

DC-60: twenty years of research in nuclear physics, radiation materials science, and advanced technologies in Kazakhstan

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Abstract

This review summarizes twenty years of research at the Astana Branch of the Institute of Nuclear Physics, centered on the DC-60 heavy-ion accelerator. The facility supports experimental nuclear physics, radiation materials science, and the development of advanced functional materials and ion-beam technologies. Research carried out by the Laboratory of Nuclear Physics, the Laboratory of Solid-State Physics, and the Technological Laboratory of Track-Etched Membranes covers nuclear reactions and scattering processes, radiation-induced structural and phase transformations, and the design of materials for operation under extreme conditions.

Particular attention is given to ceramic materials for radiation shielding, fusion and nuclear-energy applications, as well as to the development of track-etched membranes. Membrane research has evolved from controlled pore formation and surface functionalization to multifunctional systems for membrane distillation, oil-water separation, sensing, catalysis, adsorption, gas capture, radionuclide removal, environmental remediation, and electrochemical energy storage.

The review also highlights the role of the DC-60 facility in the development of accelerator-based technologies, international scientific collaboration, and the training of researchers. The accumulated results demonstrate how a common accelerator infrastructure can connect fundamental nuclear physics with materials science and emerging energy and environmental applications.

1 Introduction

Accelerator-based research plays an important role in modern nuclear physics, radiation materials science, and the development of advanced technologies. In Kazakhstan, the Institute of Nuclear Physics provides experimental infrastructure for both fundamental and applied studies in these areas. Its research activities cover the full cycle from investigations of nuclear and radiation processes to materials development, testing, and technological applications.

An important part of this infrastructure is the Astana Branch of the Institute of Nuclear Physics. Over the past two decades, it has developed into a multidisciplinary research center built around the DC-60 heavy-ion accelerator complex. The facility was established in cooperation with the Joint Institute for Nuclear Research (JINR), and the first accelerated heavy-ion beam was obtained in 2006. Since then, the DC-60 has become the main experimental platform of the Branch, supporting research in nuclear physics, radiation materials science, ion-beam modification, functional materials, and track-etched membrane technologies.

The research program is organized around three main units: the Laboratory of Nuclear Physics, the Laboratory of Solid-State Physics, and the Technological Laboratory of Track-Etched Membranes. Together, these laboratories provide a continuous research chain, from ion irradiation and studies of radiation-induced processes to structural characterization, materials modification, and the development of functional systems for practical applications.

The Laboratory of Nuclear Physics investigates nuclear reactions induced by accelerated ions, nuclear structure, and reaction mechanisms at low and intermediate energies. Experimental measurements at the DC-60 are combined with theoretical analysis to study elastic scattering, transfer and breakup processes, weakly bound nuclei, and nucleus–nucleus interaction potentials. The research program has also expanded toward neutron-producing reactions, nuclear astrophysics, and applied nuclear-data studies.

The Laboratory of Solid-State Physics focuses on the interaction of energetic ions with solids and the resulting changes in their structure and properties. Research includes radiation-induced defect formation, phase transformations, ion-beam modification, and the development of materials capable of operating under extreme conditions. Particular attention is given to oxide, nitride, carbide, and composite ceramics for radiation shielding, nuclear and fusion energy systems, dispersed nuclear-fuel matrices, and other structural and functional applications.

A major applied research direction is the development of track-etched membranes. Polymer films irradiated with swift heavy ions at the DC-60 contain latent ion tracks that are subsequently converted into pores by selective chemical etching. This approach enables precise control of pore size and pore density. Research in this area has evolved from conventional filtration and surface modification toward multifunctional membrane systems. Oxidative treatment, graft polymerization, incorporation of nanoparticles, electrospun nanofibers, graphene oxide, and metal–organic frameworks have expanded the application range of track-etched membranes to membrane distillation, water–oil separation, sensing, adsorption, catalysis, gas capture, radionuclide removal, environmental remediation, and electrochemical energy storage.

The DC-60 facility itself has undergone continuous modernization. Upgrades of

the ion source, accelerator control systems, and experimental infrastructure have improved beam stability, reliability, and operating conditions. The facility is used intensively for both scientific experiments and technological irradiation, providing a common platform for several research directions.

International cooperation has also played an important role in the development of the Astana Branch. Joint projects with research institutions from Europe, Asia, North America, and Australia have covered nuclear physics, radiation materials science, irradiation of functional materials, and track-etched membrane technologies. Cooperation with JINR has been particularly important for the establishment and development of the DC-60 complex, joint experiments, infrastructure modernization, and specialist training.

Over the past two decades, the Astana Branch has established an interdisciplinary research model in which accelerator physics, nuclear physics, materials science, membrane technology, nanotechnology, and analytical methods are connected through a common experimental infrastructure. The DC-60 forms the core of this system, while the individual laboratories provide the expertise required to study radiation-induced processes, modify materials, characterize their properties, and develop practical applications.

This review summarizes the main research directions and results obtained at the Astana Branch, with particular emphasis on work performed using the DC-60 accelerator. The following sections describe the accelerator complex, advanced ceramic materials, experimental nuclear physics and nuclear astrophysics, and the development of track-etched membranes from surface functionalization to multifunctional systems for energy and environmental applications.

2 DC-60 heavy-ion accelerator complex

The DC-60 heavy-ion accelerator, commissioned in October 2006, is an isochronous cyclotron that accelerates ions from ${}^6,7\text{Li}$ to ${}^{132}\text{Xe}$ to energies of 0.4-1.75 MeV/nucleon. An external DECRIS-3M electron cyclotron resonance (ECR) ion source supplies ions for injection into the cyclotron. The complex also includes a low-energy beam-line with ion energies up to 25 keV per unit charge. Its main technical specifications are summarized in Table 1.

The four beamlines support experiments in nuclear and atomic physics, radiation materials science, ion implantation, simulation of cosmic radiation, and the production of track-etched membranes. Available irradiation conditions include liquid-nitrogen temperatures and sample temperatures of 300-1000 K, at which Kr and Xe ions are used to simulate fission-fragment damage. Ionoluminescence measurements allow the optical response of materials to be studied during irradiation. Polymer films are irradiated for the production of track-etched membranes used in water purification, blood plasmapheresis, and microbiological filtration.

Three methods are used to introduce materials into the ECR source. Gas feeding is used to produce ${}^4\text{He}$, ${}^{12,13}\text{C}$, ${}^{14}\text{N}$, ${}^{16,17}\text{O}$, ${}^{20,22}\text{Ne}$, ${}^{40}\text{Ar}$, ${}^{84}\text{Kr}$, and ${}^{132}\text{Xe}$ ions. Evaporation of organometallic compounds is used for ${}^{10,11}\text{B}$, ${}^{28}\text{Si}$, ${}^{48}\text{Ti}$, ${}^{52}\text{Cr}$, ${}^{56}\text{Fe}$, ${}^{58}\text{Ni}$, ${}^{59}\text{Co}$, ${}^{74}\text{Ge}$, and ${}^{180}\text{Hf}$. Micro-oven heating is used for ${}^6\text{Li}$, ${}^{24}\text{Mg}$, ${}^{31}\text{P}$, and ${}^{40}\text{Ca}$.

Tables 2-4 list the ion-beam currents measured at the ECR source for different charge states. These measurements characterize ion-source performance rather than

Table 1: Main technical specifications of the DC-60 accelerator complex.

Parameter	Specification
Particle type	Positive ions
Low-energy beamline	Up to 25 keV per unit charge
Cyclotron beam energy	0.4-1.75 MeV/nucleon
Ion source	DECRIS-3M ECR source
Ion-source operating frequency	14.0-14.5 GHz
Main electromagnet	E-core
Average magnetic field at the extraction radius	1.25-1.65 T
Pole diameter	162 cm
Number of sectors	Four
Injection system	Electrostatic spiral inflector
Resonant system	Two diametrically opposed quarter-wave coaxial resonators with oxygen-free copper-lined steel tanks and copper stems extending into the dees; a copper shorting plate with spherical pressure contacts; an RF coupling loop; and frequency trimmers
RF frequency	11.0-16.65 MHz
Acceleration harmonics	4 and 6
Dee voltage	50 kV
Extraction system	Electrostatic deflector
Deflector electric field	Up to 70 kV/cm
Accelerator vacuum volume	Approximately 2000 L
Pumping system	Rotary vane backing pumps, turbomolecular pumps, and cryogenic pumps
Component cooling	Multi-circuit water cooling

the currents delivered to experimental targets. The range of ions produced by the source should also be distinguished from the range accelerated in the cyclotron.

Beam losses during injection, acceleration, extraction, and transport reduce the current relative to that measured at the source. The accelerated-beam current typically ranges from a few to several hundred nanoamperes. For irradiation experiments, the relevant conditions are therefore determined by the beam delivered to the sample, including its energy, current, spatial distribution, and accumulated fluence. Together with sample temperature, these quantities provide the basis for comparing irradiation conditions and interpreting the resulting material changes.

3 Advanced ceramic materials for future energy technologies

Ceramic materials and ceramic-based composites are among the most promising functional materials for advanced energy technologies. Their high thermal and chemical stability, radiation resistance, hardness, and wear resistance make them suitable for conditions in which conventional metallic and polymeric materials may

Table 2: Ion-beam currents at the ECR source for charge states from 1+ to 7+. All currents are in μA ; dashes indicate that no value is reported.

Ion	1+	2+	3+	4+	5+	6+	7+
^6Li	10.2	11.4	12.8	-	-	-	-
^7Li	115.9	105.0	51.1	-	-	-	-
^{10}B	32.3	30.4	19.8	-	-	-	-
^{11}B	33.2	27.1	18.5	-	-	-	-
^{12}C	-	150.4	97.6	57.2	-	-	-
^{13}C	-	15.5	9.2	4.7	-	-	-
^{14}N	151.0	130.8	100.6	-	-	-	-
^{16}O	180.2	200.9	143.4	98.6	-	-	-
^{20}Ne	-	172.7	177.8	186.6	193.5	90.0	44.1
^{22}Ne	-	170.8	182.7	197.5	157.6	73.1	17.3
^{24}Mg	-	50.2	55.4	57.6	69.1	-	38.6
^{28}Si	-	18.2	48.2	-	40.8	-	-
^{31}P	-	108.1	77.7	52.4	33.6	30.2	34.3

Table 3: Ion-beam currents at the ECR source for charge states from 5+ to 13+. All currents are in μA ; dashes indicate that no value is reported.

Ion	5+	6+	7+	8+	9+	10+	11+	12+	13+
^{40}Ar	59.1	81.6	78.1	94.2	105.0	95.8	45.1	16.9	-
^{40}Ca	33.3	67.1	67.7	62.9	19.4	33.4	-	-	-
^{48}Ti	10.9	35.7	15.1	-	-	22.5	9.8	-	-
^{52}Cr	10.5	17.8	18.9	14.9	21.9	9.2	3.8	-	-
^{56}Fe	-	19.1	17.6	24.3	-	24.8	12.9	5.3	-
^{58}Ni	-	4.2	-	12.3	14.4	-	26.9	5.9	-
^{59}Co	-	19.7	39.7	49.9	56.5	-	32.4	12.6	3.6
^{74}Ge	-	-	5.9	11.1	28.4	20.8	28.9	-	29.1
^{84}Kr	-	-	46.8	63.2	73.6	75.6	68.2	-	45.2

rapidly degrade. Of particular interest are ceramics designed for operation at high temperatures, under ionizing radiation, in chemically aggressive environments, and under cyclic thermal and mechanical loading.

The development of such materials is primarily based on controlling their phase composition, microstructure, and defect structure through the appropriate selection of starting materials, synthesis conditions, and subsequent thermal treatment. Methods such as mechanochemical synthesis, spark plasma sintering, additive manufacturing, nanostructuring, alloying, and the fabrication of composite or multilayer structures are used to obtain ceramics with tailored properties. These approaches allow the density, porosity, grain size, and characteristics of interphase boundaries to be controlled, thereby determining the mechanical and functional performance of the final material.

Figure 1 summarizes the main approaches used for the development and modification of ceramic materials and illustrates their potential role in advanced energy

Table 4: Ion-beam currents at the ECR source for charge states from 14+ to 22+. All currents are in μA ; dashes indicate that no value is reported.

Ion	14+	15+	16+	17+	18+	19+	20+	21+	22+
^{84}Kr	31.7	16.8	-	-	-	-	-	-	-
^{132}Xe	16.4	16.5	15.2	14.5	16.9	12.4	10.3	8.5	6.6
^{180}Hf	-	-	-	17.6	18.2	17.1	13.5	8.8	4.6

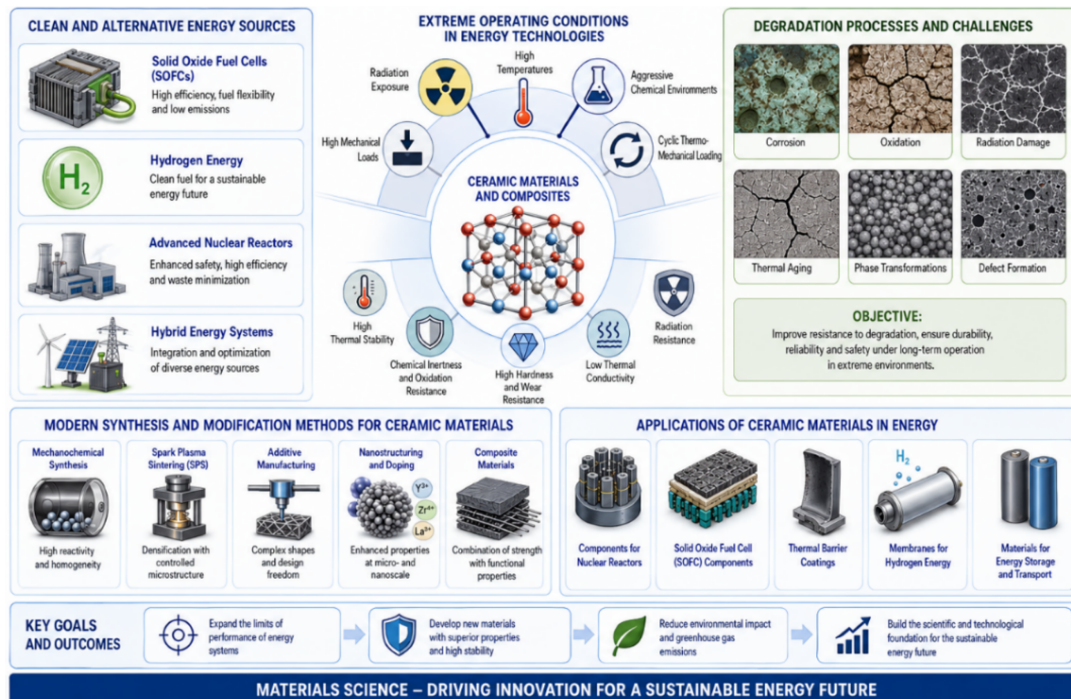


Figure 1: Main directions in the development and modification of ceramic materials investigated within the research activities of the Laboratory of Solid-State Physics at the Astana Branch of the Institute of Nuclear Physics.

systems. Possible applications include nuclear reactor components, solid oxide fuel cells, thermal-barrier coatings, membranes for hydrogen technologies, and materials for energy storage and conversion. Particular attention is given to corrosion, oxidation, radiation damage, thermal aging, phase transformations, and defect formation. Understanding these processes is essential for improving the durability, reliability, and operational safety of ceramic materials under extreme conditions and for developing more efficient and environmentally sustainable energy technologies.

3.1 Shielding and absorbing materials based on multicomponent oxide ceramics and glass-ceramics

The use of glasses and ceramics for protection against ionizing radiation requires a combination of effective radiation attenuation, mechanical strength, and stability under prolonged irradiation. A shielding material must not only reduce the incident radiation flux but also preserve its structure and functional properties during long-term operation. For this reason, multicomponent oxide systems containing

tellurium, bismuth, and tungsten oxides were investigated, with their properties further adjusted through the addition of CeO_2 , MoO_3 , SiO_2 , and PbO and through variation of heat-treatment conditions.

The shielding performance of these materials is determined not by the presence of a single heavy element, but by the combined effects of chemical composition, density, porosity, and phase structure. The incorporation of CeO_2 into tellurite glasses promoted structural densification and reduced porosity, resulting in improved gamma-ray attenuation [1]. The modified glasses also showed greater stability after prolonged irradiation, indicating that compositional modification can improve both the initial shielding efficiency and resistance to radiation-induced degradation.

The feasibility of lead-free shielding materials was examined using Bi_2O_3 - TeO_2 - WO_3 ceramics [2]. These materials provided effective radiation attenuation at relatively small thicknesses and may therefore be considered as alternatives to conventional lead-containing shielding. In glasses based on the TeO_2 - WO_3 - Bi_2O_3 - MoO_3 - SiO_2 system, variation of the MoO_3 and SiO_2 contents made it possible to tune the shielding characteristics, including their performance in the high-energy range [3]. The practical relevance of this approach was also demonstrated for the protection of electronic microcircuits, where glass-based shields reduced irradiation-induced changes in electrical characteristics caused by gamma rays and electrons.

The formation of specific crystalline phases also strongly influenced the mechanical and shielding properties of the materials. In ZnO - Al_2O_3 - WO_3 - Bi_2O_3 ceramics, the formation of complex oxide phases was accompanied by structural densification, increased mechanical strength, and improved gamma-ray attenuation [4]. Similarly, the introduction of PbO into multicomponent glass-ceramics promoted the formation of ordered PbWO_4 inclusions, which improved both mechanical strength and radiation-absorption characteristics [5].

These results show that increasing the concentration of heavy oxides alone is not sufficient to obtain an efficient radiation shield. The final performance depends on the combined effects of composition, density, porosity, and the nature of the phases formed during synthesis and heat treatment. The established relationships provide a basis for the targeted design of oxide glasses and ceramics for both general radiation protection and localized shielding of radiation-sensitive electronic components.

3.2 Lithium-containing ceramics for tritium breeding and suppression of degradation processes in blanket materials

Lithium-containing ceramics are considered promising blanket materials for tritium breeding in future fusion systems. During operation, however, these materials are exposed simultaneously to high temperatures, neutron irradiation, and products of nuclear reactions. The accumulation of radiation-induced defects and implanted helium can cause lattice swelling, mechanical softening, and deterioration of thermo-physical properties. Therefore, considerable attention has been given to identifying structural factors that can slow these degradation processes and preserve material performance during long-term operation.

The resistance of Li_4SiO_4 , Li_2TiO_3 , and Li_2ZrO_3 ceramics to helium accumulation was investigated under high-temperature irradiation with He^{2+} ions [6]. Comparative analysis showed that Li_4SiO_4 experienced less pronounced structural and

mechanical degradation than the other investigated compounds. For all three materials, however, the most significant deterioration occurred at high irradiation doses, when volumetric swelling became a major factor controlling changes in strength and thermophysical properties. These observations indicate that additional stabilization of the ceramic structure is required for prolonged operation.

One approach is the formation of multiphase ceramic systems. The addition of MgO to Li_2ZrO_3 promoted the formation of the $\text{MgLi}_2\text{ZrO}_4$ phase and improved the retention of mechanical properties during cyclic high-temperature exposure [7]. Subsequent high-temperature irradiation studies showed that increasing the $\text{MgLi}_2\text{ZrO}_4$ fraction reduced deformation-induced swelling and slowed the degradation of both mechanical strength and thermophysical properties [8]. Electron paramagnetic resonance studies further associated this improvement with suppression of oxygen-vacancy formation and changes in the accumulation and evolution of radiolysis products within the damaged layer [9].

A similar stabilizing effect of multiphase structures was observed in Li_2ZrO_3 - Li_4SiO_4 and Li_2TiO_3 - Li_2ZrO_3 ceramic systems [10, 11]. Compared with single-phase ceramics, these materials retained their mechanical strength and thermal conductivity more effectively under helium and neutron irradiation. Interphase boundaries appear to play an important role by limiting the migration of vacancies and other irradiation-induced defects and reducing their aggregation into larger defect complexes.

The results indicate that the radiation stability of lithium-containing blanket materials depends not only on the selection of lithium-bearing phases but also on their relative fractions and on the formation of effective interphase boundaries. This provides a basis for the targeted design of ceramic blanket materials with improved resistance to swelling, mechanical degradation, and long-term thermal aging.

3.3 Ceramic materials for dispersed nuclear fuel and nuclear power engineering

One of the promising directions in nuclear energy is the development of dispersed fuel, in which fissile components are incorporated into a chemically and thermally stable matrix. Such a matrix must preserve its mechanical integrity, provide efficient heat removal, and limit damage caused by fission fragments and the accumulation of gaseous products. For this purpose, multicomponent oxide and nitride-oxide ceramics are being investigated as potential matrix materials. Their properties can be tailored through doping, variation of component ratios, and controlled phase transformations.

A significant part of this research is focused on ceramics based on the ZrO_2 - CeO_2 system, modified by yttrium additions and changes in CeO_2 content. Variation of the composition promotes the formation of solid solutions and complex substitutional phases with different degrees of structural ordering and stability under external influences. Changes in phase composition are accompanied by grain refinement and homogenization, an increase in dislocation density, and the formation of additional grain and interphase boundaries. Together, these effects promote ceramic densification and improve strength, fracture toughness, and thermal conductivity, while also increasing stability during prolonged high-temperature exposure [12, 13].

Si_3N_4 - Al_2O_3 ceramics represent another group of potential matrix materials.

Adjustment of the ratio between the nitride and oxide components makes it possible to control their microstructure as well as their mechanical and dielectric properties. An increase in the Si_3N_4 fraction, accompanied by a reduction in the amount of oxide phases, generally leads to higher hardness and improved resistance to crack formation. However, the final properties of these composites depend not only on the concentrations of the starting components but also on the distribution of phases and grains within the ceramic structure [14].

Particular attention is given to the behavior of ceramic matrices during the accumulation of radiation damage. Proton and heavy-ion irradiation are used to simulate processes related to hydrogen embrittlement, the effects of fission fragments, and gas-induced swelling. Deformation, structural disorder, and hardness loss become more pronounced as damaged regions begin to overlap. At the same time, controlled phase transformations in ZrO_2 - CeO_2 ceramics can improve resistance to irradiation-induced deformation and softening [15, 16].

The formation of $\text{Nd}_2\text{Zr}_2\text{O}_7$ - MgO composites is also considered a promising approach. The introduction of MgO into intergranular regions creates additional barriers to crack propagation and can improve thermophysical properties. However, excessive MgO content may promote undesirable phase transformations [17]. Overall, these studies show that the performance of ceramic matrices can be improved through targeted control of phase composition, grain structure, and inter-phase boundaries, allowing strength, thermal conductivity, and radiation resistance to be combined within a single material system.

3.4 Radiation-induced degradation of ceramic materials

The study of radiation-induced degradation in ceramic materials is aimed at identifying the mechanisms of damage accumulation under heavy-ion irradiation that simulates the effects of nuclear fuel fission fragments. Oxide, nitride, and carbide ceramics based on CeO_2 , WO_3 , AlN , Si_3N_4 , and SiC were investigated as model materials. Variation of ion fluence and ion species made it possible to follow the transition from the formation of isolated defects to more pronounced structural and mechanical degradation.

At the initial stages of irradiation, the observed changes are mainly associated with redistribution of electron density, formation of point defects, and local distortion of the crystal lattice. As damage accumulates, defective regions begin to overlap, residual mechanical stresses increase, and radiation-induced swelling develops. These processes are accompanied by the formation of highly disordered or amorphous-like regions, a reduction in hardness, and a decrease in fracture resistance [15].

Comparison of different ceramic systems showed that the character of degradation is determined not only by irradiation dose but also by the initial crystal structure. Among the investigated nitride and carbide ceramics, Si_3N_4 showed the most pronounced deterioration in mechanical properties, whereas AlN and SiC exhibited greater resistance to radiation-induced softening. The degradation of thermophysical properties was associated with defect accumulation, which hinders heat transport through the material. Irradiation with xenon ions generally produced more pronounced changes [18].

Studies of CeO_2 and WO_3 confirmed that the loss of mechanical stability is

closely related to lattice distortion, swelling, and the formation of complex defect clusters [19]. Taken together, these results establish a relationship between radiation-induced structural damage and changes in the mechanical, optical, and thermophysical properties of ceramic materials. They also provide a basis for identifying general degradation mechanisms relevant to ceramics intended for nuclear energy applications.

3.5 Degradation of near-surface layers during hydrogenation and helium swelling

The interaction of hydrogen and helium with ceramic materials is an important factor in the degradation of near-surface layers under the operating conditions of nuclear and fusion systems. Because implanted gases have low solubility in many ceramics, they tend to accumulate in defect-rich regions, promoting the formation of gas-filled cavities and local mechanical stresses. To determine the main mechanisms of these processes, nitride, carbide, and oxide ceramics were investigated under high-dose proton and helium-ion irradiation.

Studies of AlN showed that the degradation mechanism depends strongly on the type of implanted ion. Helium irradiation caused more pronounced swelling, lower crack resistance, and greater deterioration of thermophysical and dielectric properties than proton irradiation [20]. The most significant changes were observed after a critical level of accumulated damage had been reached, leading to helium-bubble formation and partial embrittlement of the near-surface layer. At the same time, AlN showed comparatively higher resistance to hydrogen accumulation than to helium-induced damage.

Several stages of damage development were identified in SiC. At the initial stage, structural changes were associated with grain reorientation and fragmentation, together with changes in dislocation density. These processes can temporarily delay the formation of microcracks. With further helium accumulation, swelling and anisotropic lattice deformation become dominant. These changes are accompanied by the breaking of chemical bonds and the formation of gas-filled inclusions in the near-surface region [21].

Several approaches were investigated to suppress this type of degradation. One involved preliminary modification of the ceramic structure using pulsed ion beams. The resulting increase in grain-boundary density and defect concentration created additional barriers to helium migration and reduced the formation of large gas-filled cavities. Another approach was based on the formation of multiphase materials. In ZrO_2 - Al_2O_3 ceramics, additional interphase boundaries and higher dislocation density reduced the tendency of hydrogen to form agglomerates. The incorporation of AlN into NiAl_2O_4 also promoted structural strengthening and improved the stability of mechanical and thermophysical properties during hydrogenation [22].

Overall, these results demonstrate that control of phase composition, interphase boundaries, grain structure, and defect distribution is an effective strategy for reducing swelling and slowing the degradation of near-surface layers in ceramic materials exposed to hydrogen and helium.

3.6 Ferrimagnetic ceramic composites

One direction in the development of functional ceramic materials focuses on ferrimagnetic systems whose magnetic and electrical properties can be controlled through composition, phase structure, and synthesis conditions. These materials combine magnetic ordering with high electrical resistance and tunable dielectric properties, making them suitable for magnetic, dielectric, and high-frequency applications. Particular attention is given to spinel ferrites and iron-containing perovskite-like ceramics, in which functional properties are closely related to cation distribution, structural ordering, and oxygen content.

CoFe_2O_4 ceramics represent an important spinel-type system within this research direction. Thermobaric synthesis combines elevated temperature and pressure, accelerating solid-state reactions and enabling the production of dense magnetic ceramics within a substantially shorter processing time. Variation of the applied pressure affects both phase composition and microstructure, including the average grain size, and leads to non-linear changes in saturation magnetization, coercivity, and remanent magnetization. At the same time, ceramics synthesized at higher pressures exhibit increased electrical resistivity and dielectric permittivity. These results demonstrate that thermobaric processing provides an effective approach for controlling the balance between magnetic and electrical properties in CoFe_2O_4 ceramics [23].

A complementary approach involves double perovskite-like $\text{Ce}(\text{FeTi})\text{O}_x$ ceramics prepared by solid-state synthesis followed by thermal treatment. Their structure contains several cerium-iron and cerium-titanium oxide phases, whose relative fractions change during annealing. These phase transformations modify the main crystallographic parameters and promote structural densification. A decrease in the oxygen content of the crystal lattice is accompanied by an increased contribution of oxide phases and the development of magnetic ordering [24].

These studies demonstrate that the functional properties of ceramic materials are governed by the combined effects of chemical and phase composition, microstructure, defect structure, and interphase boundaries. Control of these parameters makes it possible to improve mechanical and thermal stability, increase resistance to radiation damage, hydrogenation, and helium-induced swelling, and tailor shielding, magnetic, electrical, and dielectric properties. These results provide a scientific basis for the development of functional ceramics and ceramic composites intended for long-term operation in nuclear and fusion energy systems, as well as in microelectronic and high-frequency devices.

4 Experimental nuclear physics at the DC-60 facility and nuclear astrophysics

The Laboratory of Nuclear Physics conducts experimental and theoretical studies of nuclear reactions, nuclear structure, and interaction mechanisms at low and intermediate energies. A significant part of the experimental program is based on measurements of angular distributions for elastic and inelastic scattering using ion beams accelerated at the DC-60 cyclotron. Charged reaction products are detected using semiconductor detector systems and ionization chambers. These measurements

provide information on nucleus-nucleus interaction potentials, reaction mechanisms, and the contributions of different reaction channels.

Low-energy heavy-ion interactions are of particular interest because elastic and quasi-elastic scattering near the Coulomb barrier is highly sensitive to the properties of the internuclear potential. Experimental angular distributions therefore provide an effective means of testing optical-model and semimicroscopic interaction potentials. A series of experiments performed at the DC-60 facility investigated elastic scattering in several light- and medium-mass systems [25–30].

Elastic scattering of ^{15}N on ^{16}O at an energy of 11.59 MeV was analyzed using optical-model and coupled-reaction-channel approaches [30]. The $^{15}\text{N} + ^9\text{Be}$ system was subsequently studied over a broad angular range, and the experimental data were analyzed using optical-model and double-folding calculations [29].

For the $^{10}\text{B} + ^{12}\text{C}$ system at 17.5 MeV, measurements performed with the DC-60 beam showed that the optical model reproduced the forward-angle part of the angular distribution, whereas description of the full angular range required inclusion of the deuteron-transfer mechanism. Calculations using the FRESKO code yielded a spectroscopic amplitude of 1.78 for the $^{12}\text{C} \rightarrow ^{10}\text{B} + d$ configuration, indicating a significant cluster contribution to the reaction mechanism [28].

More recent studies have focused on the $^{15}\text{N} + ^{11}\text{B}$ system. Experimental angular distributions were obtained at several energies using DC-60 beams and analyzed with phenomenological and microscopic interaction potentials [26, 27].

4.1 Weakly bound and halo nuclei

An important research direction is the study of reactions involving weakly bound and halo nuclei. These systems have relatively low breakup thresholds, which can lead to strong coupling between elastic scattering, breakup, transfer, and other reaction channels near the Coulomb barrier.

The ^6He nucleus is a characteristic Borromean halo system consisting of an α core and two weakly bound neutrons. Its extended neutron distribution can significantly influence collision dynamics at near-barrier energies. Stable weakly bound nuclei such as ^6Li , ^7Li , and ^9Be provide experimentally accessible systems for investigating similar effects and for testing theoretical descriptions of breakup and channel-coupling phenomena.

Of particular interest is the effect of breakup channels on the energy dependence of the nucleus-nucleus optical potential. For strongly bound projectiles, interaction potentials near the Coulomb barrier commonly exhibit the conventional threshold anomaly. Weakly bound nuclei may show different behavior because of strong coupling to breakup channels. This phenomenon is generally described in terms of the breakup threshold anomaly and the associated dynamic polarization potential.

The research group has investigated these effects through theoretical analyses of weakly bound systems. Recent work on the $^7\text{Li} + ^{144}\text{Sm}$ system, for example, re-analyzed elastic-scattering angular distributions over the energy range 21.6–52 MeV using different interaction potentials to clarify the influence of breakup on the elastic channel [25]. Such analyses complement the experimental program at the DC-60 facility and contribute to a broader understanding of near-barrier reactions involving weakly bound nuclei.

4.2 Theoretical analysis of nuclear scattering

Experimental measurements are closely integrated with theoretical analysis. Angular distributions are interpreted using phenomenological optical models, semimicroscopic folding potentials, coupled-channel approaches, and distorted-wave methods. For reactions involving weakly bound projectiles, continuum-discretized coupled-channel calculations can be used to account explicitly for coupling to breakup states.

Computational tools such as FRESKO are used to analyze experimental data and distinguish the contributions of elastic scattering, transfer, and other reaction mechanisms. This combined experimental and theoretical approach has been applied in several studies conducted by the group. In particular, analysis of the $^{10}\text{B} + ^{12}\text{C}$ system showed that inclusion of the deuteron-transfer channel was necessary to reproduce the increase in the elastic-scattering cross section at large angles [28].

The use of both phenomenological and microscopic interaction potentials is particularly important for systematic studies involving several projectile-target combinations. Such comparisons make it possible to identify trends in nucleus-nucleus interactions and provide additional information on nuclear clustering and density distributions.

4.3 Nuclear astrophysics and neutron-producing reactions

Another research direction concerns nuclear astrophysics and charged-particle-induced neutron reactions. Cross sections for reactions involving protons and α particles are important input parameters for models of stellar evolution and nucleosynthesis. The same reactions can also be important for several nuclear technology applications.

Particular attention is given to (α, n) reactions on light nuclei. In nuclear fuel and other actinide-containing materials, neutrons are produced both by spontaneous fission and by reactions induced by α particles interacting with light elements present in the material. The $^{19}\text{F}(\alpha, n)$ reaction is of particular interest because fluorine-containing materials can generate a significant neutron yield under α irradiation. Figure 2 summarizes available experimental cross-section data for this reaction.

Although the excitation function of the $^{19}\text{F}(\alpha, n)$ reaction has been measured previously, discrepancies remain between experimental datasets, particularly in the low-energy region relevant to α particles emitted by actinides. More precise measurements of the excitation function, neutron-energy distributions, and angular correlations are therefore important for reducing uncertainties in nuclear-data evaluations and in calculations related to reactor materials, nuclear fuel storage, radiation shielding, and neutron-background estimation.

Experimental data on (α, n) reactions are also important for testing nuclear-reaction codes such as TALYS and EMPIRE, which combine compound-nucleus and pre-equilibrium reaction mechanisms. Improved experimental datasets can therefore contribute both to a better understanding of neutron-emission processes and to the development of more reliable evaluated nuclear-data libraries.

4.4 Pre-equilibrium processes and applied nuclear data

At higher excitation energies, pre-equilibrium mechanisms become increasingly important. These processes occur before the compound nucleus reaches complete sta-

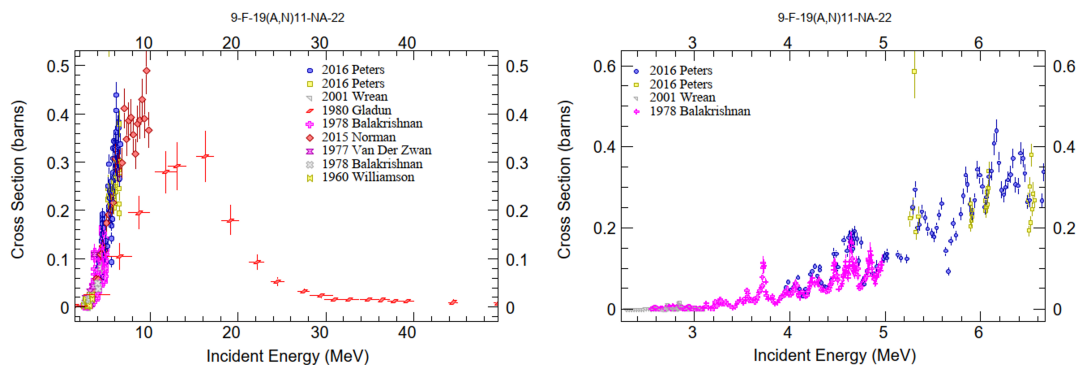


Figure 2: Experimental cross-section measurements for the $^{19}\text{F}(\alpha, n)$ reaction compiled from the EXFOR database [31].

tistical equilibrium and can significantly affect excitation functions, emitted-particle spectra, and angular distributions.

Systematic measurements of α -induced reactions over broad energy ranges can therefore be used to test modern statistical and semistatistical nuclear-reaction models. This is particularly important because evaluated nuclear data are widely used in particle-transport calculations, detector simulations, reactor physics, and radiation-shielding design.

The nuclear-physics research program at the Astana Branch therefore combines fundamental studies of nuclear interaction mechanisms with the production and analysis of nuclear data for practical applications. Elastic-scattering experiments, studies of transfer and breakup processes, investigations of weakly bound nuclei, and measurements of neutron-producing reactions together form a coherent research direction linking experimental nuclear physics, nuclear astrophysics, and applied nuclear technologies.

5 Track-etched membranes: from surface functionalization to multifunctional membrane systems

Track-etched membranes represent one of the long-standing research directions developed using the DC-60 accelerator infrastructure. Their fabrication is based on irradiation of polymer films with swift heavy ions, which produces latent damage tracks along the ion trajectories, followed by selective chemical etching of these tracks to form pores. Poly(ethylene terephthalate) (PET) has been widely used as the starting material because of its mechanical strength, chemical stability, availability, and well-established track-etching behavior.

In a typical procedure developed and used at the Astana Branch, 12 μm PET films were irradiated with $^{84}\text{Kr}^{15+}$ ions at an energy of 1.75 MeV/nucleon using the DC-60 accelerator. The ion fluence and subsequent chemical etching conditions were varied depending on the required membrane structure and intended application.

Figure 3 summarizes the main modification strategies developed within this research direction and illustrates the evolution of track-etched membranes (TeMs) from simple porous materials into multifunctional platforms for sensing, water pu-

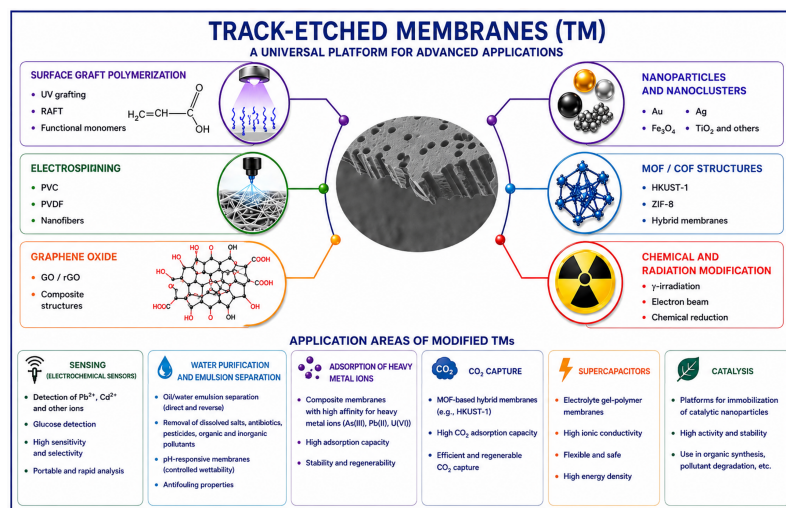


Figure 3: Main modification strategies and application areas of track-etched membranes developed within the research activities of the Astana Branch of the Institute of Nuclear Physics.

rification, emulsion separation, adsorption of heavy metal ions and radionuclides, CO₂ capture, catalysis, and electrochemical energy-storage applications.

5.1 Oxidative modification and functionalization of PET track-etched membranes

One of the first systematic research directions focused on modification of the surface chemistry of PET track-etched membranes. Despite the favorable mechanical and structural properties of PET, its relatively hydrophobic and chemically inactive surface limits further functionalization and restricts applications in which interactions between the membrane surface and transported species are important [32]. Therefore, considerable attention was given to increasing membrane hydrophilicity and introducing reactive functional groups while preserving the original pore structure.

Several advanced oxidation systems were investigated, including H₂O₂ under visible or UV irradiation, Fenton-type systems, ozone treatment, and KMnO₄/H₂SO₄. Among these approaches, H₂O₂/UV and ozone treatment provided a favorable combination of increased surface hydrophilicity and formation of carboxyl groups under relatively mild conditions. Structural characterization also showed that excessively aggressive oxidation can alter surface morphology and affect the polymer structure. This emphasizes the need to balance chemical activation with preservation of membrane integrity.

Further optimization showed that H₂O₂/UV treatment increased the water permeability of PET TeMs by approximately 28%, whereas Fenton treatment produced an increase of approximately 13% [33]. Importantly, the improved hydrophilic properties remained stable during prolonged storage, indicating that the effect was not limited to temporary surface wetting. These results established controlled oxidation as a simple pretreatment that can modify membrane transport properties while simultaneously introducing reactive groups for subsequent chemical functionalization.

The next stage involved UV-induced graft polymerization of functional monomers onto the activated PET surface. Acrylic acid was photografted onto oxidized PET

TeMs using benzophenone as a photoinitiator [34]. The H_2O_2 /UV oxidation step was used to increase the concentration of carboxyl groups. Benzophenone was then immobilized on the cylindrical pore surfaces, after which the pores were filled with an aqueous acrylic acid solution and irradiated from both sides of the membrane. This procedure resulted in the formation of poly(acrylic acid) chains on the internal surfaces of the pores.

An important result was that preliminary oxidation substantially increased benzophenone adsorption and, consequently, improved grafting efficiency compared with etched but non-oxidized PET TeMs. This demonstrated that the internal surfaces of ion-track channels can be selectively activated and subsequently functionalized. The result provided a basis for considering track-etched membranes not simply as passive porous barriers but as three-dimensional functional substrates whose internal channels can actively participate in adsorption, separation, and chemical transformations.

5.2 Protein transport and membrane fouling

Controlled modification of PET TeM surface chemistry also made it possible to investigate relationships between membrane properties and interactions with biological macromolecules. Protein fouling is an important factor limiting membrane performance in biological and water-treatment applications because adsorption of proteins on membrane surfaces and within pores can significantly reduce permeability.

Protein transport through pristine, oxidized, and graft-modified PET TeMs was investigated using bovine serum albumin and lysozyme as model proteins [35]. The results showed that protein transport strongly depended on solution pH and on the relative charges of the protein molecules and membrane surface. Maximum protein fluxes were generally observed near the corresponding isoelectric points, where electrostatic interactions were minimized.

The modification route had a pronounced effect on fouling behavior. Oxidation of PET TeMs improved their antifouling properties, whereas grafting with acrylic acid or N-vinylimidazole could increase membrane-protein interactions and lead to stronger fouling. These results showed that increasing the number of surface functional groups does not necessarily improve membrane performance. Instead, membrane behavior is determined by the combined effects of hydrophilicity, surface charge, functional-group density, protein charge, and solution conditions.

These findings provided an important basis for the subsequent development of functional track-etched membrane systems in which surface chemistry could be tailored to specific separation, adsorption, or analytical applications.

5.3 Development of hydrophobic membranes for membrane distillation

A major application-oriented research direction involved the adaptation of PET TeMs for membrane distillation (MD). Track-etched membranes have several structural characteristics that are advantageous for MD, including small thickness, low pore tortuosity, controlled pore density, and a narrow pore-size distribution [36]. However, PET TeMs obtained after chemical etching are not sufficiently hydropho-

bic for direct use in membrane distillation and therefore require additional surface modification.

One approach involved UV-induced graft polymerization of hydrophobic monomers. Styrene was grafted onto PET TeMs using benzophenone as a photoinitiator, producing hydrophobic membranes that were subsequently tested in direct-contact membrane distillation (DCMD) of saline solutions and low-level liquid radioactive waste. The modified membranes showed rejection values generally in the range of 90-100%, while the decontamination factor for ^{137}Cs reached 1727 [36]. These results demonstrated that track-etched membranes can be used not only for conventional water purification but also for the treatment of complex radioactive aqueous media.

The effect of pore size on membrane-distillation performance was subsequently investigated using PET TeMs with larger pores. Hydrophobic membranes with pore diameters of approximately 700-1300 nm were prepared by UV-initiated graft polymerization of lauryl methacrylate [37]. The resulting membranes had a water contact angle of approximately $94 \pm 4^\circ$ and were evaluated in DCMD using NaCl solutions with concentrations of 7.5-30 g L $^{-1}$. Water fluxes ranged from 1.88 to 11.70 kg m $^{-2}$ h $^{-1}$, while salt rejection reached 91.4%. These experiments provided further insight into the relationships between pore size, membrane hydrophobicity, feed concentration, permeate flux, and salt rejection.

The accumulated results were also summarized in a broader review of track-etched membranes for membrane distillation [38]. This analysis emphasized the importance of precisely controlled pore size and pore density for understanding transport phenomena in MD and showed that TeMs can serve both as functional separation membranes and as model systems for studying the influence of membrane structure on mass transfer.

5.4 Separation of water-oil emulsions and stimuli-responsive membranes

Control of membrane wettability was further applied to the separation of water-oil emulsions. PET TeMs were hydrophobized using trichloro(octyl)silane, producing membranes capable of efficiently separating chloroform-water and cetane-water systems [39]. The hydrophobic membranes demonstrated separation efficiencies of approximately 99.5-99.9% and retained their performance over repeated operating cycles. These results confirmed that the combination of a narrow pore-size distribution and controlled surface wettability can provide efficient selective separation of immiscible liquids.

The concept was subsequently extended from permanently hydrophobic membranes to stimuli-responsive TeMs whose wettability could be reversibly controlled by external conditions. UV-initiated reversible addition-fragmentation chain-transfer (RAFT) graft block copolymerization of styrene and acrylic acid was used to prepare PET TeMs-g-PS-g-PAA membranes [40]. The presence of the pH-responsive poly(acrylic acid) (PAA) block enabled the membrane wettability to change with solution pH. The water contact angle decreased from approximately 97° at pH 2 to 65° at pH 9, corresponding to a reversible transition from a more hydrophobic to a more hydrophilic surface state.

This reversible wettability enabled the same membrane architecture to separate both direct and reverse water-oil emulsions. Separation efficiencies exceeded 90%,

with fluxes reaching approximately $2500 \text{ L m}^{-2}\text{h}^{-1}$ for chloroform-in-water emulsions and $1700 \text{ L m}^{-2}\text{h}^{-1}$ for water-in-benzene systems. The membranes also showed favorable antifouling behavior, including a chloroform flux recovery of approximately 96%. The development of these responsive systems marked an important transition from membranes with fixed surface properties to dynamically tunable separation materials.

5.5 Hybrid track-etched membrane-nanofiber systems

Another strategy for improving membrane performance involved the formation of hierarchical structures by combining PET TeMs with electrospun nanofibers. In this configuration, the track-etched membrane provides mechanical stability and well-defined through-pores, while the nanofibrous layer introduces high surface roughness, additional porosity, and enhanced hydrophobicity.

Hybrid PET TeM/PVC membranes were prepared by electrospinning poly(vinyl chloride) fibers directly onto PET track-etched substrates [41]. Increasing the PVC concentration during electrospinning increased the water contact angle from approximately 55° for the initial PET TeMs to as high as 155° , producing strongly hydrophobic membrane surfaces.

The hybrid structures were evaluated for both water-oil separation and membrane distillation of saline solutions, natural waters, and low-level liquid radioactive waste. The nanofibrous layer substantially increased membrane productivity compared with the corresponding unmodified TeMs while maintaining a high degree of purification. This approach demonstrated that the structural precision of ion-track membranes can be combined with the high surface area and tunable morphology of electrospun nanofibers.

5.6 Track-etched membranes as templates for metal nanoparticles

In parallel with separation applications, PET TeMs were investigated as templates for the formation and stabilization of nanoscale inorganic structures. Following oxidation and graft polymerization of acrylic acid, carboxyl-containing polymer chains inside the pores were used to complex Cu^{2+} ions. Subsequent γ -radiation-induced reduction converted the immobilized copper ions into metallic nanoparticles [42].

Gamma irradiation using a ^{60}Co source at doses of 46-250 kGy resulted in the formation of copper nanoparticles within the functionalized PET channels. The grafted PAA matrix restricted nanoparticle mobility and aggregation, while the track channels provided a confined nanoscale environment. Characterization by XRD, TEM, SEM, EDX, ESR, and FTIR confirmed the formation and immobilization of copper nanoparticles with an average size of approximately 70 nm.

This work demonstrated an additional functionality of TeMs. In addition to serving as separation barriers, their pores can act as nanoreactors and templates for the controlled synthesis of inorganic nanostructures. This concept subsequently contributed to broader research on metal-containing and hybrid membranes for catalysis, adsorption, sensing, and environmental remediation.

5.7 Track-etched membranes as electrochemical sensing platforms

A further development of track-etched membrane technology involved the use of chemically modified PET TeMs as flexible substrates for electrochemical sensors. Their well-defined porous structure provides a large accessible surface area for analyte accumulation, while grafted polymer layers can introduce selective binding groups. After deposition of conductive gold layers, the membrane can function simultaneously as a porous support, a preconcentration medium, and an electrochemical electrode.

One application involved the electrochemical detection of Pb^{2+} and Cd^{2+} ions. PET TeMs were modified by photografting 2-hydroxyethyl methacrylate (HEMA), followed by formation of a polyelectrolyte complex with poly(allylamine) and further functionalization with 4-mercaptophenylboronic acid [43]. Square-wave anodic stripping voltammetry was used for metal-ion determination. The resulting sensors showed analytical responses over broad concentration ranges and satisfactory selectivity and reproducibility in tests with real water samples.

The same membrane-functionalization concept was subsequently adapted for the detection of organic molecules. A non-enzymatic glucose sensor based on PET TeMs modified with PHEMA, poly(allylamine), and 4-mercaptophenylboronic acid was developed [44]. Boronic acid groups provided glucose recognition through the formation of cyclic boronate ester structures. The sensor showed a linear response over the glucose concentration range of 0.1–8 mM and was successfully tested using apple juice and human blood serum samples. Stabilization of the gold layer by the functional polymer interface also improved electrode durability and enabled repeated measurements.

More recently, the sensing platform was extended to the simultaneous detection of toxic heavy metals and rare-earth elements. PET TeMs modified by graft copolymerization of N-hydroxymethyl acrylamide and HEMA were used for electrochemical detection of Pb^{2+} , Ni^{2+} , Eu^{3+} , Gd^{3+} , and La^{3+} ions [45]. The reported limits of detection were 8.7×10^{-7} M for Pb^{2+} , 7.4×10^{-6} M for Ni^{2+} , 8.5×10^{-7} M for Eu^{3+} , 6.3×10^{-6} M for Gd^{3+} , and 2.51×10^{-6} M for La^{3+} . The sensors were additionally tested using tap-water samples and showed reproducible determination of the investigated ions.

These results demonstrate the evolution of TeM-based sensing from the detection of individual toxic metals toward multifunctional analytical platforms capable of detecting both environmentally hazardous and technologically important species.

5.8 MOF-containing track-etched membranes for CO_2 capture

A more recent development of the TeM research direction involves the integration of track-etched membranes with metal-organic frameworks (MOFs). MOFs provide high internal surface areas and tunable adsorption properties, but their crystalline nature can complicate their handling and incorporation into mechanically stable membrane systems. PET TeMs offer a suitable supporting platform because they combine mechanical strength, controlled pore architecture, and chemical functionalization capability.

A method for immobilizing HKUST-1 directly within PET TeMs was developed through conversion of previously deposited copper structures [46]. The resulting PET TeM-HKUST-1 composites reached a BET specific surface area of up to $382 \text{ m}^2\text{g}^{-1}$ and showed a CO_2 adsorption capacity of $0.53 \pm 0.03 \text{ mmol g}^{-1}$ for membranes prepared by the solvothermal route. The composites also retained stable performance over 12 adsorption-desorption cycles.

Further development of this approach involved combining PET TeMs, electrospun PVC nanofibers, and HKUST-1 within a hierarchical hybrid membrane [47]. In this architecture, the PET TeM acts as a mechanically stable porous support, while the electrospun PVC layer provides a three-dimensional matrix for incorporation and secondary growth of HKUST-1.

Secondary MOF growth increased the BET surface area to approximately $135 \text{ m}^2\text{g}^{-1}$, compared with $1.72 \text{ m}^2\text{g}^{-1}$ for the initial PET TeM. The resulting PVC/HKUST-1@PET TeM system showed a CO_2 adsorption capacity of 1.48 mmol g^{-1} at 25°C . After 12 adsorption-desorption cycles, the capacity remained approximately 1.39 mmol g^{-1} , corresponding to retention of about 94% of the initial performance. Storage for three months under ambient conditions caused only a minor change in adsorption capacity.

These results show that combining track-etched membranes with nanofibrous layers and porous crystalline adsorbents provides an effective strategy for mechanically stable hierarchical materials for gas capture.

5.9 Composite track-etched membranes for environmental remediation and photocatalysis

Another rapidly developing direction is the transformation of track-etched membranes into composite catalytic materials for environmental remediation. Unlike conventional membrane separation, in which the membrane mainly acts as a selective barrier, composite TeMs combine a mechanically stable porous polymer matrix with catalytically active metallic or metal-oxide phases. This makes it possible to combine contaminant adsorption and catalytic degradation within the same material. More broadly, composite TeMs have demonstrated potential in environmental remediation, sensing, energy storage, and related applications through the integration of metals, metal oxides, and functional nanostructures into precisely controlled porous architectures [48].

A series of studies focused on template-assisted formation of metallic and metal-oxide micro- and nanostructures within the channels of PET and polycarbonate TeMs. One example is a $\text{Cu}_2\text{O}/\text{ZnO}@PET$ composite membrane developed for photocatalytic degradation of carbendazim. Cu_2O and ZnO microtubes were synthesized within PET TeMs by electroless template deposition, while a mixed $\text{Cu}_2\text{O}/\text{ZnO}$ system was produced using a two-step deposition procedure. The resulting heterostructured composite showed enhanced photocatalytic activity under UV-visible irradiation, reaching approximately 98% carbendazim degradation under optimized conditions [49].

The concept was subsequently extended to pharmaceutical contaminants. PET TeMs grafted with poly(1-vinyl-2-pyrrolidone) by UV-initiated RAFT polymerization were used as supports for palladium nanoparticles [50]. Controlled grafting introduced functional polymer chains both on the membrane surface and along the

nanopore walls, increasing sorption capacity toward metronidazole while also stabilizing Pd nanoparticles. The catalytic performance depended on the reducing agent used during nanoparticle formation, with the ascorbic-acid-assisted system reaching approximately 89.9% metronidazole removal. Photocatalytic activity was retained over ten consecutive cycles.

Mixed metal/metal-oxide architectures were further investigated using Cu/Ni₂O₃@PC composite membranes for the degradation of norfloxacin [51]. Copper and nickel oxide microtubes were formed within polycarbonate TeM channels by electroless template deposition. The mixed composite showed higher photocatalytic activity than the corresponding individual Cu@PC and Ni₂O₃@PC systems. Under optimized conditions, the Cu/Ni₂O₃@PC membrane achieved approximately 59% norfloxacin degradation and retained catalytic activity during repeated use.

More recently, CuO/Cu@PC composite TeMs were developed for combined photocatalytic degradation and sorption removal of roxithromycin [52]. Copper microtubes were deposited within PC TeMs using an environmentally preferable glyoxylic-acid-based electroless deposition route and were subsequently thermally converted to form a catalytically active CuO-containing phase. The resulting composite achieved 96.8% photocatalytic degradation of roxithromycin within 180 min and a maximum adsorption capacity of 410 mg g⁻¹ at pH 5.5. The membranes retained more than 85% photocatalytic efficiency after ten reuse cycles.

Taken together, these studies demonstrate a transition from passive membrane separation toward reactive membrane systems. In these materials, the well-defined channels of TeMs serve simultaneously as templates for nanostructure formation, supports for catalytic phases, and interfaces for contaminant adsorption and degradation. This approach considerably expands the potential of track-etched membranes for advanced water purification.

5.10 Track-etched membrane sorbents for toxic metals and radionuclides

Alongside photocatalytic degradation of organic contaminants, considerable attention has been given to the development of TeM-based sorbents for toxic metal ions. In these systems, selective functionality is introduced either through polymer grafting and nanoparticle immobilization or through template synthesis of metal-containing microstructures inside membrane channels.

For example, PET TeMs functionalized by RAFT-mediated grafting of poly(2-(dimethylamino)ethyl methacrylate) (PDMAEMA) and subsequently loaded with Ag nanoparticles were investigated as hybrid sorbents for As(III) [53]. Controlled RAFT polymerization made it possible to adjust both the grafting degree and polymer-chain length within the nanochannels. The contribution of PDMAEMA functional groups and Ag nanoparticles substantially improved arsenic removal. After 10 h, As(III) removal efficiencies reached 85.6% for Ag@PDMAEMA-g-PET, compared with 56% for PDMAEMA-g-PET and 17.5% for pristine PET TeMs.

Copper-containing composite TeMs were also developed for Pb²⁺ removal [54]. Copper microtubules were synthesized inside PET TeMs by electroless deposition using several reducing agents, including ascorbic acid, glyoxylic acid, and dimethylamine borane. The resulting composites showed effective Pb²⁺ sorption. The adsorption kinetics followed a pseudo-second-order model, while equilibrium behav-

ior was better described by the Freundlich isotherm. An important feature of this approach was the use of environmentally preferable reducing agents, reflecting a gradual transition toward more sustainable routes for preparing functional composite membranes.

A particularly significant recent extension of this research direction is the use of MOF-functionalized TeMs for radionuclide removal. PET membranes were first grafted with poly(N-vinylformamide) by UV-initiated RAFT polymerization and subsequently hydrolyzed to poly(vinylamine). After introduction of terminal alkyne groups, azide-functionalized MIL-101(Cr) particles were covalently immobilized through Cu(I)-catalyzed azide-alkyne cycloaddition. This “click” immobilization strategy enabled stable attachment of the MOF phase to the polymer support rather than simple physical deposition.

The resulting MIL-101(Cr)-functionalized TeMs showed a U(VI) adsorption capacity of 418 mg g^{-1} at pH 6.3 and strong selectivity toward uranium in the presence of competing metal ions [55]. After five adsorption-regeneration cycles, approximately 70% of the initial sorption capacity was retained.

This development is particularly relevant to the nuclear and environmental research profile of the Institute because it extends track-etched membrane technology toward selective radionuclide removal and treatment of contaminated aqueous media.

5.11 Track-etched membranes for electrochemical energy storage

A new direction in track-etched membrane research is their application in electrochemical energy-storage devices. While earlier studies mainly focused on separation, adsorption, catalysis, and sensing, recent work has explored the use of continuous TeM nanochannels as controlled pathways for ion transport in solid-state supercapacitors.

One approach combines controlled polymer grafting with electrospun ion-conducting nanofibers. PET TeMs were functionalized with poly(acrylic acid) (PAA) by RAFT-mediated grafting on both the membrane surface and the pore walls, creating continuous ion-conducting pathways. The membranes were subsequently modified with electrospun PVDF-HFP nanofibers containing the ionic liquid 1-ethyl-3-methylimidazolium tetrafluoroborate and graphene oxide (GO). This hierarchical architecture combines the structural stability and controlled porosity of TeMs with the high surface area of electrospun fibers and the ion-transport properties of the ionic-liquid/GO system [56].

A further development involved modifying not only the surface of an already formed track-etched membrane but also the composition of the polymer precursor before irradiation. Graphene oxide was incorporated directly into polycarbonate films, which were subsequently subjected to ion irradiation, track etching, and RAFT-mediated grafting of PAA within the resulting nanochannels. This approach represents an important transition from post-fabrication modification of TeMs to the preparation of intrinsically composite track-etched membranes [57].

The optimized membrane showed high cycling stability in symmetric supercapacitor cells, retaining 99.6% of its initial capacitance after 1500 cycles [57]. These results demonstrate that the controlled nanochannel architecture originally devel-

oped for membrane separation can also serve as a well-defined ion-transport network. Track-etched membrane technology is therefore expanding into electrochemical energy storage and flexible solid-state devices, representing one of the newest research directions at the Astana Branch.

Overall, the development of track-etched membrane research at the Astana Branch shows a gradual transition from membranes with precisely controlled pore geometry to complex multifunctional and hybrid systems. Early studies established methods for oxidative surface activation, graft polymerization, and control of membrane–solute interactions, providing a basis for applications in membrane distillation, water–oil separation, and stimuli-responsive systems.

Thus, DC-60-based track-etching technology has evolved from a method for producing structurally well-defined porous membranes into a versatile materials platform that combines polymer chemistry, controlled radical polymerization, nanotechnology, electrochemistry, catalysis, adsorption, electrospinning, and porous functional materials.

6 Conclusions

Over the past two decades, the Astana Branch of the Institute of Nuclear Physics has developed into a multidisciplinary research center built around the DC-60 heavy-ion accelerator. The facility has become a common experimental platform connecting nuclear physics, accelerator technologies, radiation materials science, and the development of advanced functional materials.

In nuclear physics, the DC-60 has supported studies of elastic and inelastic scattering, transfer and breakup processes, weakly bound nuclei, and nucleus–nucleus interaction mechanisms at low and intermediate energies. The combination of experimental measurements with optical-model, coupled-channel, and semimicroscopic calculations has provided a consistent framework for interpreting reaction dynamics. The extension of this program toward neutron-producing reactions, nuclear astrophysics, and applied nuclear-data studies further broadens the role of the facility beyond scattering experiments.

Materials research has shown that the radiation resistance and long-term stability of ceramics are governed not only by their chemical composition but also by phase balance, defect structure, grain boundaries, and interphase interfaces. These factors determine the response of ceramic systems to heavy-ion irradiation, hydrogen and helium accumulation, thermal exposure, and associated degradation processes. The results provide a basis for the development of shielding materials, lithium-containing blanket ceramics, nuclear-fuel matrices, and other structural and functional materials intended for operation under extreme conditions.

Track-etched membrane research has undergone a particularly clear evolution from controlled pore formation and surface modification toward multifunctional membrane systems. Successive developments in graft polymerization, nanoparticle immobilization, electrospinning, graphene-oxide incorporation, and MOF functionalization have expanded the application range of TeMs to membrane distillation, water–oil separation, sensing, catalysis, adsorption, gas capture, radionuclide removal, environmental remediation, and electrochemical energy storage. Recent work on ion-conducting and intrinsically composite TeMs demonstrates that this platform

is now extending beyond conventional separation technologies into emerging energy-storage applications.

Taken together, these research directions show how a single accelerator infrastructure can support both fundamental studies and the development of application-oriented materials and technologies. The accumulated experience of the Astana Branch provides a basis for further work in nuclear-reaction and nuclear-data studies, long-term radiation testing of functional ceramics, and the development and integration of multifunctional track-etched membrane systems for energy and environmental applications.

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