Preliminary result of investigation of element composition of Kyathos (6th-4th centuries BCE) from the necropolis Volna 1 on the Taman Peninsula by Neutron Resonance Capture Analysis

N. V. Simbirtseva[1,2], P. V. Sedyshev[1], S. T. Mazhen[1,2], A. M. Yergashov[1,2], I. A. Saprykina[3], R.A. Mimokhod[3]

[1]*Frank Laboratory of Neutron Physics, Joint Institute for Nuclear Research, Dubna, Russia, simbirtseva@jinr.ru*

[2]*Institute of Nuclear Physics, Almaty, 050032, the Republic of Kazakhstan*

[3]*Institute of Archaeology of the Russian Academy of Sciences, Moscow, Russia*

Abstract **– Neutron Resonance Capture Analysis (NRCA) has been applied for a determination of an element composition of an archeological object. The method is non-destructive and based on registration neutron resonances in radiative capture and measurement the yield of reaction products in these resonances. The experiment was carried at the IREN Facility in Frank Laboratory of Neutron Physics.**

During the excavation of the burial ground Volna 1 on the Taman Peninsula in 2016-2018, a representative collection of archaeological material was obtained, dated within the 6th-4th centuries BCE. The Kyathos is one of these objects, which has been investigated by NRCA.

I. INTRODUCTION

The Neutron Resonance Capture Analysis (NRCA) is non-destructive; the induced activity of the sample is practically absent. All this makes it promising for a research of archeological artifacts and objects of cultural heritage. NRCA is currently being developed in the Frank Laboratory of Neutron Physics [1]. The method is based on the use of a pulsed neutron source and time-of-flight technique [2]. The experiment was carried at the Intense Resonance Neutron Source (IREN) facility with multi-sectional liquid scintillator detector (210 liters) which was used for the registration prompt gamma-quanta and was created at FLNP JINR [3].

The method is based on registration neutron resonances in radiative capture and measurement the yield of reaction products in these resonances. The resonance energies are known practically for all stable nuclei and set of energies doesn't coincide completely for any isotopes pair. The energy positions of resonances give information about isotope and element composition of an object. Also, if you know area under the resonances, you can calculate the number of the element or isotope's nuclei.

Apparently, Hans Postma from the Delft University of Technology (Delft, the Netherlands) should be considered the founder of research in cultural-heritage objects using neutron spectrometry methods. Under his leadership, experiments on the GELINA pulsed neutron source of the Institute of Reference Materials and Measurements of the Joint Research Center (Gel, Belgium) were carried out as part of a number of scientific programs devoted to this area (see, for example, the review [4] and references therein). Now such measurements are also being carried out on the ISIS pulsed neutron and muon source in the United Kingdom [5] and the J-PARC pulsed neutron source in Japan [6]. At the JINR FLNP, studies are being conducted on the IREN pulsed source of resonance neutrons [7, 8].

To implement neutron resonance analysis, the same methodology for measuring and processing experimental data is used as for determining resonance parameters. However, there are a number of features associated with the study of samples of irregular shape and heterogeneous composition, which is typical for archaeological sites.

This analysis was carried out for the kyathos (Fig. 1) which was transferred by the Institute of Archeology RAS.

Fig. 1.The Kyathos (6th-4th centuries BCE) from the necropolis Volna 1 on the Taman Peninsula[9].

In 2016-2018 a Sochi Expedition group of Institute of Archaeology of the Russian Academy of Sciences under the leadership Roman A. Mimokhod conducted excavations of an antique town soil necropolis Volna 1 on the Taman Peninsula. During the excavation of the burial ground, a representative collection of archaeological material was obtained, dated within the 6th-4th centuries BCE. Rather rare objects were found in the burials: an artificial limb, musical instruments (cithara, harp), a bronze Corinthian helmet, and a series of kyathoi - ancient Greek vessels for pouring wine. In contrast to various similar finds made of clay, the kyathoi found on the territory of the necropolis Volna 1 were made of metal, what moves them in to the category of special objects.

II. EXPERIMENT

The investigations were carried out at IREN facility. The main part of the IREN facility is a linear electron accelerator. The facility parameters: the average energy of electrons was ~ 60 MeV, the peak current was ~ 1.5 A, the width of electron pulse was ~ 100 ns, and the repetition rate was 25 Hz. Neutron producing target is made of tungsten-based alloy and represents a cylinder 40 mm in diameter and 100 mm in height placed within an aluminum can 160 mm in diameter and 200 mm in height. Distilled water is circulated inside the can, providing target cooling and neutron moderation. Water layer thickness in a radial direction is 50 mm. The total neutron yield was 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. The sample was placed inside the detector. The neutron flux was permanently monitored by the SNM-17 neutron counter.

The signals from the detector and the monitor counter were simultaneously fed to the two independent inputs of time-to-digital converter (TDC).

The measurements with the sample lasted about 95 hours. The resonance energies were determined according to the formula:

$$E = \frac{5227L^2}{t^2} \tag{1}$$

where, t – time of flight in microseconds, L – flight path in meters, E – kinetic energy of a neutron in eV.

The resonances of silver, tin, copper and arsenic were identified on the time-of-flight spectrum (Fig. 2) [10, 11].

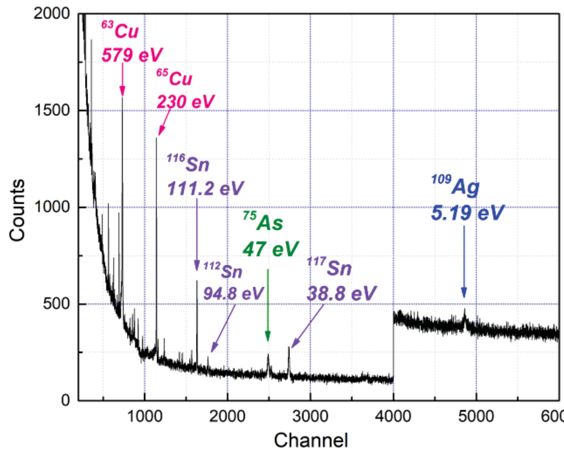

Fig. 2. The part of time-of-flight spectrum of reactions (n,γ) on the kyathos material. The width of the time channel from 0 to 4000 channels is 0.25 μs; from 4000 to 6000 - 1 μs.

The measurements with standard samples of silver, tin, copper and arsenic were made in addition to the measurement with the investigated sample (Fig. 3, 4, 5,6).

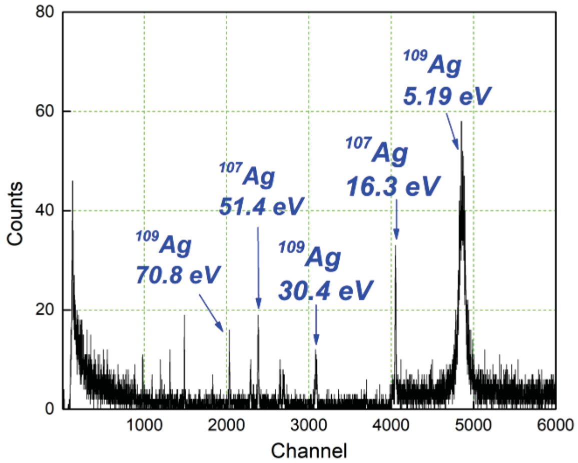

Fig. 3. The part of time-of-flight spectrum of reactions (n,γ) of the standard silver sample. The width of the time channel from 0 to 4000 channels is 0.25 μs; from 4000 to 6000 - 1 μs.

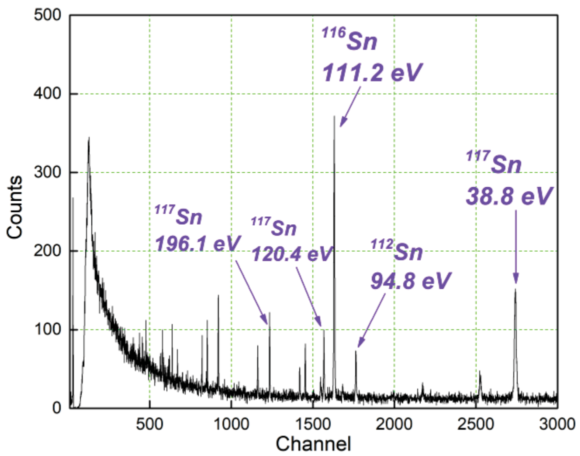

Fig. 4. The part of time-of-flight spectrum of reactions (n,γ) of the standard tin sample. The width of the time channel is 0.25 μs.

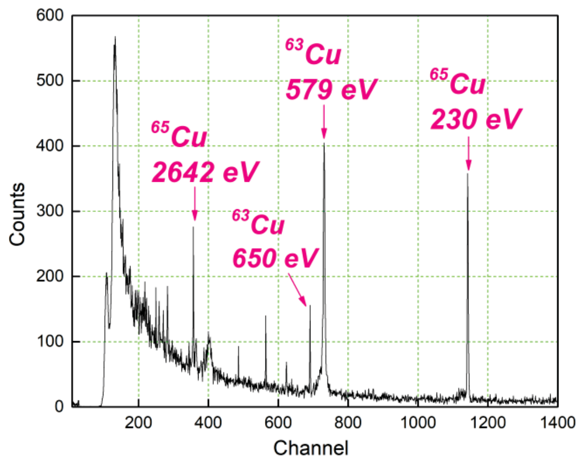

Fig. 5. The part of time-of-flight spectrum of reactions (n,γ) of the standard copper sample. The width of the time channel is 0.25 μs.

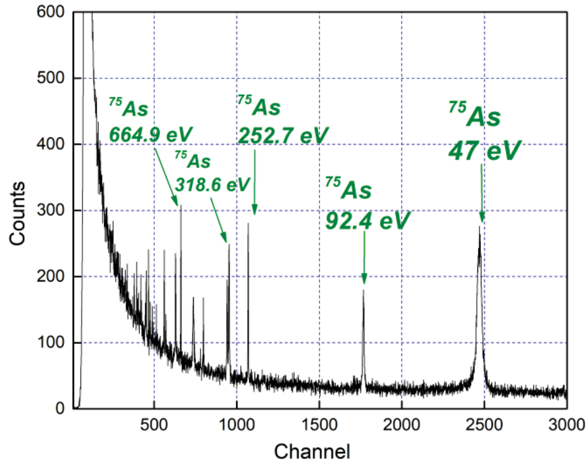

Fig. 6. The part of time-of-flight spectrum of reactions (n,γ) of the standard arsenic sample. The width of the time channel is 0.25 μs.

III. DATA ANALYSIS AND RESULTS

Five resonances of tin, two resonances of copper, one resonance of silver and one resonance of arsenic were selected during the analysis of the experimental data. The sum of the detector counts in resonance is expressed by the formula:

$$\sum N = f(E_0)\cdot S\cdot t\cdot \varepsilon_\gamma \cdot \frac{\Gamma_\gamma}{\Gamma} A \qquad (2)$$

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

$$A = \int_{E1}^{E2}[1 - T(E)]\,\mathrm{dE} \qquad (3)$$

– resonance area on the transmission curve, where *E1,E2* – initial and final values of energy range near resonance.

$$T(E) = e^{-n\sigma(E)} \qquad (4)$$

– the energy dependence of the neutron transmission by the sample; σ(*E*) – the total cross section at this energy with Doppler broadening, *n* – the number of isotope nuclei per unit area. The value *A* was determined from experimental data for investigated sample by the formula:

$$A_x = \frac{\sum N_x \cdot M_s \cdot S_s}{\sum N_s \cdot M_x \cdot S_x}\cdot A_s \qquad (5)$$

Here, $\sum N_x$, $\sum N_s$ counts under the resonance peak of the investigated and standard samples, S_x, S_s – the area of the investigated and standard samples. M_x, M_s – the number of monitor counts during the measurement of the investigated and standard samples.

The value A_s was calculated by means of well-known parameters of resonances for the standard sample, the value n_x was determined from the value of A_x for the investigated sample. The values of σ (E) and A were numerically determined, by using the algorithm which was described in [12]. This procedure is schematically shown in (Fig.7). The analysis results are presented in the Table 1.

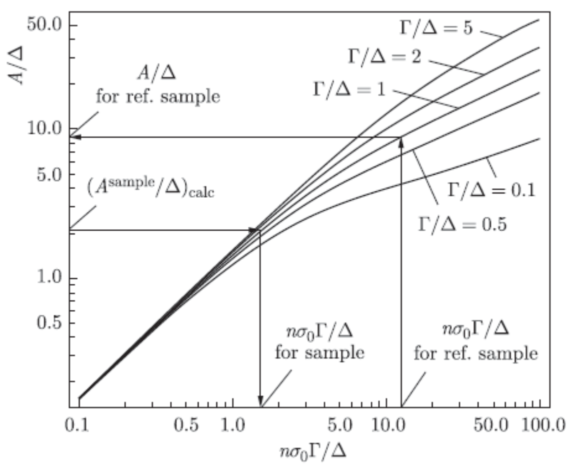

Fig. 7. The dependence of value A from number of nuclei and resonance parameters [13].

Table 1. The results of measurements with the kyathos by NRCA (the bulk).

№	Element	Mass, g	Weight, %
1	Cu	65±10	75±12
2	Sn	4.75±0.52	5.5±0.6
3	As	0.0284±0.0018	0.033±0.002
4	Ag	0.0151±0.0021	0.0174±0.0024

IV. CONCLUSION

This paper presents the results of investigation of the kyathos which was found in the necropolis Volna 1 on the Taman Peninsula. The elemental and isotopic composition of the sample was determined by NRCA. The mass of kyathos is 86.7 g. According the result of analysis the value of determine total elements mass coincides with the kyathos mass within the margin of error.

Acknowledgements. The authors express their gratitude to the staff of the IREN facility and to A. P. Sumbaev, the head of the development of the facility, to V.V. Kobets, the head of sector No.5 of the Scientific and Experimental Injection and Ring Division of the Nuclotron (Veksler and Baldin Laboratory of high energy physics), for the supporting with uninterrupted operation of the facility in the process of measurements.

ceedings.

REFERENCES

[1] N. V. Bazhazhina, Yu. D. Mareev, L. B. Pikelner, P. V. Sedyshev, V. N. Shvetsov, “Analysis of element and isotope composition of samples by neutron spectroscopy at the IREN facility”, Physics of Particles and Nuclei Letters, vol. 12, 2015, pp. 578–583.

[2] O. V. Belikov, A. V. Belozerov, Yu. Becher, Yu. Bulycheva, A. A. Fateev, A. A. Galt, A. S. Kayukov, A. R. Krylov, V. V. Kobetz, P. V. Logachev, A. S. Medvedko, I. N. Meshkov, V. F. Minashkin, V. M. Pavlov, V. A. Petrov, V. G. Pyataev, A. D. Rogov, P. V. Sedyshev, V. G. Shabratov, V. A. Shvec, V. N. Shvetsov, A. V. Skrypnik, A. P. Sumbaev, A. V. Ufimtsev, V. N. Zamrij, “Physical start-up of the first stage of IREN facility”, Journal of Physics: Conf. Ser. 205, 2010, 012053.

[3] H. Maletsky, L. B. Pikelner, K. G. Rodionov, I. M. Salamatin, E. I. Sharapov, “Detector of neutrons and gamma rays for work in the field of neutron spectroscopy”, Communication of JINR 13-6609 (Dubna, JINR, 1972) 1-15 (in Russian).

[4] H. Postma and P. Schillebeeckx, “Neutron resonance analysis,” in Neutron Methods for Archaeology and Cultural Heritage. Neutron Scattering Applications and Techniques, Ed. by N. Kardjilov and G. Festa (Springer, Cham, 2017), pp. 235–283.

[5] G. Gorini (Ancient Charm Collab.), “Ancient charm: A research project for neutron-based investigation of cultural-heritage objects,” Nuovo Cim. C 30, 2007, pp. 47–58.

[6] H. Hasemi, M. Harada, T. Kai, T. Shinohara, M. Ooi, H. Sato, K. Kino, M. Segawa, T. Kamiyama, and Y. Kiyanagi, “Evaluation of nuclide density by neutron transmission at the NOBORU instrument in J-PARC/MLF,” Nucl. Instrum. Methods Phys. Res., Sect. A 773, 2015, pp. 137– 149.

[7] O. V. Belikov, A. V. Belozerov, Yu. Becher, Yu. Bulycheva, A. A. Fateev, A. A. Galt, A. S. Kayukov, A. R. Krylov, V. V. Kobetz, P. V. Logachev, A. S. Medvedko, I.N.Meshkov, V. F. Minashkin, V. M. Pavlov, V. A. Petrov, et al., “Physical start-up of the first stage of IREN facility,” J. Phys.: Conf. Ser. 205, 012053 (2010).

[8] E. A. Golubkov, V. V. Kobets, V. F. Minashkin, K. I. Mikhailov, A. N. Repkin, A. P. Sumbaev, K. V. Udovichenko, and V. N. Shvetsov, “The first results of the commissioning of the second accelerating

section of the LUE-200 accelerator of the IREN installation,"Soobshch. OIYaI R9-2017-77 (Dubna, OIYaI,2017).
[9] R.A. Mimokhod, N.I. Sudarev, P.S. Uspensky, "The necropolis Volna 1(2017)", Rescue archaeological research materials, vol. 25, 2017, pp. 220–231.
[10] S. F. Mughabghab, "Neutron Gross Sections, Neutron Resonance Parameters and Thermal Gross Sections", Academic Press, New York, 1984.
[11] S. I. Sukhoruchkin, Z. N. Soroko, V. V. Deriglazov, "Low Energy Neutron Physics. Landolt-Bornstein.V. I/16B", Berlin: Springer Verlag, 1998.
[12] V.N. Efimov, I.I. Shelontsev, "Calculation for graphs of determining the parameters of neutron resonances by the transmission method", Communications of the JINR P-641 (Dubna, 1961) 1-19 (in Russian).
[13] P. V. Sedyshev, N. V. Simbirtseva, A. M. Yergashov, S. T. Mazhen, Yu. D. Mareev, V. N. Shvetsov, M. G. Abramzon, and I. A. Saprykina, "Determining the Elemental Composition of Antique Coins of Phanagorian Treasure by Neutron Spectroscopy at the Pulsed Neutron Source IREN in FLNP JINR", Pis'ma v Zhurnal Fizika Elementarnykh Chastits i Atomnogo Yadra, ISSN:1547-4771, Physics of Particles and Nuclei Letters, vol.17, No.3, pp.389-400.