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Investigations at the LUE-75 Linear Accelerator Facility of A.I. Alikhanyan National Science Laboratory

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Abstract—The results of recent years work, performed at the scientific electron linear accelerator LUE-75 of the A.I. Alikhanyan National Science Laboratory (AANL) on accelerator physics and low-energy nuclear physics, are briefly described. The operating installation allows varying the beam current and energy over a wide range 10^{-18}–10^{-5} A and 10–75 MeV, respectively. The experiments were carried out jointly with research groups both from scientific centers in Armenia and other countries. The main directions of research with the use of electron beams of LUE-75 are outlined.

Keywords: linear accelerator, low intensity beams, low-energy nuclear physics

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1. INTRODUCTION

The scientific linear accelerator LUE-75 [1, 2], the proton medical cyclotron C18/18 with the possibility of conducting physical experiments, as well as the linear accelerator AREAL of the Synchrotron Research Institute CANDLE [3], create an experimental base in Armenia for the application of acceleration physics and technology in fundamental and applied scientific and scientific-methodological research in low-energy nuclear physics, radiobiology, nanotechnology, to obtain new radiotheranostic isotopes, etc.

The linear accelerator LUE-75 (linac) was projected and served as an injector for the Yerevan electron ring accelerator ARUS, at one time the largest electron synchrotron in the Soviet Union with energies up to 6.1 GeV. Currently the linac successfully operates in an autonomous mode. It is an accelerator on a traveling wave of the S-band. It contains four accelerating sections. In the first section, electrons are grouped into bunches and simultaneously accelerated to an energy of 3 MeV. The other three sections are the same. A thermal cathode placed in an electron gun with Pierce optics serves as a source of electrons.

Owing to the growing interest in the low-energy nuclear physics and in connection with the expansion of the range of scientific researches planned by the experimenters, the tasks of expanding the capabilities of the operating accelerator facility were accordingly solved. We briefly list the main ones.

1. A more powerful metal-ceramic cathode was installed, as a result of which the beam current was doubled.

2. An additional accelerator station was restored and put into operation, thanks to which the energy was brought to the design value of 75 MeV.

3. An electron Beam Transport Path (BTP) was designed and built in the synchrotron hall, including a section of parallel beam transfer to a zone remote from the operating electrical and radio equipment of the linac, where, with the synchrotron turned off, there are practically no interference and pickups on the measuring equipment (Fig. 1). This creates favorable conditions for precision experiments. At the initial stage, the BTP magnetic optics was calculated and designed for an electron energy of about 20 MeV. Subsequently, the magnetic optics of the parallel transfer path was modernized, after which it became possible to guide the beam up to 75 MeV.

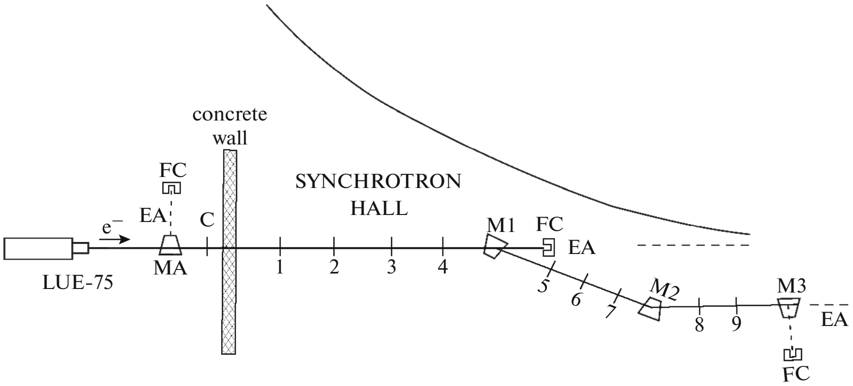

Fig. 1. The sketch of the transport and parallel transfer path in the synchrotron hall. MA—dipole analyzing magnet at the output of the LUE-75; FC—Faraday Cup; C—collimator; M1 and M2—bending magnets of the parallel transfer; M3—beam dump, used to obtain photon beams; 1—9—quadrupole lenses; EA—experimental area.

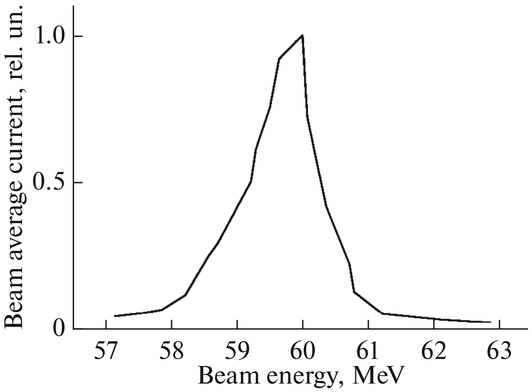

Fig. 2. Typical energy spectrum of linac LUE-75.

4. On the basis of the linac a technique for obtaining controlled primary electron beams with an extremely weak flux of single flying electrons with intensity of several tens electrons per second in the energy range up to 75 MeV was developed and applied; a stand for calibrating elementary particle detectors was created.

Due to these works, currently, the complex of the linac and beam transport system makes it possible to provide experimenters with electron beams in the energy range 10—75 MeV with average currents from extremely low to 10 μA, depending on the collimation and the chosen energy. Figure 2 shows the characteristic energy spectrum of accelerated electron beam with a full width at half maximum about 2%. The accelerator operates at a repetition rate of 50 Hz. Detailed parameters of the LUE-75 linear complex are given in [2].

2. CREATION OF EXTREMELY LOW INTENSITY BEAMS

On the basis of the linear electron accelerator LUE-75 AANL, a technique for obtaining controlled primary electron beams with an intensity of several tens of electrons per second in the energy range 15—75 MeV was developed and applied, and a stand for calibrating elementary particle detectors was created.

Figure 3 shows the profile of a 40 MeV low-intensity beam measured without an exit collimator at the end of the transport path using a plastic finger counter; the counter was moved across the beam discretely with a step of 5 mm using a scanner remotely controlled by a computer; the maximum corresponds to an intensity of 60—70 e^-/s.

Together with colleagues from the Laboratory of Nuclear Problems of the Joint Institute for Nuclear Research (JINR, Dubna, RF), a technique was developed for energy testing of elementary particle detec-

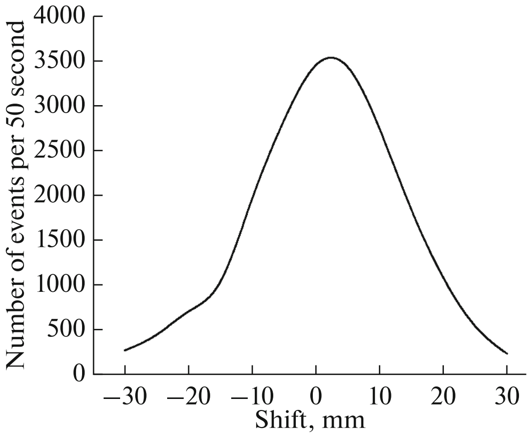

Fig. 3. Horizontal profile of a low-intensity electron beam with an average energy of 40 MeV at the path exit in the crystal testing zone.

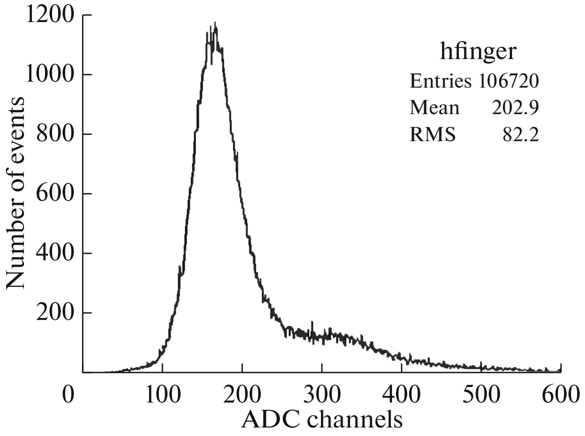

Fig. 4. Histogram of the distribution of the number of events in the ADC channels at an electron energy of 30 MeV; the small hump on the right corresponds to the intensity of the two electron events.

tors by beams an extremely low intensity of 10–20 electrons per second, in particular, for calibrating scintillation crystals for calorimeters. This intensity was chosen taking into account the time of crystal emission, which made it possible to minimize signal overlap (pile up) and measure the detector response to single electrons; in this case, the number of one-electron events was no less than 70% of the total number of particles incident on the crystal surface (Fig. 4). This technique was used to test the electromagnetic calorimeter prototype for the Mu2e experiment planned at Fermilab (FNAL, USA) [4, 5].

The results of testing crystals at the AANL linear accelerator in the energy range (15–75) MeV were in good agreement with the testing data in the range 80–120 MeV obtained by JINR physicists in Frascati (BTF, Italy) [5, 6].

Low-intensity beams are also obtained in other scientific centers [7, 8]. LUE-75 is distinguished by the wide energy range indicated above.

Such low-intensity beams can also be used to study individual events, diffraction problems, study the emission of electrons in single crystals, study the biological effects of ionizing radiation at low doses, in nanotechnologies, etc.

3. WORKS ON METHODS OF ELECTRON ACCELERATION

The experimental works on the interaction of relativistic modulated electron beams with low-temperature plasma were carried out at LUE-75 by research groups of the Yerevan accelerator [9]. A setup for studying the coherent interaction of a beam with an energy of several tens MeV with gas discharge plasma was created. Passing through the plasma created in the quartz tube, a sequence of electron bunches excited high-gradient wakefields. Experiments were carried out both with decaying plasma and microwave discharge plasma. A powerful RF wave from the high-frequency power supply system of the linear accelerator was fed into an open resonator containing a rarefied gas quartz chamber, i.e. the plasma was created by the same microwave field as for the formation and acceleration of electron bunches. This created conditions for the coherent interaction of a relativistic modulated electron beam with plasma. Using a magnetic analyzer built specifically for these experiments, a shift of the integral energy spectrum of the beam passing through the plasma towards higher energies was observed. The dependences of the energy shift and the amplitude of the beam current at the output on the phase of the RF wave that creates the discharge in the tube and on the plasma density were studied. The plasma density was measured by radio interferometric method. It was shown that in strong electric fields generated by coherent interaction, the beam current is very sensitive to the phase of the microwave field.

The work [10] is devoted to the development of the theory of the laser acceleration method. The interaction of electrons in vacuum with a circularly polarized electromagnetic wave in the presence of a longitudinal magnetic field is considered. It was shown that at using ultrashort and superintense laser pulses (1 ps, 10^{18} W/cm^2, CO_2 laser), the electron energy can reach 2.1 GeV; according to calculations, the accelerated beam has a small energy spread of the order of $\delta\varepsilon/\varepsilon \leq 10^{-2}$.

The work [11] theoretically substantiates the possibility of precision measurement of the absolute energy of an electron beam by measuring the energy losses of a laser beam due to the absorption of radiation by electrons in a uniform magnetic field. It was shown that the relative accuracy of the considered method is up to 10^{-4}, and the parameters of the electron beam will not noticeably change during the energy measurement. The proposed method is a practically unperturbing control of the absolute energy of the electron beam in a wide energy range from tens of MeV to hundreds of GeV, as well as the possibility of determining the real energy spread of the electron beam. The author emphasizes that the industry produces high-speed detectors with high spectral sensitivity, which are necessary for measuring the absorption of radiation.

4. STUDY OF COHERENT X-RAY BREMSSTRAHLUNG OF CHANNELED ELECTRONS IN THE PRESENCE OF ACOUSTIC FIELDS IN A CRYSTAL

The research groups of the Institute of Applied Problems of Physics (IAPP) NAS of Armenia carried out experiments on an extracted beam with an energy of 20 MeV. The work was carried out at the end of the parallel transfer path, where there is practically no interference from the operating equipment of the accelerator. The phenomenon of coherent X-ray bremsstrahlung of channeled relativistic electrons in the presence of external acoustic fields in a single crystal was studied.

One of the effective methods for generating quasi-monochromatic gamma radiation is coherent bremsstrahlung. Acoustic oscillations excited in a crystal can serve as an additional mechanism for controlling the parameters of radiation processes in a medium. The energy distributions of the characteristic radiation outputs of electrons that passed through the studied samples of a piezoelectric quartz single crystal were measured. The measurements showed that when high frequency hypersonic oscillations act on a piezoelectric single crystal, the intensity increases and the energy yields shift. The dependence of the bremsstrahlung cross section on the parameters of the acoustic wave and on the angle of incidence of electrons relative to the crystallographic planes of a single crystal of quartz was studied also [12, 13].

The possibility of controlling the spatiotemporal parameters of the characteristic radiation of channeled electrons with the help of electromagnetic fields, which was substantiated in the early works of IAPP employees, was also studied. For this purpose, the phenomenon in these targets was studied at different wavelengths and powers of external fields in the microwave range.

It should be noted that earlier, for the first time, a group of researchers on the internal beam of the Yerevan Synchrotron ARUS [14] experimentally observed the emission of channeled electrons with an energy of 4.7 GeV in a diamond single crystal with 100 μm thick.

5. EXPERIMENTS CONDUCTED ON LOW-ENERGY NUCLEAR PHYSICS

The electron linear accelerator LUE-75 is one of the experimental bases of AANL for carring out experiments both in the fields of fundamental science and applied nuclear physics.

Investigations of photonuclear reactions on the bremsstrahlung of a LUE-75 were carried out jointly by scientists from Yerevan State University (YSU) and AANL.

A number of experiments were carried out in order to study the possibility of producing isotopes for medicine by means of photoneutron reactions.

^{99m}Tc is the most widely used isotope in nuclear medicine today [15, 16] with over 30 million diagnostic medical imaging scans every year around the world [17, 18]. Medical centers or commercial radiopharmaceutical distributors typically purchase ^{99}Mo/^{99m}Tc generators from which ^{99m}Tc (and as a by-product also ^{99g}Tc) can be extracted periodically in a simple chemical process as it accumulates from the decay of the ^{99}Mo parent.

For the production of an isotope that is very important for medicine, a method was proposed for obtaining technetium on a bremsstrahlung beam of a linear electron accelerator LUE-75. A target made of natural molybdenum was irradiated with a bremsstrahlung of photons from electrons with energy of 40 MeV and a current of 10 μA. The most important results is the normalized specific activity A ≈ 3000 Bq/mg μA h which could allow production of ^{99m}Tc by the use of high intensity electron beams via photonuclear reactions [19].

At the same parameters of bremsstrahlung beam the possibility of production medical interest isotope ^{123}I have been studied [20]. The normalized specific activity is A ≈ 143 Bq/(mg μA h), which is in a good agreement with the results of 110 Bq/(mg μA h) [21, 22].

Experiments related to medical isotopes production ^{111}In, ^{117m}Sn, ^{124}Sb, and ^{177}Lu at the LUE-75 at the bremsstrahlung end point energy of 40 MeV was carried out. The results show that the yield and purity of radioisotopes ^{111}In and ^{117m}Sn are acceptable for their production via photonuclear reaction. Using of the Te and HfO_2 targets with natural isotopic composition led to the small yields of ^{124}Sb and ^{177}Lu and the photoproduction of these isotopes is hardly appropriate even in the case of enriched targets.

Production of Medical theragnostic isotope ^{67}Cu in photonuclear reactions on Zn targets of natural isotopic composition were studied by bremsstrahlung photons with end-point energies of 30 and 40 MeV. Cross-sections per equivalent quantum of ^{67}Cu, ^{64}Cu, ^{62}Zn, ^{63}Zn, ^{65}Zn, and ^{69m}Zn activation products were measured. The specific activities of ^{67}Cu were found to be 2.04 and 4.78 μCi/(μA h g) at the end of the bombardment for 30 and 40 MeV bremsstrahlung maximum energies, respectively [23].

Production of theragnostic isotope ^{47}Sc in photonuclear reactions have been carried out at the bremsstrahlung end-point energy of 30 and 40 MeV using titanium targets of natural composition. The yields of ^{47}Sc at the end of the bombardment were measured to be 0.45 ± 0.07 MBq/(μA h g) and 1.34 ± 0.12 MBq/(μA h g) for 30 and 40 MeV, respectively.

Along with experiments in the field of applied physics by means of bremsstrahlung beam of LUE-75 have been carried out a number of experiments in the field of fundamental investigations also.

The measurements of the yields of products of reactions that proceed on ^{112,118,124}Sn, ^{nat} Te, and ^{nat}Hf targets as well as to measurements and analyze the isomeric ratios for the products of the reactions ^{120}Te(γ,n)^{119m,g}Te, ^{122}Te(γ, n)^{121m,g} Te,^{118}Sn(γ, p)^{117m,g} In, and ^{124}Sn(γ, n)^{123m,g} Sn have been performed at LUE-75 in case of the end-point energy of the bremsstrahlung spectrum was $E_\gamma^{max} = 40$ MeV [24].

On the bremsstrahlung beam of LUE-75 at two electron energies of 30 and 40 MeV the flux-weighted average cross sections for the reactions ^{nat}Re(γ,*x*n)^{182m,182g,184m,184g,186g}Re and ^{nat}Nb(γ,*x*n)^{90g,91m,92m}Nb have been measured by the activation method followed by spectrometric analysis using the high purity germanium detector (HPGe). For obtaining a bremsstrahlung photon beam as a converter tantalum 2 mm thick was used. A target device was installed behind the tantalum converter, in which plates of natural copper (^{65}Cu—30.83%, ^{63}Cu—69.17%) were sequentially arranged as a photon beam monitor. The studied targets were made of natural niobium (^{93}Nb—100%) and natural rhenium (^{185}Re—37.4%, ^{187}Re—62.6%). Two irradiation sessions were carried out at end-point breamsstrahlung energies of 30 and 40 MeV with durations of 2 hours and 1 hour, respectively. In the course of target irradiation with bremsstrahlung photons, the beam current was stabile and equal 1 μA.

The experimental gamma-ray flux during irradiation was determined by means of a copper monitor and amounted to 6.5×10^{15} photons/hour and 3.86×10^{16} photons/hour at electron energies of 30 MeV and 40 MeV, respectively. On Figure 5 the energy spectra of bremsstrahlung photons simulated by the GEANT4 program [25] with taking into account the physical sizes and locations installed on the beam line collimator and tantalum converter are shown.

The flux-weighted average values of the cross sections for the reactions ^{nat}Re(γ,xn)^{182m,182g,184m,184g,186g}Re are received. The obtained flux-weighted average values of the cross sections for the reactions ^{nat}Nb(γ,xn)^{90g,91m,92m}Nb at end-point breamsstrahlung energies 30 and 40 MeV was compared with the

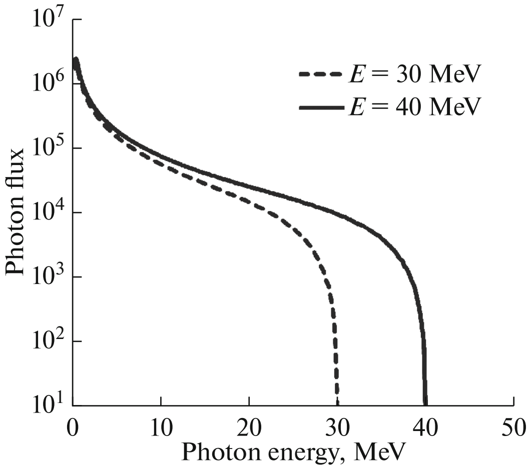

Fig. 5. Energy spectra of bremsstrahlung photons for 30 and 40 MeV electron energy calculated by the GEANT4.

published data of other authors [26, 27] as well as with theoretical calculations by codes TALYS 1.9 [28] and EMPIRE 3.2 [29].

The results of measuremenbts the flux-weighted average values of the cross sections for the reactions ^{nat}Re(γ,xn) and ^{nat}Nb(γ,xn) was published in [30, 31].

The production of alpha particles in photonuclear reactions on ^{65}Cu, ^{115}In, ^{92}Mo and ^{207}Pb targets at the bremsstrahlung end-point energies $E_\gamma^{\max} = 21$ and 40 MeV was studied jointly by groups of AANL and Yerevan State University (YSU). The measurement results represent the yields of reactions studied as functions of the mass number of nuclei and the photon energy. The data obtained enable one to suggest a change in the mechanism of alpha particle photoproduction with increasing energy of incident photons and target mass.

The process of photoproduction of a series of radioisotopes from copper nuclei at the bremsstrahlung end-point energies $E_\gamma^{\max} = 21$, 30 and 40 MeV was studied jointly by groups of AANL and YSU. The relative yields of ^{61}Co, ^{60}Co, ^{58}Co, ^{57}Co with respect to the ^{61}Cu are measured. It is shown that the predictions of the TALYS model, as well as the model inserted in the GEANT4 software package are as a whole in strong contradiction (especially in the case of the GEANT4 code) with the measured relative yields. A continuously decreasing energy dependence was observed for the ratio of unfolded (weighted with bremsstrahlung spectrum) cross sections of reactions ^{65}Cu(γ,α)^{61}Co and ^{63}Cu (γ,2n)^{61}Cu, similarly to that observed earlier for the ratio of cross sections of electronuclear reactions ^{65}Cu(e, e' + α)^{61}Co and ^{63}Cu (e, e' + 2n)^{61}Cu, however the latter ratio is by about 2.5 times higher as compared to data on photonuclear reactions. The ratio of the ^{61}Co and ^{64}Cu yields is also measured; its value $(2.6 \pm 0.2) \times 10^{-3}$ at $E_\gamma^{\max} = 21$ MeV is consistent with the general trend of the dependence of this ratio on the atomic number Z, measured recently at $E_\gamma^{\max} = 23$ MeV for heavier nuclei with atomic numbers from $Z = 47$ to $Z = 82$. The results of these joint works with YSU were published in [32, 33].

The process of the photoemission of one, two, three and four neutrons from the ^{209}Bi nuclei with producing, respectively, ^{208}Bi, ^{207}Bi, ^{206}Bi and ^{205}Bi daughter radioisotopes was investigated by the research group of AANL at the end-point energies of $E_\gamma^{\max} = 30$ and 40 MeV. It is shown that the predictions of the TALYS model, as well as the model which is contained in the GEANT4 package are in a contradiction with the experimental data. For instance, the predictions of GEANT4 at $E_\gamma^{\max} = 40$ MeV for relative yields of ^{208}Bi/^{207}Bi and ^{205}Bi/^{207}Bi and the prediction of TALYS for ^{205}Bi/^{207}Bi about twice are smaller than the experimental values. At $E_\gamma^{\max} = 30$ MeV, the predictions of both models for ^{205}Bi/^{207}Bi about two order of magnitude are smaller than the experimental values [34].

The inclusive process ^{16}O(γ, X)^{7}Be of the ^{7}Be isotope photoproduction from oxygen nuclei was studied at the boundary energies of bremsstrahlung photons $E_\gamma^{\max} = 40$ and 70 MeV. This process in the near-threshold energy range E_γ <40 MeV is observed for the first time owing to low-background conditions in the underground laboratory of the AANL, where spectroscopic measurements were carried out. The cross section averaged over the spectrum of bremsstrahlung photons and the cross section per equivalent photon have been measured. The measured cross sections are compared with the available experimental data and with the predictions of the TALYS1.9, GEANT4 and FLUKA models. It is shown that the predictions of TALYS and GEANT4 are strongly underestimated (especially at $E_\gamma^{\max} = 40$ MeV) in comparison with experimental data, which is associated with a strong underestimation in model calculations of the role of two main near-threshold reaction channels: the ^{16}O(γ, ^{9}Be)^{7}Be photofission channel and the ^{16}O(γ, n + α + α)^{7}Be spallation channel. *FLUKA* predictions are qualitatively comparable with experimental data at $E_\gamma <$ 40 MeV and $E_\gamma = 50$–60 MeV, however, they greatly exceed them in the energy range $E_\gamma = 40$–50 MeV, this excess being almost entirely due to the overestimated contribution of the ^{16}O(γ, n + α + α)^{7}Be spallation reaction cross section [35].

An experiment on the neutron production in nuclear reactions induced by bremsstrahlung photons at 70 MeV end-point energy has been performed by a research group from Brno Technological Institute (Czechia). The experimental setup consisted of a wolfram convertor for generation of bremsstrahlung photons by 70 MeV beam of incident electrons, followed by: a cylindrical aluminium moderator for extra stopping of electrons; an aluminium foil for the photon beam monitoring, a cylindrical target (photoneutron converter) serving for generation of neutrons; and, finally, 12 different activation targets for measurement of the neutron flux. Three different expositions of the setup were realized, using as a photoneutron convertor the targets made of, respectively, LiCl, BeO, D_2O chosen because of their low threshold energy and relatively high cross section for the (γ,n) reaction. During expositions, a fixed energy (with a precision of 1–2%) and practically constant (up to a few percents) intensity 5.61×10^{12} e^-/s of the electron beam were provided.

Neutron-activated targets subsequently undergone gamma-spectroscopic analysis with the help of a high purity germanium (HPG) detector, and for each of 12 targets the yields of a number of radionuclides produced in neutron-nuclear interactions (mainly, in (γ,n) reactions) were measured. The obtained experimental data were compared with theoretical predictions based on the MCNP6.2 computer simulation code, demonstrating an agreement between experimental and theoretical results.

6. PLANNED AND POSSIBLE WORKS AT LUE-75

Planned:

— Modernization of the linear accelerator LUE-75;

— Improvement of the existing stand for calibration of highly sensitive detectors of elementary particles by introducing silicon photomultipliers and modern VME equipment. To ensure the possibility of testing crystal detectors with extremely low intensity test beams for calorimeters for experiments on colliders under construction in the world;

— In-situ study of phenomena induced by electron irradiations in high temperature superconductors, semiconductor and laser crystals;

— In order to cover a wide range of bremsstrahlung photon energies, it is planned to continue studying $^{\mathrm{natNb}}$(γ,*x*n)^{90g,91m,92m}Nb at electron energies 20 and 70 MeV. Measurements over a wide energy range will allow one to estimate the predictive power of theoretical models;

— In the last decade, the reaction ^{181}Ta(γ,n)^{180}Ta has been intensively studied from the astrophysical point of view. The carried out of experiment to measure the flux-weighted average cross section of formation ^{180}Ta at electron energies of 20 and 70 MeV is planned. It was assumed that the ^{181}Ta(γ,n)^{180m}Ta cross section could explain the solar abundance of ^{180m}Ta;

— Measurement of the photo-yields of a number of poorly studied multi-nucleon spallation reactions (γ,*x*n) and (γ, α+*x*n) on nuclei heavier than iron, as well as fission reactions on heavy nuclei, such as bismuth and gold, aiming at the supplementation of the photonuclear reactions data base and testing available theoretical models of low-energy photonuclear interactions which are widely used in many fields such as the nuclear astrophysics, production of medical radioisotopes, photogeneration of neutron fluxes, radiation protection, nuclear transmutation, etc.;

— Study of photoemission of lightest radionuclides (such as ^{7}Be) from light nuclei, including carbon, nitrogen, oxygen, fluorine, sodium, magnesium and aluminum at poorly studied near-threshold energy region of bremsstrahlung photons;

— Searching for tetraneutron ^{4}n ejected in the reaction ^{209}Bi(γ, 4n)^{205}Bi;

— Searching for indications on the emission of multineutron bound states ^{x}n ($x \geq 4$) in the photofission (electrofission) of the thorium nucleus (γ/e) + ^{232}Th $\rightarrow$ ^{x}n + X_f, where X_f denotes undetected fragments of the thorium fission;

— Measurement of the photo-yields of several poorly studied reactions of environment protection interest, such as: ^{116}Cd (γ, n) ^{115}Cd, ^{75}As (γ, n)^{74}As, ^{121}Sb (γ, n) ^{120}Sb, ^{123}Sb (γ, n) ^{122}Sb, ^{198}Hg(γ, n)^{197m}Hg. Photoactivation analysis of a number of alloys (brass, bronze, amalgam) and minerals (arsenopirit FeAsS, antimonit Sb_2S_3) aiming at the diagnostics for the admixture of heavy metals and other toxic elements in different samples. These tasks are important for ecological monitoring of the environment.

Possible:

— Possibility to study the influence of various types of radiation, including electromagnetic radiation from accelerator microwave sources on microorganisms – on populations of bacteria, viruses. The task may be of interest for the fight against viral diseases.

— The possibility of operating the synchrotron in the stretcher mode with a beam energy of 50–75 MeV without acceleration in the synchrotron, i.e., the creation of circulating low-energy electron beams with slow extraction. The stretcher mode will make it possible to carry out an actual program of studying the cluster structures of neutron-rich isotopes of light nuclei (He, Li, Be, C) in the ground and excited states in two- and three-particle photodisintegration reactions in the photon energy range $E_\gamma = 30$–75 MeV [36]. The problem is of interest for theoretical nuclear physics and nuclear astrophysics. Such a regime is in demand also for studying the radiation of electrons in single crystals.

7. CONCLUSION

The electron linear accelerator LUE-75 is the important science experimental base of AANL. It can also be used for educational purposes. At present, the accelerator is in working condition and provides electron beam current and energy over a wide range 10^{-18}–10^{-5} A and 10–75 MeV, respectively. Although the experimental works carried out in recent years at LUE-75 showed its reliable operation, it is planned it is planned to upgrade it by introducing modern technologies. The results obtained in the course of scientific experiments show the promise of the chosen areas of experimental research on the study of nuclear reactions in the low-energy region and indicate the need for further research in this area.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

REFERENCES

1. Clendenin, J., Rinolfi, L., Takata, K., and Warner, D.J., *Compendium of Scientific Linacs. 18-th Int. Linac Conf.* Geneva, Switzerland, August 26–30, 1996, CERN/PS 96-32 (DI), November, p. 108, 1996.
2. Hakobyan, A.S., *J. Contemp. Phys.*, 2021, vol. 56, p. 169.
3. Ivanyan, M.I., Danielyan, V.A., Grigoryan, B.A., Grigoryan, A.H., Tsakanian, A.V., Tsakanov, V.M., Vardanyan, A.S., and Zakaryan, S.V., *Nuclear Instruments and Methods in Physics Research*, A, 2016, vol. 829, p. 187.
4. Bartoszek, L. et al., *arXiv:*1501.05241, 2015.
5. Artikov, A. et al., *Conference New Trends in High Energy Physics*, Budva Montenegro, 24–30 September 2018. https://indico.jinr.ru/event/410/contributions/3321/attachments/ 2563/3334/Davydov_NTIHEP2018.pdf.
6. Davydov, Yu.I., *The Beam Requirements to Test Detectors (in particular, for CsI Crystals)*, The Experience in Yerevan, https://indico.jinr.ru/conferenceDisplay.py? confId=363.
7. Taniguchi, R., Kojima, T., and Okuda, S., *Radiation Physics and Chemistry*, 2007, vol. 76, p. 1779.
8. Yu, L.D., Yue, J.H., Li, Y.L., and Sui, Y.F., *Proceedings of IPAC2017*, Copenhagen, Denmark, 292 (2017).
9. Oksuzyan, G.G., Ivanyan, M.I., and Vardanyan, A.S., *Plasma Physics Reports*, 2001, vol. 27, no. 6, p. 507.
10. Melikian, R., *Laser and Particle Beams*, 2014, vol. 32, no. 2, p. 205.
11. Melikian, R.A., *J. Contemp. Phys.*, 2012, vol. 47, p. 206.
12. Mkrtchyan, A.R., Mkrtchyan, A.H., Grigoryan, L.S., et al., *J. Contemp. Phys.*, 2013, vol. 48, p. 154.
13. Mkrtchyan, A.R. and Mkrtchyan, E.A., *J. Contemp. Phys.*, 2013, vol. 48, p. 158.
14. Aganyants, A.O., Vartanov, Yu.A., Vartapetian, G.A., Kumakhov, M.A., Trikalinos, Kh., and Yaralov, V.Ya., *Pisma Zh.Eksp.Teor.Fiz.*, 29 554 (1979) [in Russian].

15. S.J. Adelstein, F.J. Manning. Isotopes for Medicine and the Life Sciences. USA, Washington: National Academy Press, 1995.
16. Wagner, H.N., Szabo, Z., and Buchanan, J.W., *Principles of Nuclear Medicine.* 2nd ed, USA, Philadelphia: W. B. Saunders, 1995.
17. International Atomic Energy Agency (IAEA). Production and supply of Molybdenum-99, IAEAGC(54)/INF/3 Suppl. https://projectx-docdb.fnal.gov:440/cgi-bin/RetrieveFile?
18. Nuclear Technology Review. Annex: production & supply of 99Mo, 2010, no. August; 2010. p. 36.
19. Avagyan, R. et al., *Nuclear Medicine and Biology*, 2014, vol. 41, p. 705.
20. Avetisyan, A. et al., *Nuclear Medicine and Biology*, 2017, vol. 47, p. 44.
21. Zvara, I., *Communication of the JINR*, Russia: Dubna, 18–82-20, 1982.
22. Nordell, B., Wagenbach, U., and Sattler, E.L., *Int. J. Appl. Radiat. Isot.*, 1982, vol. 33, p. 183.
23. Hovhannisyan, G.H., Bakhshiyan, T.M., and Dallakyan, R.K., *NIM B*, 2021, vol. 498, p. 48.
24. Hovhannisyan, G.H., Bakhshiyan, T.M., Balabekyan, A.R., and Kerobyan, I.A., *Applied Radiation and Isotopes*, 2022, vol. 182, p. 110138.
25. GEANT4. *A Simulation Toolkit*, March 5th, 2019; https://geant4.web.cern.ch/.
26. Naik, H., Kim, G.N., Schwengner, R., Kim, K., Zaman, M., Tatari, M., Sahid, M., Yang, S.C., John, R., Massarczyk, R., Junghans, A., Shin, S.G., Key, Y., Wagner, A., Lee, M.W., Goswami, A., and Cho. M.-H., *Nucl. Phys. A*, 2013, vol. 916, p. 168.
27. Rahman, A.K.Md.L., Kato, K., Arima, H., Shigyo, N., Ishibashi, K., Hori, S., and Nakajima, K., *J. Nucl. Sci. Technol.*, 2010, vol. 47, p. 618.
28. Koning, A., Hilaire, S., and Goriely, S., *TALYS 1.9 nuclear reaction program*, 2017.
29. Herman, M., Capote, R., Sin, M., Trkov, A., et al., *EMPIRE-3.2 Rivoli modular system for nuclear reaction calculations and nuclear data evaluation*, 2013.
30. Avetisyan, A.E. et al., *Physics of Atomic Nuclei*, 2021, vol. 84, p. 245.
31. Avetisyan, R.V. et al., *Nuclear Instruments and Methods in Physics Research, B*, 2021, vol. 507, p. 7.
32. Balabekyan, A.R., Demekhina, N.A., Melyan, E., Faltajanyan, S., Aleksanyan, A., Amirkhanyan, S., Gulkanyan, H., Kotanjyan, T., and Hakobyan, A.S., *J. Contemp. Phys.*, 2020, vol. 55, p. 1.
33. Aleksanyan, A.Y., Amirkhanyan, S.M., Balabekyan, A., Demekhina, N.A., Gulkanyan, H.R., Kotanjyan, T.V., Mangasaryan, V., Pogosov, V.S., Poghosyan, L.A., and Faltajanyan, S., *J. Contemp. Phys.*, 2020, vol. 55, p. 275.
34. Hakobyan, A.S., Aleksanyan, A.Y., Amirkhanyan, S.M., Gulkanyan, H.R., Kotanjyan, T.V., Pogosov, V.S., and Poghosyan, L.A., *J. Contemp. Phys.*, 2020, vol. 55, p. 111.
35. Aginian, M.A., Arutunian, S.G., Harutyunyan, G.S., Gukasyan, E.E., Lazareva, E.G., Margaryan, A.V., Poghosyan, L.A., Chung, M., Kwak, D., and Reetz, R., *J. Contemp. Phys.*, 2022, vol. 57, p. 20.
36. Sirunyan, A.M., http://book.lib-i.ru/25fizika/393013-1-o-sozdanii-erfi-eksperimentalnoy-bazi-dlyaissledovaniy-yadernoy-fizike-nizkih-energiy-osnove-lue-75-eku.php.

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