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IMPORTANCE OF BASIC RESEARCH FOR TECHNOLOGY ADVANCES

Abstract: This paper is devoted to the importance of basic research for advancement of applied research, innovation and technology. Transfer of new knowledge along the chain of research and development is often successful only if it includes direct interactions of well-trained scientists and engineers all along the chain. However, the primary responsibility for advancement of basic research lies with the scientific community. The essence of basic research will be illustrated with the brief descriptions of two theories. The former theory is the astronomical theory of climate change, developed by Milutin Milanković. It has had a paramount importance for development of astronomy and physics. The latter theory is the theory of crystal rainbows, developed by us following the research desire of the former theory's author.

Key words: *Basic research, climate change, crystal rainbows*

INTRODUCTION

The subject of this paper is the role of basic research in advancement of applied research, innovation and technology. The importance of this role will be explained in the second section of the paper. Then, in the third and fourth sections of the paper, we shall illustrate the essence of basic research with the brief descriptions of two theories. The former theory is the astronomical theory of climate change, which provides a description of the long-term climate change in time on each planet of the solar system, caused by the change of its position relative to the Sun. The latter theory is the theory of crystal rainbows. It enables one to explain the rainbow effects appearing in propagation of charged particles along crystal channels and nanotubes, which are analogous to the meteorological rainbow effect, occurring in scattering of sunlight from water droplets. The former theory is much more general than the latter one and has had a paramount importance for development of astronomy and physics. The latter theory was developed following the research desire and determination of the former theory's author — to find an uninhabited area and

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acquire a humble scientific property. In the fifth section of the paper, we shall draw several conclusions from the discussion in the previous sections.

RESPONSIBILITY FOR BASIC RESEARCH

As it is well known, basic research is theoretical and experimental activity undertaken with the aim to advance knowledge without a specifically envisaged application in practice [1]. It is the exploration of the unknown. There is no clear dividing line between basic and applied researches. In fact, they are inextricably intertwined. Most of research, whether in academia or in industry, is a combination of new knowledge generation and its subsequent exploitation. Usually, if the extent of basic research is diminished, the same will happen to the results of applied research. The ideal situation is to have strong basic research and strong applied research that are strongly interconnected.

New knowledge is essential for fostering innovation, technology and production, but also as a stable foundation of education and training as well as of other activities that should contribute to development of a society [1]. It is sometimes naively argued at a national level that, since we live in a global society, investment in science should be concentrated primarily on applied research, with the necessary basic scientific information acquired indirectly, *e. g.*, via the internet. However, new knowledge is more than a set of results of basic research. It also includes developed cognitive capabilities of the involved teams of scientists. Therefore, transfer of new knowledge along the chain of research and development is often successful only if it includes direct interactions of well-trained researchers and engineers all along the chain. There have been numerous examples in which the objective of a crucial scientific experiment was attained only upon the realization of a severe technological requirement.

One of the necessary conditions for sustained growth and inclusive development of a country is to have a thriving scientific community capable of generating new knowledge and using it [1]. This condition can be met only with an appropriate strategy of scientific and technological development complemented with an adequate long-term investment plan, which must be applied consistently and continuously, even in the periods of economic crises.

But how will the government of a country make an appropriate strategy of basic research and the corresponding long-term investment plan? It can do that only on the basis of proposals made by the scientific community of the country, *i. e.*, by its independent scientific institutes and such institutes within its universities and industry. This means that the primary social responsibility for maintaining, actualizing and enhancing basic research lies with the scientific community individually and collectively, *i. e.*, with those who have committed themselves to the exploration of the unknown. This includes the responsibility of scientific institutes in the country to communicate and collaborate with each other as well as with similar institutes in other countries worldwide.

ASTRONOMICAL THEORY OF CLIMATE CHANGE

The astronomical theory of climate change was formulated by Milutin Milanković, a Serbian astronomer, climatologist and geophysicist. He was born in 1879 and died in 1958. The idea from which that mathematical theory emerged was to connect the motion of a planet around the Sun with the long-term change of its climate [2–5]. He used the theory, which is known as the Milanković theory, to predict the present climate conditions on Mars, Venus and Mercury as well as on the Moon. These predictions have been proven. But, his most important contribution was the explanation of the glacial and interglacial periods within the present ice age on the Earth, on the basis of the calculations of the insolation variations at the geographical latitudes at 55, 60 and 65 north in summer for the past 1 million years.

Milanković began his work with a detailed analysis of the components of the Earth's motion, which is governed by the gravitational forces it experiences from the Sun, the other planets of the solar system and the Moon. These motions are: (i) the revolution of the Earth around the Sun, (ii) its rotation around the axis defined by the north and south poles, and (iii) the nutation and precession of its rotational axis. His attention was concentrated on the cyclical characters of those motions. As a result of existence of these cycles, the Sun's radiation reaching the Earth's surface varies, inducing the change of its climate, and, thus, impacting the advance and retreat of the ice sheets on the surface.

The Earth revolves around the Sun along an elliptical orbit. This is shown in Fig. 1. Looking from above the orbit, the revolution is counterclockwise. The average distance of the Earth from the Sun is about 150 million km. It moves along the orbit with the speed of about 30 km/s and makes a revolution in about 365 days. The eccentricity of the orbit is the relative difference between the largest and smallest distances of the Earth from the Sun. The larger the eccentricity, the orbit is more like an ellipse, *i. e.*, less like a circle. The eccentricity changes between 0 and about 5% with a cycle of about 95,000 years. Today, the eccentricity equals about 2%.

With respect to the Sun and in average during the year, the Earth rotates once in 24 hours. This is illustrated in Figs. 1 and 2. Looking from above the Earth, the rotation is counterclockwise. The Earth's rotational axis is tilted from the normal to the plane of the orbit. The nutation of the rotational axis, in

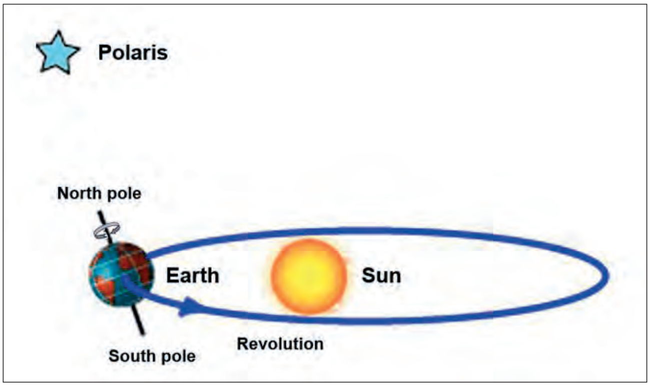

Figure 1. Illustration of the Earth's revolution around the Sun and of its rotation around the axis defined by the north and south poles. Currently, the rotational axis is very close to pointing toward Polaris.

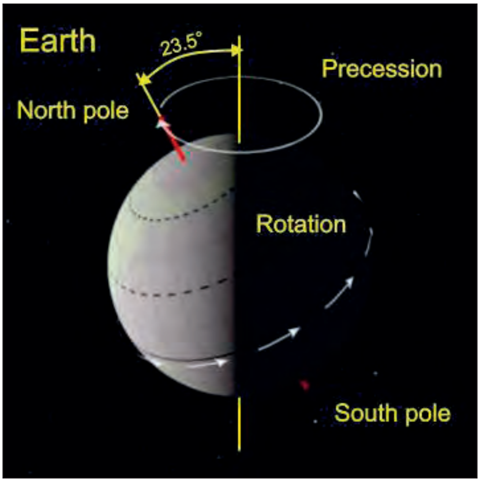

Figure 2. Illustration of the Earth's rotation around the axis defined by the north and south poles and of the precession of the rotational axis. Currently, the rotational axis is tilted from the normal to the plane of the orbit for 23.5°.

which its tilt angle changes, goes on between 22.1 and 24.5° with a cycle of about 41,000 years. Today, the tilt angle equals 23.5°. The precession of the rotational axis goes on in a way that the axis traces a circle on the celestial sphere determined by the positions of the stars Polaris and Vega. Looking from above the Earth, the precession is clockwise. The cycle of this motion is about 26,000 years. Today, the rotational axis is very close to pointing toward Polaris.

Thus, if the eccentricity of the Earth's orbit and the position of its rotational axis at a moment in the past or in the future are known, the Milanković theory enables one to determine the temperatures at that moment at various points on the Earth's surface. It should be noted that we live in an interglacial period that began about 12,000 years ago and belongs to the ice age that started about 2.6 million years ago. The previous glacial period started about 110,000 years ago. It has been anticipated that the next glacial period will not began in the forthcoming about 50,000 years [6].

The first proof of the Milanković theory was obtained in 1976, within a project in which the sediments at the bottom of the Indian Ocean were analyzed [7]. The research team of the project concluded that over the past 500,000 years, the climate on the Earth had changed depending on the position of its rotational axis. That happened 18 years after his death. Among other things, it was shown in 1999 that the variations in the isotopic composition of oxygen in the ocean bottom sediments follow the Milanković theory [8]. Today, it is accepted that the astronomical factors play the key role in the climate change on the Earth.

THEORY OF CRYSTAL RAINBOWS

Each of us has seen many times a rainbow in the sky, coming after the rain. This is a part of the meteorological rainbow effect, which occurs as a result of scattering of sunlight from the water droplets that remained in the air [9]. Which are the main characteristics of this effect? Usually, one observes a bright circular line at an observation angle of 42°, separating the bright and dark regions below and above it, respectively. This is the principal primary rainbow, which occurs as a result of one reflection of sunrays within the droplets. It is accompanied with several bright lines on its bright side, which appear as a result of interference of the sunrays generating the primary rainbow. These are the supernumerary primary rainbows. Sometimes, one can see another bright circular line, at an observation angle of 50°, separating the bright and dark regions above and below it, respectively. This is the principal secondary rainbow, which occurs as a result of two reflections of sunrays within the droplets. The circular shape of the rainbows is attributed to the spherical shape of the droplets. It should be noted that sunlight is polychromatic. This means that its different components, having different colors, refract for different angles at the droplet boundaries. As a result, instead of one principal rainbow and its supernumeraries, one sees a composition of violet, blue, green, yellow, orange and red principal rainbows and their supernumeraries. In other words, if sunlight were monochromatic, *e. g.*, if it had red color, one would see only a red principal rainbow and its red supernumeraries.

Rainbows also occur and play important roles in nucleus-nucleus collisions, in atom or ion collisions with atoms and molecules, in electron-molecule collisions, in atom, ion or electron scattering from crystal surfaces, and in ion or positron channeling in crystals or nanotubes.

Let us now concentrate on the last of the above mentioned cases, in which ions or positrons are transmitted through axial crystal channels or nanotubes. But what is a crystal? What is an axial channel? A crystal is a three-dimensional periodic arrangement of atoms. However, the crystal can also be viewed as a two-dimensional periodic arrangement of atomic strings, being parallel to each other. In this case, the part of the crystal in between the neighboring strings is called an axial channel. It was discovered in 1963 that an ion can long move through the channel, staying close to its axis [10]. This motion is called ion channeling.

The rainbow effect in ion channeling was predicted by us in 1983 during a longer stay in the Oak Ridge National Laboratory, Tennessee, USA [11, 12]. Soon after that, it was experimentally observed in the same laboratory [13, 14]. For us, who sincerely believed in the research desire and determination of Milutin Milanković, that event meant the finding of an uninhabited area in the field of condensed matter physics. We decided to try to inhabit it and acquire a humble scientific property. As a result, about 14 years after that, a group from the Vinča Institute of Nuclear Sciences, Belgrade, Serbia, led by us, formulated the theory of crystal rainbows [15, 16], which has proven to be the proper theory of ion channeling in crystals [17, 18]. The idea from which that mathematical theory emerged was to analyze in detail the mappings of the initial ion transverse position plane to the final transverse position plane or the transmission angle plane.

We have used the theory of crystal rainbows to explore in detail the classical and quantum mechanical propagations of ions and positrons along axial crystal channels and nanotubes. Among other things, we have shown that crystal rainbows can be used to extract from high-resolution experimental results very accurate information on the forces acting in the channels. The approach was morphological — we assumed that the crucial information on those forces was embedded in the shapes of crystal rainbows. Figure 3 gives the high-resolution experimental angular distributions of protons of energies of 2.0, 1.5, 1.0 and 0.7 MeV transmitted through a 55 nm thick (100) silicon crystal, obtained at the National University of Singapore, together with the associated rainbow patterns, generated using the theory of crystal rainbows [18]. The incident proton beam radius was about 0.5 mm. In

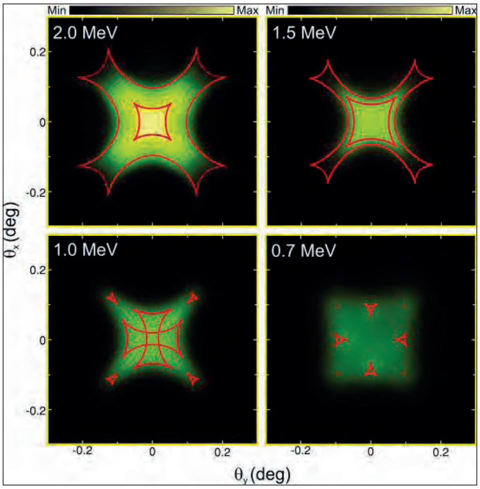

Figure 3. Experimental angular distributions of 2.0, 1.5, 1.0 and 0.7 MeV protons transmitted through a 55 nm thick (100) silicon crystal and the associated theoretical rainbow patterns (red lines).

order to perform the experiment, it had been necessary to develop the method of making ultrathin silicon crystals with negligible surface roughness, the method of preparing submicrometer proton beams, and the method of producing highly-sensitive scintillator screens. For an energy of 2.0 MeV, there are two rainbow lines, a cusped square and a line with four pairs of cusps, and the situation is similar for an energy of 1.5 MeV. For an energy of 1.0 MeV, there are two crossed cusped rectangles and four cusped isosceles triangles, while for an energy of 0.7 MeV, there are four cusped isosceles triangles and four points. The symmetry of all these patterns is explained by the square symmetry of the channel under consideration. In all these cases, the inner side of each rainbow line is the bright side of the rainbow while its outer side is the dark side of the rainbow. It is clear that the theoretical patterns fully determine the experimental distributions — they appear as the „skeletons" of the distributions. That agreement was reached after a careful adjustment of the parameters of the forces acting in the channels, the result being a precise extraction of these parameters from the experimental results.

We have also found that a proton beam entering an axial crystal channel can be focused to a radius of several picometers, *i. e.*, considerably below that of an atom [19–21]. The effect, designated as the superfocusing effect in ion channeling, occurs when a rainbow line, defining the beam, reduces to a point. Thus, if a foreign atom is inserted in the channel, one can use the superfocused beam to probe it. This is illustrated in Fig. 4. The scanning of the interior of the foreign atom is performed by changing the beam incident angle. This idea is the basis for possible development of a measurement technique with subatomic resolution — the rainbow subatomic microscopy. The technique could be used for more precise measurements of atomic and nuclear reactions than so far and, consequently, for deducing detailed new information on atomic and nuclear structures. However, its practical realization requires a lot of additional research and development. On the other hand, if the technique is successfully carried out, one will also obtain a well-developed method of preparation of picometer ion beams, to be employed in other fields.

And what are nanotubes? They can be described as the sheets of atoms rolled up into cylinders. They were discovered in 1991 [22]. Nanotubes have remarkable physical properties and have begun to play an important role in the field of nanotechnology. It was predicted that they could be used to channel positively charged particles [23]. Upon that, we have used the theory of crystal rainbows to show that

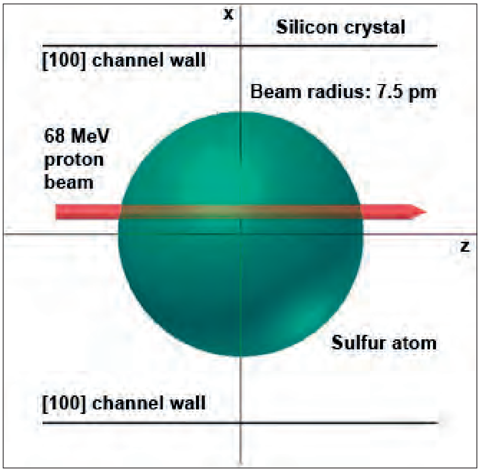

Figure 4. Illustration of the interaction of the 68 MeV superfocused proton beam with a sulfur atom inserted in a [100] crystal channel. The beam radius is 7.5 pm.

rainbows occur in ion channeling in nanotubes as well [24]. In one of our studies, it was shown that a carbon nanotube of a length of 7 mm could ensure the effective bending of the proton beam of an energy of 1 GeV for an angle of 0.25 mrad [25]. It must be emphasized that the bending power of such a nanotube coincides with that of a dipole magnet with the magnetic induction of 330 T. This means that it is about 40 times higher than the bending power of the superconducting dipole magnets within the most powerful accelerator in the world, the Large Hadron Collider, in the European Organization for Nuclear Research (CERN), Geneva, Switzerland. Thus, in principle, it is possible that very small and cheap passive elements composed of nanotubes substitute very big and expensive dipole magnets within accelerator facilities. However, experimental investigations of ion channeling in nanotubes are still in the initial phase, and one cannot anticipate if and when this exciting prediction will be realized in practice.

Let me also mention our investigations of quantum rainbows occurring in positron channeling in carbon nanotubes [26, 27]. As the rainbows occurring in scattering of sunlight from water droplets, a quantum rainbow is composed of the principal and supernumerary rainbows. We have disclosed and described a full quantum mechanical mechanism of generation of these rainbows, which comprises the effects of wave wrinkling, concentration and coordination.

CONCLUSIONS

It has been said here that new knowledge is essential for fostering innovation, technology and production, but also as a stable foundation of education and training as well as of other activities that should contribute to sustained growth and inclusive development of a country. However, it is more than a set of results of basic research. It also includes developed cognitive capabilities of the involved teams of scientists. We have concluded that the government of a country can make an appropriate strategy of basic research and the corresponding long-term investment plan only on the basis of proposals made by the scientific community of the country. This means that the primary social responsibility for maintaining, actualizing and enhancing basic research lies with the scientific community — individually and collectively.

We have demonstrated the essence of basic research with the brief descriptions of the astronomical theory of climate change and the theory of crystal rainbows.

The former theory is valid on the planetary level — it provides a description of the long-term climate change in time on each planet of the solar system. The latter theory is applicable on the atomic level — it enables one to explain the rainbow effects appearing in propagation of charged particles along crystal channels and nanotubes. The former theory has had a paramount importance for development of astronomy and physics. The authors of the latter theory were among those inspired by it. The two theories have been chosen to be presented here since they have one thing in common — they represent the exclusive scientific properties of their authors acquired on the previously uninhabited areas.

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