APPLICATION OF UPK-2-1 CHARGED BEAM IN FUNDAMENTAL RESEARCH IN RADIATION SOLID STATE PHYSICS AND LOW ENERGY NUCLEAR PHYSICS

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Since the establishment of the Nuclear Physics Institute, fundamental researches there have focused on low and medium energy nuclear physics and radiation solid-state physics. A brief overview of these directions is provided below.

1. Radiation solid-state physics. Interest in research in radiation solid-state physics is connected with the study of processes that occur in substances after their exposure to nuclear radiation. Changes in the physical properties of materials being exposed to nuclear radiation depend on both the nature of the material exposed and the nature and energy of projectile particles. The simplest defects, such as a vacancy or a mixed atom, appear when material is exposed to electrons and γ-quanta with a low energy of 1.5-2 MeV. More complex defects appear after bombardment with heavy ions. In such collisions the energy received by the displaced atoms of a lattice can be very high. In such conditions, nearly all the atoms along the pass of the primary knocked-out ion will be displaced from their location, thus, creating areas of considerable deformation of the lattice, the so-called "displacement peak". A temporary very high temperature zone can appear along the pass of the primary knocked-out atom. A similar, but more pronounced local deformation takes place when solid bodies are bombarded with fission fragments. Therefore, both thermal peaks and displacement peaks appear in materials exposed to radiation in a reactor or bombarded with heavy ions. As far as application to a controlled thermonuclear reactor is concerned, there are three major problems to be solved: 1) the acquisition of stable enough plasma, 2) heating the plasma to the ignition temperature, and 3) the prevention of intensive interaction of the hot plasma with the solid walls of the reactor. Certain success has been achieved in this field in the recent years. Understanding of the physical mechanisms that influence plasma behavior has advanced considerably, as well as the development of theoretical models that allow current results to be extrapolated on large machines being developed as prototypes of future fusion reactors.

The study of surface effects in metals began in the sixties with research conducted by Primakov [1] and Kaminsky [2] who found blistering in materials exposed to deuterium ions with energy of 120 keV. These studies have been continued, and now they are especially intensive due to the problem of the fusion reactor's first wall. They cover a wide range of materials and energies of projectile hydrogen and helium ions from keV to MeV. Various methods of study are used. For example, an interferometric method was employed [3] to detect blistering on the metal surface. The problem was also studied successfully with a scanning microscope [4]. In cases of low
energy, blistering formation is limited to light ions such as hydrogen, deuterium and helium. This is because the surface layer of materials studied is the limiter for heavy ions that prevents them from penetration into the depth of the crystal.

As noted above, the quantity, the arrangement of ions and radiation defects, the location of impurity atoms and own interstitial atoms in the lattice play an important role in the phenomena leading to significant changes in the physical and mechanical properties of materials.

Analysis of the research methods employed in this field shows that the considerable success achieved in the study of radiation defects is based on conventional research methods, including electron and field-ion microscopy and radiography, as well as on methods that include the analysis of changes in physical and chemical properties of materials exposed to radiation. However, the discovery of the orientation effects (the effects of channeling and blocking) in the mid-sixties [5] gave rise to a wide application of nuclear physics methods in radiation solid-state physics. The most successful was the Rutherford scattering (RS) method combined with the channeling and blocking effects of charged particles in single-crystals. The nature of these phenomena is completely based on the structural composition of the studied objects. The advantage of this method over the traditional ones is the ability to study damage kinetics in the course of exposure to radiation, the non-destructive character of the analysis, and the ability to obtain the quantitative information on radiation defects.

The use of a charged beam in researches in radiation solid-state physics has been discussed in the Nuclear Physics Institute since the mid-sixties. However, practical steps were not taken until the mid-seventies when the radiation solid-state physics department, headed by academician Sh. Ibragimov, was established. Several new laboratories, oriented toward the use of a reactor and cyclotron, were established to study the effects of the exposure to radiation on the physical and mechanical properties of materials. A laboratory for the ion implantation of metals was created in 1975. Its major goal was the development and introduction of the most advanced methods of studying the mechanism of radiation defect formation during exposure to radiation. The practical physical tasks were: a) to study the types of radiation defects appearing after exposure to various particles; b) to study the distribution of radiation defects with depth, and effects of the dose, energy and type of the projectile particles; and c) to determine the location of impurity atoms and own interstitial atoms in the lattice of the objects under study.

An accelerator was installed in the Nuclear Physics Institute in the middle of the eighties to solve the above problems in radiation solid state physics, and also to understand the mechanism of several fundamental phenomena in the low and medium energy physics (below 1MeV for protons), that we will consider further. This facility allowed for the acceleration of various ions (from hydrogen to uranium) to the maximum energy of 2 MeV.

2. Nuclear physics. To conduct research in nuclear physics, the Kazakhstan government approved the construction of two basic units, a reactor and a cyclotron, in the Nuclear Physics Institute.
1) WWR-K reactor with a heat rating of 10 MW and a neutron flow of $10^{14} \text{n} / \text{cm}^2$ in the center of the active zone was commissioned in 1967.

2) In 1972, an isochronous cyclotron was built. This unit has superior features that allow the energy of ions to be regulated and high energies of light ions to be reached (30 MeV for protons, 25 MeV for deuterons, 50 MeV for alpha particles, and 60 MeV for helium-3 ions).

The isochronous cyclotron is the basic experimental unit for studies in low and medium energy nuclear physics (nuclear spectroscopy, nuclear reactions, and fission physics), in radiation testing of properties of materials, in production of radioactive isotopes, and in precision ultimate analysis. As mentioned above, a cascade accelerator of heavy ions, UKP-2, was commissioned in the middle of the eighties. Its accelerating voltage is 1 MV with the beam stability and energy spread of $2 \times 10^{-4}$. Various ions, from hydrogen to uranium, including ions of noble gases, are accelerated. The high beam performance allows unique research in atomic, radiation, and plasma physics to be conducted along with ultimate analysis and material engineering [6]. More detailed information on the UKP-2-1 accelerator will be provided in the Experiment section of this presentation.

Considerable success was achieved in the last 30-40 years in fundamental research in nuclear physics and low and medium energy physics, which is based on these basic units. In particular, the obtained experimental data, which in fact has no equivalent in the international literature, allowed several problems of modern nuclear physics to be solved. These include the shape of nuclei in ultimate deformations, the multi-particle and single-particle effects on the density of exited states of atomic nuclei, constraints for the drop model, etc. Principally new phenomena and patterns have been found and studied: asymmetric nuclear fission (the area of lead), and correlation of the fission fragment distribution width with the form of a fissionable nucleus in the saddle point. These results allowed the understanding of some aspects of the nucleus fission mechanism to be deepened and a number of parameters of atomic nucleus models to be defined more accurately. However, keen interest is observed in the revision of old, and the acquisition of new, nuclear physics data at low energies, and in the creation of a databank for new experimental and estimated data on cross-sections of light nucleus reactions. This is first of all connected with problems of controlled nuclear fusion, and with astrophysical and medical applications. The importance of reliable nuclear data is obvious for nuclear-oriented research and applications. In particular, the vigorously developing astrophysics experiences acute need in such data. Whether the further exploration of interstellar space by mankind is successful depends greatly on our understanding of the processes occurring in stars. Analysis of solar gamma radiation gives information on solar cosmic rays, e.g. on spectrum of generation of particles, generation duration, time pattern of the generation, density, temperature and nuclear composition of substance in the outburst area, and the depth of penetration of accelerated particles in the atmosphere of the Sun.
There are various generation mechanisms of gamma radiation. One of them is the reaction of radiation capture of protons by nuclei. This reaction takes place at relatively low energies of interacting particles. Although its cross-sections are small, the concentration of protons with $E_p \leq 1\text{MeV}$ in the outburst is so high that the reaction of radiation capture of protons by atmospheric nuclei becomes very important. The reaction makes its contribution in gamma radiation with the energy of $< 5\text{ MeV}$ and with a maximum being near $1\text{ MeV}$.

The further flux of quanta emitted in the time of the radiation capture depends greatly on the low energy ($< 1\text{MeV}$) part of the spectrum of particles accelerated at the outburst; this allows the possibility of the practical use of radiation for studying the generation spectrum in its low energy part. In addition, the study of these reactions will provide important data on the nucleus structure and speed of nuclear reactions in the sun and stars, and on nuclear fusion and spread of heavy elements in nature.

The results of work [7] to establish a databank of experimental and estimated data on the interaction of charged particles with light nuclei show an urgent necessity for precision experiments that measure the cross-sections of reactions $(\rho\gamma)$ and $(\rho\alpha)$ on the light nuclei that accompany hydrogen, alpha and CNO star burning cycles. In this connection, our task was to obtain experimental information on cross-sections, formation mechanisms, and excitation functions of nuclear reactions initiated by charged particles on light nuclei at low energies, and a theoretical description of the processes under study for compiling a base of theoretical and experimental data on nuclear reaction cross-sections, which is required for controlled nuclear fusion and nuclear astrophysics. The complexity of the problem lies in the fact that the interaction energy of substance in stars is relatively low (from hundreds of eV to hundreds of keV) and this complicates a direct experimental determination of the nuclear constants required for astrophysical calculations. The common approach is to measure cross-sections of nuclear reactions at relatively high energies with their further extrapolation to those energies that are of interest for astrophysics.

The UKP-2-1 unique accelerating unit in the Nuclear Physics Institute, which generates crossed proton beams with an energy spread of 150 eV within the range from 0.2 MeV to 1.5 MeV, allows precision experiments to measure nuclear constants to be performed in a wide energy range, which, in turn, creates the ability to provide a solid theoretical extrapolation of the experimental data obtained in the area of low and super-low energies.

**SECTION II**

**EXPERIMENT SECTION**

1. The **UPK-2-1 heavy ion accelerator**. The UPK-2-1 heavy ion accelerator is the major research instrument for both nuclear and radiation physics. As mentioned above, the accelerator was commissioned in middle of the eighties.
Let us consider in brief the operating principle of the accelerator and its physical parameters. The UPK-2-1 electrostatic tandem, as it is called sometimes, incorporates two independent transportation channels and a cascade generator of the Cockcroft-Walton type with accelerating voltage up to 1 MeV. The use of two independent transportation channels united by one accelerating potential allows highly monochromatic beams of protons and of heavy ions to be produced. One of the accelerator’s channels is designed to accelerate hydrogen ions and inert gases produced in a duoplasmotron. The second channel includes a source with cesium sputtering, which is designed to accelerate heavy ions. The accelerator specifications are shown in Table 1.

Table 1

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<table>
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<tr>
<td>1. Energy range</td>
<td>0.2 ( \pm ) 2 MeV</td>
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<tr>
<td>2. Minimal increment of energy of accelerated particles</td>
<td>( \sim ) 50eV</td>
</tr>
<tr>
<td>3. Range of accelerated masses</td>
<td>1 ( \div ) 250 a.m.m.</td>
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<tr>
<td>4. Energy spread (proton beam)</td>
<td>( \sim ) 0.01%</td>
</tr>
<tr>
<td>5. Energy stability</td>
<td>( \sim ) 40 eV/h</td>
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<tr>
<td>6. Proton beam current</td>
<td>up to 60 ( \mu )A</td>
</tr>
<tr>
<td>7. Stability of current in specimen</td>
<td>( \sim ) 10%</td>
</tr>
<tr>
<td>8. Size of proton beam on target</td>
<td>up to 1 mm</td>
</tr>
<tr>
<td>9. Scanned area</td>
<td>20 x 20 mm</td>
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The schematic diagram of the UPK-2-1 accelerator is shown on figure 1 with all the ion transportation channels: “1” is the channel for heavy ions, “2” is the channel for light ions, and “3” is a new channel [6,8].

2. **Experimental chamber and target device.** The vacuum work chamber is an octahedron with side walls of stainless steel. The distance between the parallel faces is 600 mm, and the chamber height is 370 mm. There are holes closed with flanges in each of the faces. This design allows for higher experimental capabilities of the unit. The chamber has two major inlets connected to the channels for light and heavy ions with two bellows joints (see Figure 2).
The target holder: A goniometric head is used as a target holder. The head has six degrees of freedom to make it possible to fix and to orient specimens of any structure in relation to the beam of incident particles. The above-mentioned six degrees of freedom include: the reciprocal one along the vertical axis, two perpendicular in the horizontal plane (one along the direction of the reflected beam of particles and the second is perpendicular to it), rotary movement around the vertical axis, and oscillatory movement along the horizontal axis. The head also has an additional degree of freedom that allows a specimen to be revolved on its axis. In general, the goniometric head we created is a spectromechanical device that ensures the independent movement of a specimen along three reference axes within ± 8 mm and independent rotation around the axes within the following intervals: x=±20°, y=±30°, and z=±30°. The control system of the goniometric head is placed outside the vacuum chamber. The vacuum in the system is 10^{-7} \text{mm} and more.

The head automation software developed in our Institute allows the head to be controlled remotely using a computer with no disturbance to the vacuum.

Geometry of the experiment: A schematic diagram of the accelerator and the geometry of experiment are shown in Figure 3.
The geometry includes four basic parts: the monitoring unit and the system of analyzing ion beam formation. A device for correcting the initial beam of particles (position 1, figure 3) is installed in the beam monitoring chamber alongside a registration system for the reflected beam of particles that allows the distance between the detector and vibrator to be changed with no disturbance of the vacuum (position 2, figure 4).

The vibrator is made of aluminum with a sputtered layer of gold (200 mcg/cm²). The reflector (vibrator) is driven by a vacuum motor. The frequency is determined by analysis of beam intensity. The initial beam is formed with two diaphragms with varying orifices (0.3, 0.5, 1, 3, 20 mm) installed at a distance of 3m from each other. Such a collimation scheme allows various single-crystal and polycrystalline specimens to be used, as this system enables the access of any necessary degree of collimation, even in channeling conditions of the analyzed beam. The first diaphragm is installed in the monitoring chamber in front of the vibrator (7), while the second is placed in the dispersion chamber before the specimen holder (7) (position 3, figure 3).

**Measurement of energy spectra of nuclear reaction products.** Nuclear reaction products are analyzed using three detectors: 1. A germanium gamma-detector to registers gamma-quanta with energies of up to 10 MeV. The cryostat with the detector is connected to the vacuum chamber from the bottom at an angle of 90° against the incident beam. The vacuum space of the chamber is separated from the cryostat and the detector by an aluminum cap with an open inlet from below. The distance from the cap surface can be changed on the target side to get closer to the beam axis (position 4, figure 3). In this case, a Ge(Li)γ-detector of the DGDK-40V type is used as a detector. Its volume is 40 cm³ and the energy resolution is 2 keV on the gamma-line with an energy of 133 keV. 2. To measure spectra of gamma-radiation in the 5 to 20 MeV part of the spectrum, a scintillation detection unit of the BL 6931-20 type is used with a large NaI(Tl) crystal (160 x 90 mm) and a photomultiplier tube of the FEU-49 type (see position 5, figure 3). The scintillation unit is placed in a lead cylinder with open ends in order to protect it from the natural background radiation. The system is fixed on a carriage and allows the study of the angular distribution of gamma-quanta through the side sealed windows of the vacuum chamber.

The second scintillation detector with similar overall dimensions is placed at the resonance chamber in the beam end behind the vacuum work chamber. The system has its target device with a set of specimens, and is used to study both the structure of some of resonance in nuclear reactions, and to obtain information on the distribution profile of implanted ions in a matrix (position 7, figure 3). In addition to these gamma-spectrometers, two surface-barrier detectors are installed in the main work chamber in order to use the backward scattering method for radiation and nuclear physics research. One is rigidly mounted on a holder at 135° against the incident beam, while the second is mounted on a mechanism that can rotate around the target with a 6° step (positions 8 and 9, figure 3).
A multichannel analyzer with 16304 channels and memory capacity of $2^{31}$-1 units per channel was used in this work to register and analyze reaction products. The memory of the analyzer can be segmented as follows: 16 segments with 1024 channels, 8 segments with 2048 channels, or 4 segments with 4096 channels per segment. The amplitude-digital converter in the analyzer has a fixed conversion time of 15 microseconds. An individual spectrometric tract can be connected to each selected segment, and the segments may be operated either simultaneously or individually. This multidetector system allows energy spectra to be registered at several angles (maximum 16 angles). This nuclear product registration system provides for a flexible and efficient control over an experiment.

II. EXPERIMENT RESULTS AND ANALYSIS

1. Radiation solid-state physics. Before setting out on the implementation of a program for studying radiation effects on single-crystals using a beam of low energy particles, we had to resolve several important problems. First, we had to thoroughly study the parameters of 'orientation' effects on monocrystals in relation to the energy of charged particles. Second, we had to study and find the most efficient ways to apply the 'orientation' effects of charged particles in monocrystals to research in radiation solid-state physics. Monocrystals of refractory metals were selected for the study of the parameters of such 'orientation' effects. The choice of this material, especially tungsten, is not occasional.

First, monocrystals of tungsten (and other refractory materials) were chosen for such research because the oscillation of their lattice atoms is extremely low at room temperature, and the de-channeling factor of 'oriented' particles is also low. Second, both tungsten and alloys of refractory metals are widely used in units exposed to nuclear radiation (experimental fusion reactors, fast neutron reactors, spacecraft, etc.). The parameters of 'orientation' effects on tungsten monocrystals have been studied with a proton beam having the energy of 2.5, 4, 5, and 5.5 MeV. The results obtained have played a noticeable role in the further development of 'orientation' effects theory [9]. At the same time, these data have shown that the application of the 'orientation' effects to research in radiation solid-state physics has its peculiarities.

Our further research and research of other authors has shown that 'orientation' effects at low and medium energies are the most effective and inexpensive in terms of obtaining data in radiation solid-state physics. As an example, let us analyze the results of research of radiation damage to tungsten and silicon monocrystals that have different crystalline structures. These researches were performed in the Institute of Nuclear Physics as well as in the others organizations, in particular in the Institute of Physics Energy (Obninsk-city) and in the Research Institute of Nuclear Physics under Moscow State University (Russian).

The tungsten monocrystal is then exposed to hydrogen ions with energies ranging from 50 to 100 keV. The analysis of the exposed zones was made with a surface-barrier detector mounted at an angle of 135° relative to the incident beam.
Figure 4 shows on the logarithmic scale the relation between the integral concentration of defects and the exposure to 50, 75, 85 and 100 keV hydrogen ions with the dose of \((1\times10^{16} \pm 3.04\times10^{18})\) \text{H}^+ \text{cm}^{-2}. This relationship was determined by summing up the areas of the depth distribution of radiation defects in relation to the energy of projectile hydrogen ions. For the first time, we proved that the defectiveness of tungsten monocrystals grows linearly within a certain range of radiation doses. In this specific case, saturation occurs at \(3\times10^{17} \text{H}^+ \text{cm}^{-2}\), i.e. when balance between the processes of radiation defect formation and their annihilation is achieved. The similar results was obtained also on the others monocrystals such as Mo, Nb, and Al [10,11].

2. **Study of silicon monocrystal irradiated with hydrogen ions.** A silicon monocrystal was chosen for the research because it has a lattice that differs from that of tungsten (i.e. it has face-centered crystal) and is interesting from the standpoint of studying the parameters of 'orientation' defects in relation to the structure of the objects studied. In addition, silicon is the basis of the semiconductor industry with widespread implantation, which allows atoms of any element in any amount to be doped and the purity of the impurities to be controlled. However, the impurity doping process is accompanied by formation of numerous radiation defects that produce a noticeable effect on product parameters. Therefore, the further development of the ion implantation method (which is still topical) is greatly dependent on the understanding of the distribution character of the ions implanted and radiation effects appearing during the impurity doping. We were first to use the backward scattering method in combination with channeling to solve this problem. Monocrystalline silicon that has a purity of 99.99% and an initial specific resistance of \(\rho=10\) ohm was used as a target. It was irradiated with hydrogen ions with energies of 50, 75, 100, and 150 keV. The analysis of the exposed zones was made with the energy of \(500 \div 1000\) keV [12] as with tungsten. Let us consider in detail the damaging process of a silicon monocrystal irradiated with 150 keV hydrogen ions. The obtained energy spectra of protons scattered from the silicon surface are shown in figure 5.
It should be noted that the character of changes in the spectra for the radiation dose of \((1.1 \times 10^{16} + 4 \times 10^{17}) \, \text{H}^1/\text{cm}^2\) is similar to the spectra in [12]. However, any further increase in the radiation dose results in changes in the spectra character. A gradual increase in the damage peak half-width and shift of its 'center of gravity' toward the surface of the specimen are observed beginning with the dose \(4 \times 10^{17} \, \text{H}^1/\text{cm}^2\). The damage peak gradually disappears, beginning with the dose \(6.4 \times 10^{17} \, \text{H}^1/\text{cm}^2\), and the spectrum height near the damage peak is practically equal to the spectrum of backward scattered particles measured at non-oriented position of the silicon monocrystal. At the same time, a dip in the non-oriented spectrum was found for the first time at these radiation doses, whose center coincides with the path length of implanted hydrogen ions with the energy of 150 keV. Similar effects were also found in the spectra for non-oriented silicon position after exposure to hydrogen ions with the energies of 50 keV and 100 keV [13].

Curves in figure 6 show that the centers of gravity of the maximum concentration of radiation defects that correspond to hydrogen ions with the energy of 150 keV are located at a depth of 1.5 mcm from the specimen surface and that they do not change within the dose of \((1 \times 10^{16} + 5 \times 10^{17}) \, \text{H}^1/\text{cm}^2\). A further increase in the dose results in widening half-width of the distribution profiles of radiation defects with shift of their gravity centers toward the surface of the target. It is known that the crystalline structure of substance becomes unstable at several critical concentrations of radiation defects and transition to the amorphous state takes place. Our research has shown that a silicon monocrystal transforms into the amorphous state when irradiated with hydrogen ions with the energy of 150 keV at a dose of \(7.2 \times 10^{17} \, \text{H}^1/\text{cm}^2\). This is a considerably higher value than the one theoretically calculated.

Our experiments have shown that the higher doses do not result in a complete transformation of a silicon monocrystal into an amorphous state. However, the disordered layer of thickness reaches 1.2 mcm at a dose of \(1.6 \times 10^{18} \, \text{H}^1/\text{cm}^2\) which is about 80% of the entire path of implanted hydrogen ions with an energy of 150 keV (see figure 6).
The data shows that the complete transformation of a silicon monocrystal into the amorphous state when bombarded with such hydrogen ions (at room temperature) can be reached only at doses that are considerably higher than $1.6 \times 10^{18} \text{H}^+ / \text{cm}^2$ [14].

2. PHYSICS OF ATOMIC NUCLEUS. With the preserved dispositions of the recording and analyzing systems, the products of nuclear reactions of interactions between nuclei of aluminum and beryllium have been studied.

In the frame of this section, the calibration measurements of the gamma spectra from the $(p, \gamma)$ reaction on the targets from aluminum, aluminum oxide ($\text{Al}_2\text{O}_3$) and beryllium are presented. The aluminum oxide film ~20 mkg/cm$^2$ thick has been obtained by etching the aluminum foil; as a result, the oxide has been remained as a non-etched self-confining film. The thin beryllium target has been manufactured by means of beryllium vacuum deposition on the stainless steel substrate 4 mm thick. Measurements have been carried out in the proton energy range from 340 to 1050 keV with the beam current up to 2 pA. The targets have been used without additional cooling. And the current higher than 1-2 $\mu$A haven’t been supported. A distance between the germanium detector surface and the incident proton beam axis comprises 3.5 cm. One measurement lasts from 20 minutes to three hours.
In figure 7 the $\gamma$ spectrum obtained in the $^{27}\text{Al}(p, \gamma)^{28}\text{Si}$ reaction is shown, and in figure 8 the reduced cross-section of this nuclear reaction occurred at a thin target from aluminum oxide and the yield of the reaction for the first excited state in $^{28}\text{Si}$ accompanying the gamma emission versus the proton energy are depicted.

Fig 8. Experimental 1779 keV $\gamma$-ray yield as a function of proton energy of the reaction $^{27}\text{Al}(p,\gamma)^{28}\text{Si}$ is shown for the thick (top curve) and the peaks (under top curve) this is the counts of the known resonance’s obtained for the thin aluminum target.

As in a thick target the incident protons lose its energies within the entire energy range, the yield graph has a step-like shape within the resonance energy interval, and the yield values increase when the proton energy is getting larger. For a thin target from aluminum oxide, in accordance with the data [15], peaks within the range of the $(p, \gamma)$ nuclear reaction are clearly observed.

At the same time, the proton back scattering spectrum has been measured by the silicon-lithium surface-barrier detector of charged particles. The detector energy resolution comprises 15 keV; so the spectral lines of aluminum and oxygen can be observed, and later the carbon line has appeared.

Fig 9. Pulse height spectrum of the reaction $^{9}\text{Be}(p,\gamma)^{10}\text{B}$ obtained with 1 MeV protons. The detector was at an angle of $90^\circ$ with respect to the beam. All energies are quoted in keV.
As the number of oxygen nuclei in the aluminum oxide film is even larger than the number of aluminum nuclei, we hoped to observe products of the $^{16}\text{O}(p, \gamma)^{17}\text{F}$ nuclear reaction. Actually, the appropriate $\gamma$ emission, usually occurred as a result of discharge of the $^{17}\text{F}$ excited states, hasn’t been revealed. May be, the reason is a large magnitude of the $^{27}\text{Al}(p, \gamma)^{28}\text{Si}$ cross-section, compared to that of the reaction on oxygen, leading to suppression by enhanced background from the reaction on aluminum. In measurements of the $^{9}\text{Be}(p, \gamma)^{10}\text{B}$ cross-section of the nuclear reaction (see figure 9) the curves of the $\gamma$ excitation functions can be divided into two groups (Figure 10).

![Figure 10](image.png)

**Fig 10.** The excitation functions for populating the states in $^{10}\text{B}$. Cross sections are with the relative counts.

The low-energy transitions (413.8, 718.3 and 1021.9 keV, emitting from the lower $^{10}\text{B}$ levels, refer to the first group. The appearance of curves for these $\gamma$ transition (Figure 11) functions is in good agreement with the data [16].

![Figure 11](image.png)

**Fig 11.** The runs of the cross section for populating the first-excited state in $^{10}\text{B}$ obtained with the ours data (top curve) are compared with the references [16] (down curve).
As for a lesser difference in the reaction cross-section versus the proton energy, it can be explained in our case by the fact that in our measurements a rather thick target has been used, allowing to suppress stronger the low-energy protons than the high-energy ones; so within the proton low-energy range the reaction products from a larger proton energy range are recorded in a single measurement.

Another group covers the \( \gamma \) transitions within the spectrum hard energy range: 6469, 6976 and 7484 keV. Appearance of the excitation functions for these transitions is somewhat different from that for the first group, as the produced resonances aren’t the same.

CONCLUSION

1. The presented experimental results show that the low-energy proton beams of the UKP-2-1 accelerator can be applied successfully in fundamental studies in the field of both radiation physics of solids and physics of atomic nucleus.

2. The facility we have created on a base of the UKP-2-1 accelerator has no analogues and can be used for investigation of both material radiation damage, regardless the state and the structure of a studied object, and the processes involving interaction between low-energy charged particles and nuclei.

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