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On Some Projects of Modernization of the Yerevan Synchrotron ARUS

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Abstract—The paper briefly describes the projects for the modernization and modification of the Yerevan Electron Synchrotron ARUS of the A. Alikhanyan National Science Laboratory (Yerevan Physics Institute). The described work proposed in different years is of interest related to the discussion of the issue of creating a new accelerator base in Armenia for solving actual applied and fundamental physical problems.

Keywords: accelerator physics, synchrotron modernization, stretcher mode, nuclear physics

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1. INTRODUCTION

The Yerevan fast cycling electron ring accelerator (EKU), the ARUS synchrotron (ANSL-YerPhI), designed for an energy of 6.1 GeV, was built in the 60s on the initiative and under the guidance of the outstanding scientist Artem Isaakovich Alikhanyan and was the largest electron synchrotron in the Soviet Union and one of the largest in the world (Fig. 1).

Quoting M.V. Keldysh, "... a very significant event – both in our (Soviet – authors' note) science and in the world – is the launch of several largest accelerators, in particular, an electronic accelerator in Yerevan for 6 billion electron volts ..." [1]. It has implemented a large-scale research program, the scientific results of which are widely recognized. The studies of ANSL-YerPhI scientists on the photoproduction of mesons by a unique beam of polarized gamma quanta, the hadronic properties of photons in the photoproduction of π – mesons in nuclei, the structure of nucleon resonances in multipolar experiments, the structure and properties of nuclear material are well-known in the scientific community. The YerPhI physicists obtained unique data on spin correlations in photoproduction processes using highly polarized photon beams created at the synchrotron. At the Yerevan synchrotron ARUS, JINR physicists, together with colleagues from YerPhI, measured slow protons and recoil deuterons produced by elastic scattering of electrons at small angles. The result of these experiments was the most direct method for determining the electromagnetic radii of the proton and deuterons, as well as their form factors. The properties of X-ray transition radiation and radiation of narrowly collimated beams of relativistic electrons channeled in crystals were studied [2–4]. With the use of synchrotron radiation, the research was carried out in the field of crystal physics, radiation biophysics, and radiation materials science. These and other works important for science were published in high-ranking scientific journals and were given priority.

At present, the operation of the synchrotron has been suspended for various reasons. Only the synchrotron injector, the LUE-75 linear accelerator, continues to operate, and research is being carried out in the field of low-energy nuclear physics [5–13].

Accelerator technology is the main basis of experimental nuclear physics for solving both fundamental and applied problems, including nuclear medicine, radiobiology, environmental problems, materials science, etc.

Because of the increased interest in the problems of nuclear physics and the expansion of the range of scientific research planned by the experimenters of Armenia, it becomes relevant to expand the experimental base of ANSL (YerPhI), in particular, the creation of a new or modernization/modification of the existing accelerator complex ARUS.

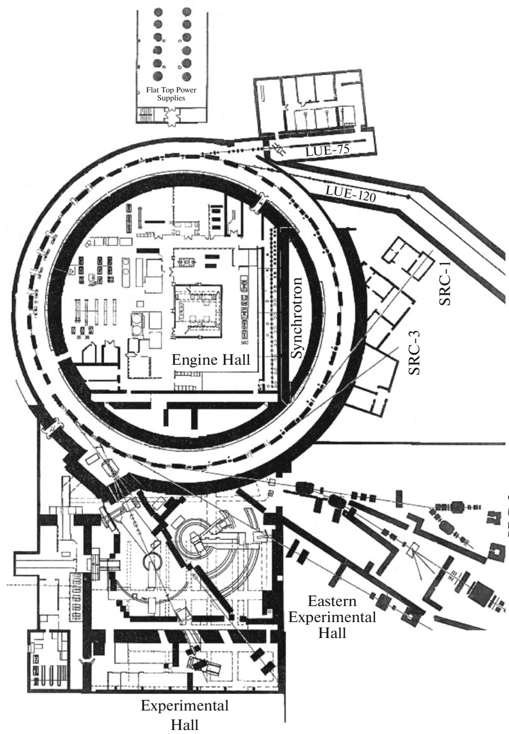

Fig. 1. Scheme of the Yerevan synchrotron ARUS.

This work aims to briefly present some of the projects and proposals made in different years to create accelerator technology in ANSL(YerPhI) that meets the needs of modern science. But before moving on to the main part of this work, we note that ANSL(YerPhI) scientists developed many significant scientific ideas and proposals, which were subsequently successfully used in other countries. For example, in 1971 in the work of the International School of High Energy Physics, annually organized in Yerevan by A.I. Alikhanyan, "... Artem Isaakovich and Yu.F. Orlov presented a project for an electron-positron colliding beam accelerator with a total energy of 100 GeV. This project contained many new ideas that were subsequently used in the construction of next-generation colliders, it was very close to the project of the future LEP accelerator at CERN, which was not even considered at the time. The project was consigned to oblivion because Artem Isaakovich refused to delete the name of the dissident Y. Orlov from the author's composition. According to B.L. Ioffe, if the project of A. Alikhanyan and Yu. Orlov was accepted, then the world center for high energy physics would move to the USSR" (quote from [14]).

2. THE ARUS SYNCHROTRON

During the operation of the synchrotron, the installation was permanently upgraded, a magnetic field "flat top" system was built, construction of a new high-current injector LUE-120 began, the synchronization system was improved, and a system for automatic control of parameters using a computer was created [15]. Therefore, the parameters given in Table 1 differ significantly from the design ones and correspond to the state of the last period of work up to 2008.

More detailed parameters are presented in [15, 16].

3. SUGGESTIONS AND RECOMMENDATIONS FOR THE CREATION OF A NEW EXPERIMENTAL BASE BASED ON HEAVY ION ACCELERATORS

At the initiative of the Government of the Republic of Armenia, an independent ICE was convened together with JINR in 2009 to conduct an independent examination to determine the prospects for the functioning of YerPhI with its accelerator base and possible ways of development taking into account the new realities after the collapse of the USSR.

Table 1. Parameters of the ARUS accelerator

The parameters of the injector – LUE-75	
The specific rotational velocity of injection	Single-turn injection
The energy at the output of the injector, MeV	Up to 75
Maximum current per pulse, mA	170
Energy spread at the injector outlet, %	2
Bunch repetition rate, GHz	2.7973
Pulse duration, μs	0.5 – 1.0
Macropulse repetition rate, Hz	50
The parameters of electron-ring accelerator (EKU-6)	
Maximum energy, GeV	
without "flat top"	6.1
with a "flat top" duration 2.0–4.5 ms	2–4.5
Equilibrium orbit length, m	216
Type and scheme of the magnetic structure of the synchrotron	Sign-variable, FOFDOD
Number of periods of the magnetic structure	24
Number of magnetic blocks	48
The number of betatron oscillations in orbit:	
radial	5.276
vertical	5.294
Number of accelerating cavities	23
Accelerating voltage frequency, MHz	132.79 ± 0.53
Vacuum, Torr	10^{-6}
Number of electrons in the acceleration cycle	1×10^{11}
Cycle frequency, Hz	50
Circulating current, mA	22
Orbital period, μs	0.7229
Acceleration time, ms	9.3
Flat top duration, ms	1.0–4.5
Energy increase per revolution, keV	
on injection	220
maximum	720
Number of channels for slow resonant extraction of primary beams	1
Number of channels for slow beam-bump output from internal targets of secondary gamma beams	3
The number of photons in SR beams in the band $\Delta\lambda/\lambda = 10^{-3}$ at an energy of 4.5 GeV and a current of 10 mA of an accelerated beam in a solid angle of I mrad at wavelengths λ from 0.6 to 2.0 Å	4×10^{10}–0.5×10^{10}

The commission was headed by an outstanding scientist specialist in the field of experimental nuclear physics, the academician of RAS Yu.Ts. Oganesyan. The Commission included prominent physicists from different countries: Russia, Germany, France, Great Britain, the USA, Switzerland, and representatives of major scientific centers – JINR, CERN, DESY, etc.

The recommendations of the Commission were made taking into account the relevance of research areas and the financial conditions associated with the new realities in the Republic. As a result of the work of the Commission, recommendations were developed, which were presented and, in general, approved by the Government of Armenia.

After approval by the Government of the Republic of Armenia, a program was prepared jointly with the JINR and other research centers to develop specific conceptual options for the YerPhI accelerator based on ICE recommendations.

For many reasons, this program was not implemented. For many reasons, this program was not been implemented. However, it still is relevant today.

Below, following the ICE recommendations, there are several examples of the development of the YerPhI accelerator base for the use of heavy ion beams in applied and fundamental research, prepared for consideration at the initial stage of the search for a solution to the problem.

1. Ion sources of heavy ions of the ECR type (electron cyclotron resonance) on a high-voltage (up to 300 kV) platform, 3–4 user channels. Areas of research: implantation and modification of materials, the study of fluorescence effects, etc.

2. Cyclotron accelerator of heavy ions with energies 0.1–2.0 MeV/nucleon for ions from Li to Xe. Directions of research: simulation of the flow of uranium fission products in nuclear reactors and study of the properties of reactor materials under the influence of flows of uranium fission products; modification of materials, creation of new ones; track membranes.

3. Cyclotron accelerator of heavy ions up to energies 2–10 MeV/nucleon. Ions from Li to U. Technologies: testing of electronic components for space purposes, and nuclear physics. Such a facility can also serve as a synchrotron injector.

4. A heavy ion synchrotron for the energy of 50–500 MeV/nucleon in the channel of the YerPhI synchrotron to obtain accelerated ion beams, starting from protons, including ^{4}He and ^{12}C for therapy, as well as a wide range of ions up to U.

Application:

— therapy of oncological formations;

— radiobiology and radiomedicine;

— testing of space application electronics;

— nuclear physics.

The question of the possibility of creating a heavy-ion synchrotron for the energy of 1–2 GeV/nucleon directly in the ARUS ring was also discussed.

The implementation of the first two points allows one to work with ion implantation in the technological processes of semiconductor electronics, the modification of the surface layer of materials of parts of machine mechanisms to improve their performance properties, increase the service lifeв, and reliability; the creation of new materials; for commercial purposes, to produce track membranes with a pore diameter from several tens of nm to microns, used as micro- and nano filters to remove impurities, from suspensions containing bacteria and viruses. The use of beam methods in nanotechnological processes is distinguished, among other things, by its environmental friendliness, which is important in conditions of threatening environmental pollution.

The second point, which makes it possible to study the influence of flows of uranium fission products on the properties of reactor materials, is especially important for Armenia, in which the nuclear power plant Metsamor is located.

The third and fourth points make it possible to implement an extensive research program, including problems that arise at the intersection of various areas: nuclear physics, radio electronics, nuclear medicine, radiobiology, ecology, etc.

It was supposed to jointly develop a conceptual design of the accelerator complex with the possible involvement of specialists from other JINR Member States [17].

4. THE PROJECT OF ELECTRON STORAGE-STRETCHER RING

Scientific accelerators of charged particles require constant modernization as a new element base arrives, and often modifications, depending on the new tasks that nuclear physics and elementary particle physics pose for scientists. In the 80–90s, projects relevant to that time were developed to modernize the Yerevan ARUS synchrotron into a powerful source of synchrotron radiation (SR)—the ERSINE project. Engineering issues of the technical project for the creation of a new storage-stretch ring (SSR) for electron energies up to 14 GeV were worked out, the booster of which was supposed to use the existing EKU-6 synchrotron ring with a new 120 MeV high-current injector under construction at that time (Fig. 2). On the straight sections of the storage ring, long wiggler and undulator devices were installed, with the help of which dozens of synchrotron channels with γ-beams of various wavelengths were created.

The aim of the project was a systematic study of nuclear forces and the structure of nuclei: in the late 80s and early 90s, the YerPhI developed an extensive program of experimental studies in the energy range 1–14 GeV. It became possible to study particle interactions at distances smaller than nucleon sizes, which

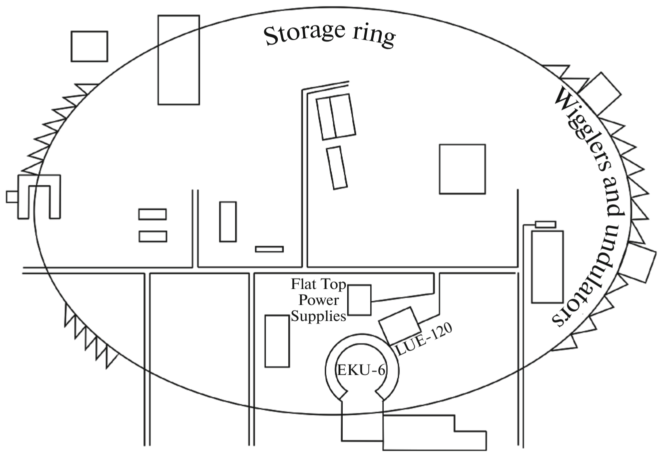

Fig. 2. Simplified sketch of the 6–14 GeV SSR structure. Rectangles indicate buildings, utility rooms, and other parts of the infrastructure of the complex; straight lines are roads.

is less than 1 F. A wide range of works was planned for the study (when listing the works given below, the material from [15, 16] was used):

— the processes of photo- and electroproduction of particles and comparison of results with the predictions of theoretical models;

— multipolarization studies on nucleons and low-nucleon systems in these processes;

— research on the detection of exotic states of elementary particles;

— the study of resonances on nuclei;

— the study of the processes of fragmentation of quarks into hadrons;

— in the specified energy range, it would be possible to study the structure of the electroweak interaction in polarization experiments on electroproduction on nuclei.

To implement these and other works, it was envisaged:

— the creation of new complex physical installations – recording spectrometers, particle monitoring systems, etc.;

— the modernization and development of the Yerevan electron synchrotron, turning it into a modern electron-photon complex for that time.

The new electron-photonic complex was planned to be created in stages:

— the first stage provided for the commissioning of the 1st stage of the system for the formation of a “flat top” magnetic field with a duration of 5 ms with a duty factor of 20%. The LUE-75 served as the synchrotron injector. At electron energies, up to 4.5 GeV, work on resonance physics, applied research on radiation materials science using SR beams, and other problems of nuclear physics would continue;

— the second stage included: the creation of the 2nd stage of the “flat top” magnetic field system with a duration of 20 ms with a duty cycle of 50%, a complete modernization of the RF system of the synchrotron - the transition to higher-frequency accelerating cavities with a frequency of 466 MHz; commissioning of a new injector - a high-current linear accelerator for 120 MeV, the LUE-120. It was possible to operate at electron energies up to 6 GeV with an average beam current increased by an order of magnitude, up to 5 μA. It was planned to create a system of tagged polarized photons, study the physics of meson resonances and search for exotic hadrons; applied research on radiation materials science on SR beams at high intensities of an electron, and gamma-ray fluxes;

— the third stage included extensive work on the reconstruction of the existing synchrotron. A large ring would be created at 6–14 GeV, according to the project, the injection energy into this ring was raised to 6 GeV, the existing synchrotron was supposed to serve as a booster for a large ring, which could also serve as a storage ring. The average beam current was increased to 100 μA, and the duty cycle was increased to 100%. It would become possible to carry out extensive work in nuclear physics, detection of quark effects, and applied research in radiation materials science using SR at high beam brightness (10^{20} photons/s) and a larger number of output channels.

In the future, it was planned to create an electron-positron collider (Fig. 3) for the energy of 30 GeV (in the center of the mass system).

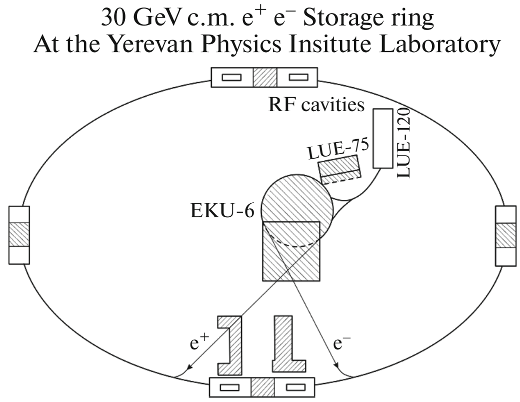

Fig. 3. Simplified sketch of the 30 GeV collider design.

According to this project, the perimeter of the collider covered the entire territory of YerPhI. It was planned to place infrastructure inside this perimeter—communication lines, roads, and underground and surface structures for various technical and control services of the complex.

5. THE POSSIBLE IMPLEMENTATION OF THE LOW-ENERGY STRETCHER MODE OF THE ARUS SYNCHROTRON

An up-to-date long-term program for studying the cluster structures of neutron-rich isotopes of light nuclei (He, Li, Be) in the ground and excited states in two- and three-particle photodisintegration reactions in the photon energy range $E_\gamma = 30–75$ MeV is proposed in [18–20]. It was planned to perform modeling and computations of these processes. The grouping of nucleons into clusters is one of the important phenomena in the structure of atomic nuclei rich in neutrons. Also relevant is the study of exotic structures with an excessive excess of neutrons, when the nucleus approaches the state of spontaneous decay; in this case, the phenomenon of a neutron halo is formed [21]. These studies are also important for understanding the processes of nuclear fusion in space objects.

To implement this program, it is necessary to create experimental equipment for the study of cluster structures. First of all, it is proposed to modernize the Yerevan Electron Synchrotron and implement a low-energy stretcher mode with a slow beam extraction for 3–5 ms, which will not only increase the time of interaction with the target but also make it possible to simultaneously have the yield to two internal targets, which is important for comparison and identifying of coincident events. In addition to the problems of studying the cluster structures of atomic nuclei, the stretcher mode can also be used for other problems, for example, for the effective study of the phenomena of coherent bremsstrahlung of relativistic electrons under the influence of acoustic fields in single crystals.

Let us briefly describe the design of the synchrotron operation in the low-energy stretcher mode, which makes it possible to use the 50–75 MeV beam injected into the ring more efficiently, because in the proposed variant the duty factor of the pulse period increases up to 25%. This is important for the analysis of the coincidence of at least two particles in the processes of electron scattering on nuclei. Increasing this parameter makes it possible to eliminate random coincidences, and to study processes with small interaction cross sections [18, 20].

A pulsed relativistic electron beam from the injector, linear accelerator LUE-75, is supposed to be introduced into the synchrotron ring (Fig. 4), and it is to be kept by the constant magnetic field of the ring electromagnet for about 5 ms. During this time, the beam will make 7000 revolutions around the ring in the region of equilibrium orbit and at the same time will be slowly brought to the inner target by the beam-bump deflecting magnet: using a software-controlled power supply of this magnet, the beam is slowly displaced in the radial direction and is aimed at the target. Thus, the withdrawal time, and hence the time of continuous interaction with the target is much longer (7000 times) than the time of one revolution. The influence of radiation effects, the synchrotron radiation on the process of slow extraction (on the extraction efficiency, beam emittance, etc.) can be neglected because of the low beam energy. An electron beam extended in time up to 5 ms with an energy of up to 75 MeV and an average current of 1 μA is formed. Along with electron beams, the γ-beams with a duration of about 5 ms were obtained by the converter method which can be used in experiments on fundamental and applied research.

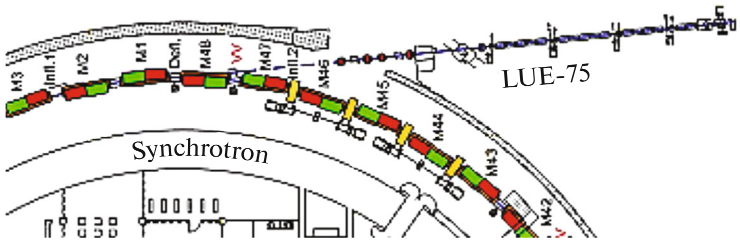

Fig. 4. Beam input structure. M1, M2, ... are the magnetic blocks; 48 rotary magnets, each of which consists of a focusing and defocusing semi-block, form 24 periods according to the FOFDOD scheme, Infl is an inflector, Defl is a deflector.

The simulation of the motion of a relativistic electron beam in the ARUS synchrotron in the low-energy stretcher mode was performed using the OptiM program, taking into account the edge nonlinearities of the magnetic track of the synchrotron electromagnet taking into account the dynamic aperture of the synchrotron ring [19]. The computation of the beam dynamics showed that in a vacuum chamber at a pressure of 10^{-6} Torr the scattering of an electron beam by residual gas nuclei increases the beam cross-section. However, the resulting beam size and emittance after multi-turn (7000 revolutions per 5 ms) circulation are admissible with the existing synchrotron acceptance, and electron scattering does not limit the operating mode of the ARUS synchrotron as a beam stretcher injected from the LUE output-75.

The stretcher mode with a beam energy of 75 MeV without acceleration in the synchrotron is low-cost: the RF power supply of the synchrotron cavities is not turned on, there is no need for cooling and temperature control of the cavities, and the ring electromagnet will be powered by a low-power current-stabilized direct current source. The computed power consumption of the synchrotron in the stretcher mode with an energy of 75 MeV is about 100 kW.

To implement the stretcher mode with an energy of 75 MeV, it is necessary:

— to modernize the existing injector LUE-75;

— to restore the waterproofing of the buildings of the ARUS accelerator complex;

— to replace the physically and morally obsolete inefficient synchrotron vacuum system with a modern one that allows computer monitoring of the vacuum path;

— ensure the operation of the input system – the deflector and the inflector – for the energy of 75 MeV;

— to create a software-controlled power supply for the deflecting magnet – the beam-bump output magnet.

6. CONCLUSION

As noted in the Introduction, there were many projects and proposals for the modernization of the ARUS synchrotron, and we have presented only a few of them. Because of the well-known events of the 90s and subsequent years, they were not realized. To date, the implementation of some projects is not feasible because of the powerful giant accelerators already operating in the world or is unlikely due to financial difficulties. The fate of the Yerevan Synchrotron remains uncertain to this day. Therefore, the problem remains relevant, and the present work intends to contribute to this issue's discussion.

Large accelerators are created for specific physical programs or even for a specific problem, the solution of which makes a major contribution to science or technology. For a country with few resources, especially during a period of financial difficulties, the multifunctionality of such large and expensive physical installations is important.

The most advisable is the proposals and recommendations of the ICE, which remain relevant to this day, namely, the creation of a new physical facility on the platform of the Yerevan Synchrotron ARUS to accelerate heavy ions, which will be used for research in the field of nuclear physics, as well as methodological, scientific and technical problems of nuclear medicine, including the production of radionuclides for medical diagnostics, radiobiology, and testing of the element base of space radio electronics. Such an accelerator can also be successfully used to create new technologies, for example, in materials science and nanotechnology. It was assumed that the final design of the new accelerator in the joint development of ANSL(YerPhI) – JINR should meet modern requirements and tasks in these areas, taking into account new achievements.

According to the ICE recommendations, the expediency of locating a new accelerator at the site of the ARUS synchrotron is based on the following considerations. Firstly, the construction site of the ARUS synchrotron was chosen to take into account the fact that Armenia is a seismically active zone. As a result of geological exploration work, a natural thick basalt platform was discovered, which served as the basis for the accelerator. Secondly, the existing infrastructure of the synchrotron can be used: buildings, structures, the existing power supply system, internal communications, etc., of course, after appropriate repairs and, where necessary, reconstruction, following the needs of the new accelerator. Thirdly, it is possible to use specialists with experience in operating and maintaining such physical installations. Although their number in recent years has decreased and the issue of training specialists in the field of accelerator physics and technology is currently acute, the available qualified personnel can be useful, at least at the first stage of work.

From the foregoing, it seems obvious that it is expedient to activate the work begun in the recent past to implement the recommendations of the International Commission of Experts on expanding the accelerator base of the ANSL(YerPhI).

Despite the suspension of the synchrotron working, Armenia continues to be a regional center for the application of accelerator physics and technology in scientific research. At the electron accelerator LAE-75, the proton medical cyclotron C-18/18 with the possibility to conduct physical experiments, as well as the linear accelerator AREAL of the CANDLE Institute of Synchrotron Research, the research work is carried out by scientists from scientific centers of Armenia and other countries.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

REFERENCES

1. Tumanyn, A.R. and Martirosyan, H.A., *Yerevan electron accelerator "ARUS"*, Yerevan, 1970.
2. Alikhanian, A.I., Ispirian, K.A., Oganessian, A.G., and Tamanian, A.G., *Nucl. Instrum. Meth.*, 1970, vol. 89, p. 147.
https://doi.org/10.1016/0029-554X(70)90817-7
3. Alikhanian, A.I., Avakian, K.M., Garibian, G.M., Lorikian, M.P., and Shikhlarov, K.K., *Phys. Rev. Lett.*, 1970, vol. 25, p. 635.
4. Aganyants, A.O., Vartanov, Yu.A., Vartapetian, G.A., Kumakhov, M.A., Trikalinos, Kh., and Yaralov, V.Ya., *Pis'ma Zh. Eksp. Teor. Fiz.*, 1979, vol. 29, p. 554.
5. Hakobyan, A.S., *J. Contemp. Phys.*, 2021, vol. 56, p. 169.
6. Hakobyan, A.S., Marukyan, H.H., Hakobyan, H.H., Babayan, A.Z., Vahradyan, L.R., Baranov, V., Davydov, Yu.I., Krasnoperov, A., Simonenko, A., Tereshchenko, V., Torosyan, H.T., Zohrabyan, H.G., Ayvazyan, G.M., Vardanyan H.S., and Papyan, A.K., *J. Contemp. Phys.*, 2022, vol. 57, p. 12.
7. Sirunyan, A., Hakobyan, A., Ayvazyan, G., Babayan, A., Vardanyan, H., Zohrabyan, G., Davtyan, K., Torosyan, H., and Papyan, A., *J. Contemp. Phys.*, 2018, vol. 53, p. 271.
8. Hovhannisyan, G.H. et al.*, Applied Radiation and Isotopes*, 2022, vol. 182, p. 110138.
9. Hovhannisyan, G.H. et al., *Nuclear Instruments and Methods in Physics Research Section*, 2021, vol. B498, p. 48.
10. Avetisyan, A. et al., *Nuclear Medicine and Biology*, 2017, vol. 47, p. 44.
11. Avetisyan, R.V. et al., *Nuclear Instruments and Methods in Physics Research Section*, 2021, vol. B507, p. 7.
12. Aleksanyan, A.Y., Amirkhanyan, S.M., Gulkanyan, H.R., Kotanjyan, T.V., Pogosov, V.S., and Poghosyan, L.A., *J. Contemp. Phys.*, 2022, vol. 57, p. 112.
13. 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.
14. Asatryan, H.M. and Hambardzumyan, T.G., *J. Contemp. Phys.*, 2009, vol. 44, p. 209.
15. Amatuni, A.Ts. et al., *Preprint YeRPHI* 1322(17)-91.
16. Amatuni, A.Ts., Alexanyan, A.S., Avakyan, R.O., et al., *EPAC1988 - CERN,* p. 305.
17. http://crd.yerphi.am/files/SAB_meeting_docs_end.pdf.
18. Sirunyan, Al., *Project submitted for the base funding of Artem Alikhanyan National Laboratory*. http://epd.yerphi.am/A.Sirunyan.pdf.
19. Babayan, A.Z., Nikogosyan, V.Ts., and Taroyan, S.P., *J. Contemp. Phys.*, 2014, vol. 49, p. 95.
20. Sirunyan, A., *On the creation in YerPhI of an experimental base for research in low-energy nuclear physics based on LUE-75 and EKU.* http://book.lib-i.ru/25fizika/393013-1-o-sozdanii-erfi-eksperimentalnoy-bazi-dlya-issledovaniy-yadernoy-fizike-nizkih-energiy-osnove-lue-75-eku.php.
21. *Nuclear clusters: from light exotic to superheavy nuclei*. http://jinrmag.jinr.ru/win/2002/43/kl43.htm.

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