APPLICATION OF NONDESTRUCTIVE NEUTRON RESONANCE ANALYSIS FOR INVESTIGATION OF METAL COMPOSITION OF RESKUPORID V STATERS (3 CENTURY AD) FROM PHANAGORIA'S TREASURE

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Abstract

The method of Neutron Resonance Capture Analysis (NRCA) is currently being developed in the Frank Laboratory of Neutron Physics (FLNP) for the purpose of determination of the element composition of samples. The method is based on registration neutron resonances in radiative capture and measurement the yield of reaction products in these resonances. To test the capabilities of this method, such investigations were carried out in collaboration with Institute of Archaeology of RAS at the pulsed neutron source IREN of FLNP for the ancient coins from Phanagoria's treasure. A cylindrical multi-sectional liquid scintillator detector was used as a detector of γ-quanta.

Introduction

The method of Neutron Resonance Capture Analysis (NRCA) is currently being developed in the Frank Laboratory of Neutron Physics for the purpose of determination of the element composition of samples [1,2]. The method is based on registration neutron resonances in radiative capture and measurement the yield of reaction products in these resonances. The resonance parameters were determined to date for practically all stable nuclei in the neutron energy region up to several tens of keV [3, 4], that allows us to solve an inverse problem. The investigations are carried out at the IREN facility by time-of-flight method. To test the capabilities of this method such investigations were carried out in collaboration with Institute of Archaeology RAS for the ancient coins from Phanagoria's treasure [5].

The main part of a treasure (more than two thirds) is staters of Reskuporid V (242/243–276/277). These coins are of special interest for studying of economic climate and inflationary processes which are followed by degradation of coinage alloy of staters. We selected to this study the staters of the following years AD (Fig. 1): 242/243 (catalog № 2), 249/250 (№ 183), 250/251 (№ 271), 251/252 (№ 355), 252/253 (№ 482), 262/263 (№ 709, 732), 263/264 (№ 860, 961), 264/265 (№ 1025). A more detailed description and photographs of coins can be found in the publication of the results of archaeological research in Phanagoria [5].

Fig. 1. Bosporan staters (3 century AD) from the Phanagoria's treasure found in 2011.

Previously, the X-ray fluorescence analysis was applied for determination the elemental composition of coins [6]. The applied type of a spectrometer allows to make measurements of a surface on depth to 10 μm. Most of the metal archaeological finds are inhomogeneous. The investigation of such objects requires a different approach. The NRCA is non-destructive and gives a possibility to study samples through all its volume. Therefore, such analysis was carried out at IREN facility.

Experiment

The main part of the IREN facility is a linear electron accelerator LUE-200 with non-multiplying neutron-producing target of the VNZH-90 alloy [7, 8]. The facility parameters in which the investigation was made are: the average energy of electrons ~ 40 MeV, the peak current ~ 1.5 A, the width of electron pulse ~ 100 ns, the repetition rate – 25 Hz. The total neutron yield is about ~ $3 \cdot 10^{11}$ s^{-1}. The measurements were carried out at the 58.6 meters flight path of the 3rd channel of the IREN. The big liquid scintillator detector was used for the registration of γ-quanta [9]. The neutron flux was permanently monitored by a neutron counter located on the 4th neutron channel of the IREN facility. The signals from the detector and the monitor counter were simultaneously fed to the two independent inputs of TDC. The time-of-flight spectra were stored on a computer disk for later processing off-line. A more detailed description of experimental setup can be found in Ref. [1].

To evaluate of the method the investigations were carried out in the "bulk-form", for all coins at once. The coins were placed in an aluminum cassette, which was placed in a beam inside the detector channel. The total mass of coins was 73.033 g. The measurements with the sample lasted about 13 hours. Only silver and copper resonances were identified on the time-of-flight spectrum (Fig. 2). The measurements with standard samples of silver and copper were made in addition to the measurement with the investigated sample.

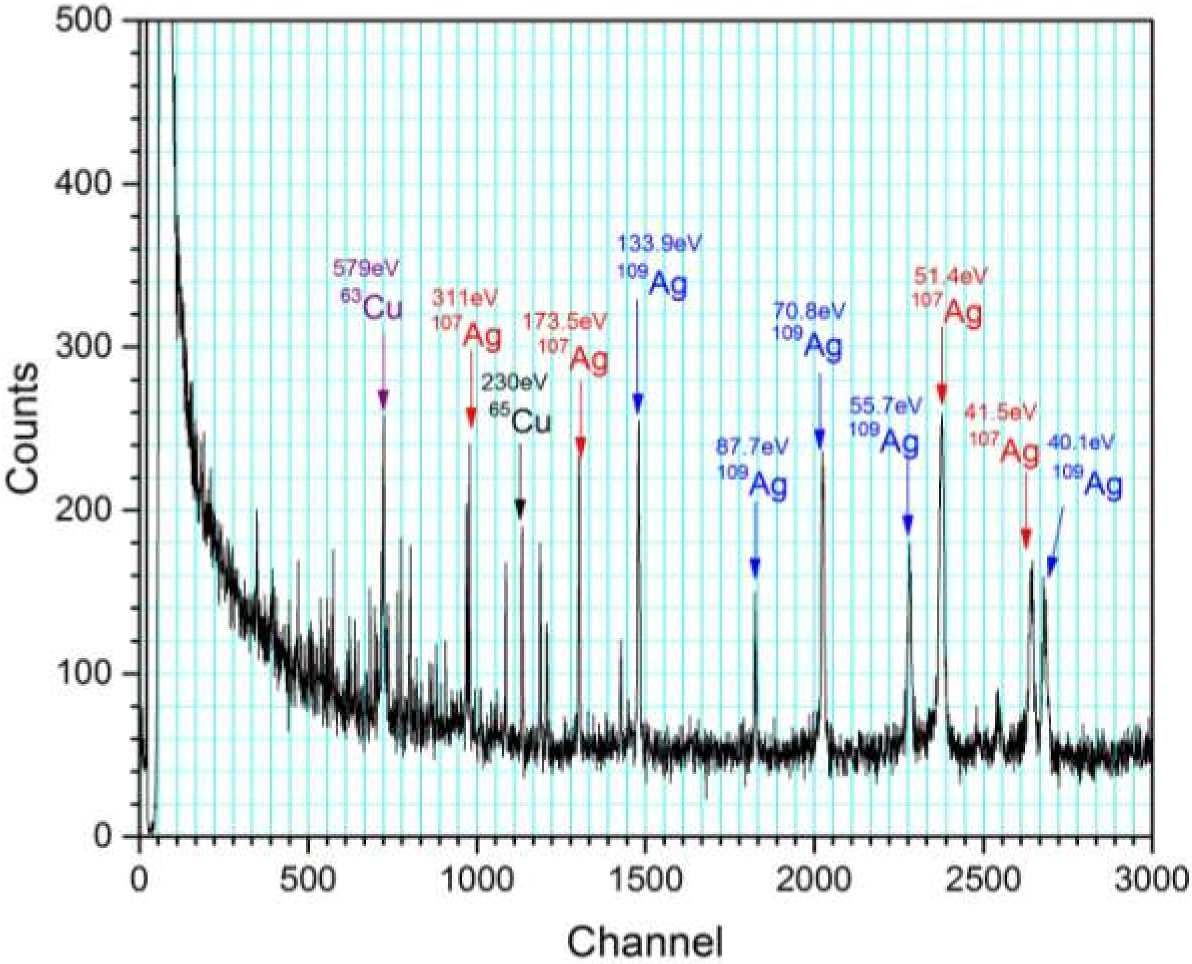

Fig. 2. Part of time-of-flight spectrum, obtained from measurement with ancient coins from the Phanagoria's treasure.

Results

The number of nuclei of the element in the sample was determined by the measurement of the yield of gamma-quanta in the resonances. The sum of events in the resonance is related with resonances parameters and experimental values by the expression [1, 10]:

$$\sum N = f(E_0) \cdot S \cdot t \cdot \varepsilon_\gamma \cdot \frac{\Gamma_\gamma}{\Gamma} A \tag{1}$$

Here, $f(E_0)$ is the energy density of the neutron flux at the resonance energy E_0, S – the area of the sample, t – measuring time, ε_γ – the detection efficiency of radiative capture by the detector, Γ_γ, Γ – the radiative and total widths of the resonance.

$$A = \int_{-\infty}^{+\infty} [1 - T(E)] dE \tag{2}$$

is resonance area on the transmission curve.

$$T(E) = e^{-n\sigma(E)} \tag{3}$$

is the energy dependence of the neutron transmission by the sample; $\sigma(E)$ – the total cross section at a given energy, n – the number of isotope nuclei per unit area. The value A for investigated sample was determined from experimental data by the formula:

$$A_x = \frac{\sum N_x \cdot M_s \cdot S_s}{\sum N_s \cdot M_x \cdot S_x} \cdot A_s \, . \tag{4}$$

Here the indices x and s refer to the investigated and standard samples, respectively; M – the number of monitor counts during the measurement time. The value A_s for the standard was determined by well-known parameters of resonances and the standard sample using a program based on the algorithm of Ref. [11]. The number of nuclei per unit area of isotope was determined from the value A_x by the same program.

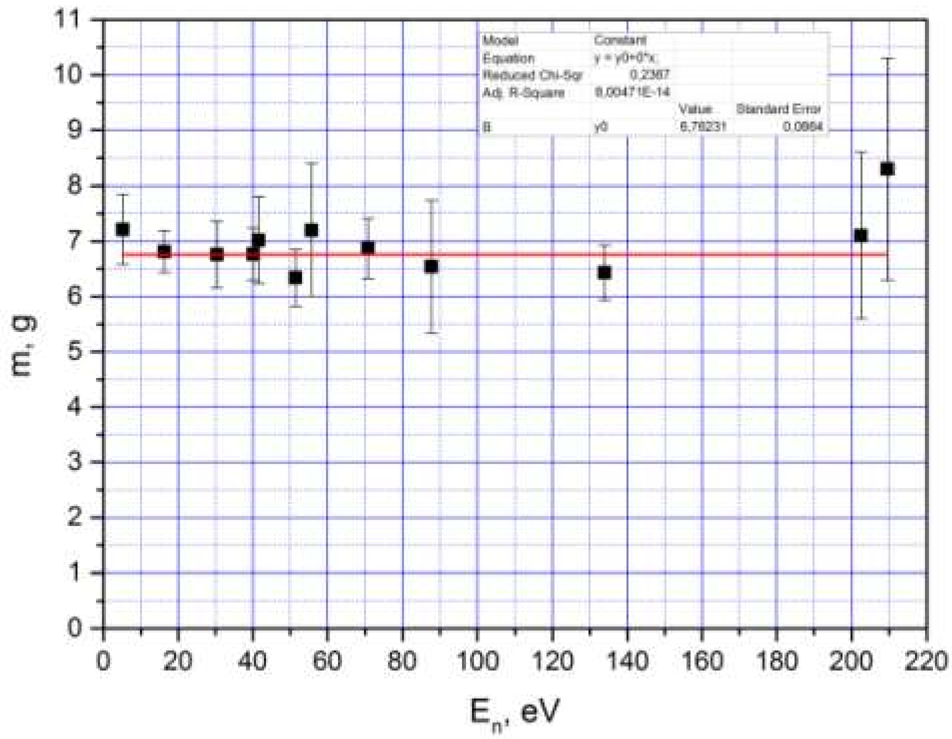

Fig. 3. The values of the mass of silver in coins obtained from individual resonances and the weighted-average value.

The twelve resonances of ^{107}Ag and ^{109}Ag were processed for determination the mass of silver in coins. The results are shown in Fig. 3. The weighted-average value of silver content in the samples was (6.762 ± 0.086) g or (9.26 ± 0.12) wt. %. The copper content was estimated only by one resonance of ^{65}Cu at 230 eV. Another observed resonance of ^{63}Cu at 579 eV is covered by closely spaced silver resonances, and it can't be used for processing. The result for copper is 62.0 ± 3.1.

Conclusion

The total mass of the elements in coins, determined from the resonances, is 68.76 ± 3.1 g. The mass of coins determined by weighing is 73.033 g. The difference does not exceed two standard deviations, in that way the result can be considered satisfactory.

We can make preliminary estimation of the possibilities of method, if it would be necessary to analyze the isotope composition of each coin separately. The weighted-average value of silver content in ten coins is 6.76 ± 0.09 g. The statistical error is about 1 %. In the case when each coin is measured separately, the statistics will be in 10 times less during the same measurement time and the error will increase by 3 times (up to 4–5 %). In that way if the difference in the silver content in coins is more than 12 % we can define it with high degree of confidence.

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