters involved in this work for the sets of global and local calculations have recently been described elsewhere [12].

5 Discussion

The comparison of the present as well as previous measured [13] and calculated activation cross sections for ^{63,65}Cu (thick curves) are shown in Fig. 3. The sum of the inelastic breakup cross sections [4], the DR cross sections provided by the code FRESCO and the PE + CN (Geometry Dependent Hybrid model + **H**auser-**F**eshbah, HF, formalism) contributions supplied by STAPRE-H, are shown together with the global predictions given by TALYS-1.0 code and within the TENDL-2009 library [14]. The appropriate consideration of the deuteron breakup as well as that of the DR contributions to the (d, p) activation cross sections increase the agreement of the measured and calculated data. A continuing underestimation of the (d, p) reaction cross section decreasing with the incident energy could be due to the limited excitation-energy range for which spectroscopic factors exist so that additional assumptions should be involved.

The main aim of this work has been to present new deuteron cross section measurement and unitary analysis of the nuclear reaction mechanisms responsible for the deuteron interactions with ^{63,65}Cu target nuclei. The agreement between the measured data and model calculations proves the correctness of nuclear mechanism description taken into account for the deuteron-nucleus interaction. Finally the comparison of the present calculations with global predictions of the TALYS code stresses out the importance of an appropriate consideration of the deuteron breakup mechanism contribution to the activation cross section calculations.

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