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History of Ultralow Temperatures at Dubna (JINR)

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Abstract

A frozen spin polarized targets cooled by the $^3He/^4He$ dilution refrigerator developed at the JINR, Dubna is described. Experience with continuously-polarized targets (dynamic mode) and achieving of very low temperatures in 1966 (JINR) gave rise to the idea of using radically new technique based on dissolving ^3He in ^4He to the frozen spin polarized target. The short history (1966-2023) of the development of such proton and deuteron targets at JINR for different accelerators (Dubna, Protvino, Gatchina, Prague, Mainz and Bonn) is given.

Keywords

Polarized Targets, Ultralow Temperatures, $^3He/^4He$ Dilution Refrigerator

"*…They got together, wave and stone,*
verse and prose, ice and flame,
were not so different from one another."
A. S. Pushkin—(translated by Vladimir Nabokov)

1. Introduction

Actually, the history of the Sector of Low Temperatures (SLT) dates back to the time when JINR's first polarized target of the dynamic type was developed and built by the specialists of two JINR laboratories, the Laboratory of Nuclear Problems (LNP) and the Laboratory of Neutron Physics (LNPh). In polarized targets of this type, dynamic polarization of target nuclei has to be a continuous process to support the achieved level of polarization, since polarization relaxation processes at temperatures of about 1 K are quite intensive, making it impossible to carry out physical measurements without continuously pumping (maintaining) polarization. That was a real innovation, like much other of the work done at that time!

It involved overcoming cryogenic and vacuum problems, finding appropriate microwave sources, and developing instruments for measuring nuclear polarization of the target and other necessary equipment for this kind of setup. The corresponding publication (Luschikov et al., 1966) ushered in the development boost of cryogenic technology as a response to the demands of rapidly developing spin physics. The first polarized target of this type was created in 1962 by French scientists headed by Anatole Abragam (Abragam et al., 1962), who did not become a Noble Laureate through pure chance (to my mind). A. Abragam (born to a family of Baltic Jews), whose life was not a bed of roses, visited JINR in the early 1970s (probably, wishing to see the dynamic polarized target operating at the LNP synchrocyclotron). In the experimental hall, one of the coauthors of our target began telling A. Abragam about the setup. After a short time, A Abragam interrupted him and asked in very good Russian, what was the language he spoke. Indeed, lacking practice, our specialists had a poor command of foreign languages, but this did not hinder them from working skillfully and successfully. Later, it was Abragam's laboratory where one of the coauthors (V. I. Lushchikov) was invited to work as a visiting scientist for one year.

2. First Attempts

In about 1964, two Moscow State University students, N. S. Borisov and M. Yu. Liburg, joined Neganov's group and were given an opportunity to put into practice a "fresh" idea of producing ultralow temperatures by a new method which was published in 1962 (London et al., 1962). This publication was brought just in time by Czechoslovakian physicist S. Safrata, who worked in the journal Cryogenics for a long time and had access to information like that clearly, there were many who knew about it, and two more attempts to implement the idea were made in different places at approximately the same time. The schematic diagram of the refrigerator $^3He/^4He$ is given below (**Figure 1**).

The results showed that Neganov's group (**Figure 2**, **Figure 3**) was best. Even at their earliest steps the record temperature of 50 mK was achieved (Neganov et al., 1966)!

The cooling power of the dilution refrigerator is defined by

$$\dot{Q} = 82\dot{n}_3\left(T_M^2 - T_{M\,\min}^2\right), \quad (1)$$

where $\dot{Q}$ is the cooling power (in Watts) at the mixing chamber, $\dot{n}_3$ is the ^3He molar circulation rate, T_M is the mixing-chamber temperature and $T_{M\min}$ is the minimal temperature in the mixing chamber at $\dot{Q} = 0$.

It was also lucky for the coauthors that the International Conference on Low-Temperature Physics chaired by Pyotr Layonidovich Kapitsa was held in Moscow in 1966, and B. S. Neganov had a good opportunity to talk to an international expert audience about the new method for production of ultralow temperatures. The legend is that after the talk which became a real scientific sensation, Pyotr said that the Scientific Council of the Institute of Physical Problems would consider it an honor to approve the defense of the doctoral dissertation by B. S. Neganov. It took some time to improve the method, and in 1968 the then lowest temperature of 5.5 mK was obtained by this group at LNP. This result entered physics handbooks all over the world.

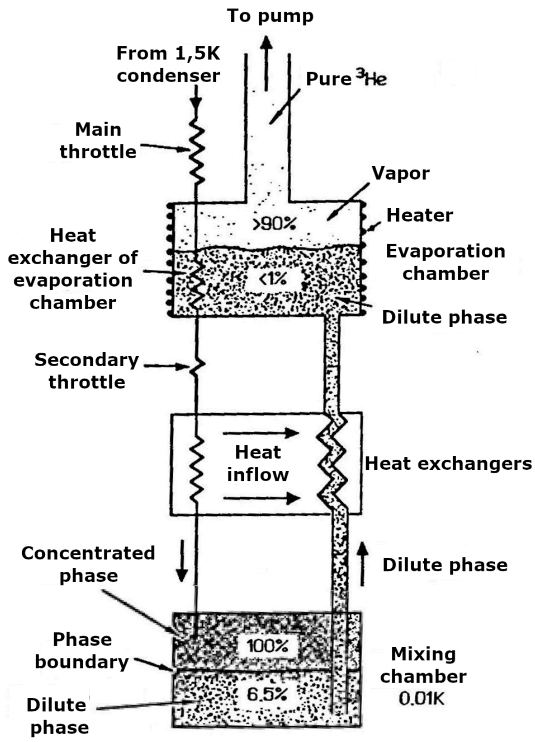

Figure 1. Typical diagram of the $^3He/^4He$ refrigerator.

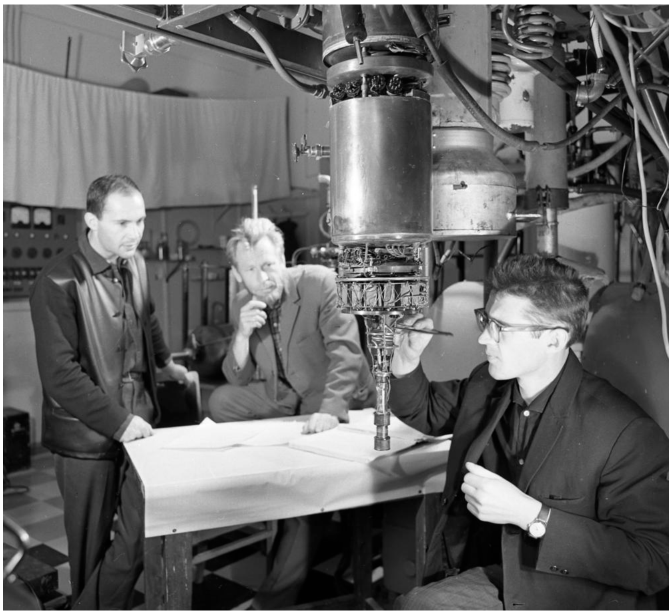

Figure 2. M. Yu. Liburg, B. S. Neganov, and N. S. Borisov by the first setup for producing ultralow temperatures, 1966.

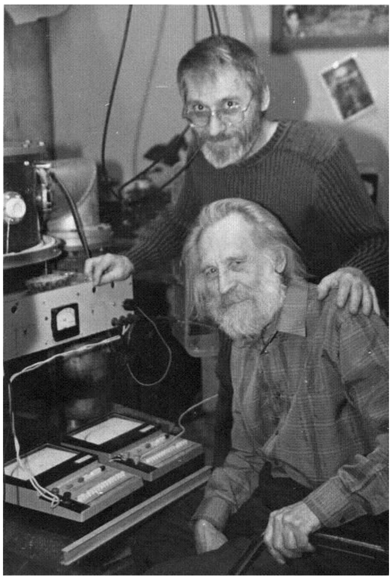

Figure 3. Family of scientists, B. S. Neganov and A. B. Neganov.

Later, ultralow temperatures will be indissolubly linked to such a field of experimental physics as investigations of polarized phenomena. Polarization investigations are concerned with studying dependence of interactions on spins of participating particles. The notion of spin was introduced into scientific discourse almost 100 years ago to describe atomic spectra, but its nature is still obscure.

When appeared, experimental polarization data stimulated theoretical comprehension of spin effects and served as a testing ground for verifying theoretical models. Characteristic in this sense are statements of the known theorists — "Experiments with spin have killed more theories than any other single parameter" by Englishman Elliot Leader (Leader, 2001) and "Polarization data has often been the graveyard of fashionable theories. If theorists had their way, they might well ban such measurements altogether out of self-protection" by American James Bjorken.

In 1973, the LNP Directorate took a decision to develop a polarized target of a new type. This means a target of the "frozen" type, which uses to the full the effect of cooling the target material to ultralow temperatures of 20 - 30 mK. That it was possible in principle was earlier asserted by B. S. Neganov at the International Conference on Electromagnetic Interactions at Low and Intermediate Energies, Dubna (Neganov, 1967).

The principle of operation of a frozen spin target is based on long nuclear spin relaxation time at low temperatures (≈50 mK) and moderate magnetic fields (≥0.3 T). After the polarization build-up with the Dynamic Nuclear Polarization process, the microwave power is turned off and the polarization is "frozen in". Then a magnetic field is lowered till about 0.3 T, so the spin relaxation time can be many days at about 50 mK. The polarization relaxation time depends on temperature in inverse proportion.

The only thing to do was to adapt the achievements in production of ultralow temperatures to the purposes of developing the experimental equipment, that is, polarized targets of the frozen type that would take full advantage of the opening possibilities. In 1975, the first (world's first, as turned out later) frozen polarized target was used at the LNP synchrocyclotron (**Figure 4**) in the experiment on the investigation of polarization effects in pp interactions at 500 to 630 MeV. That was the first use of the new method for producing ultralow temperatures in experimental physics.

In 1977, an ultralow-temperature setup for studying short-lived nuclei was developed at the SLT with the decisive participation of V. N. Pavlov. It allowed the LNP Radiochemical Laboratory (RCL) to implement its vast research program. Surprisingly soon, in 1978, the second polarized target of the frozen type (**Figure 5**), was made specially for the research at the Institute of High-Energy Physics (IHEP) in Protvino.

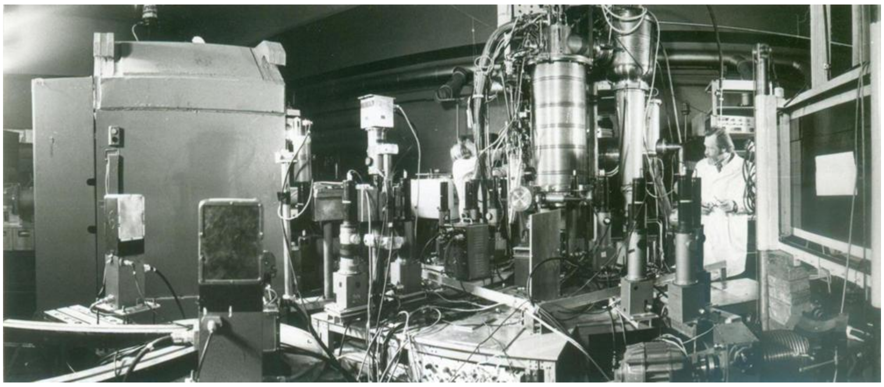

Figure 4. First frozen polarized target in the LNP synchrocyclotron beamline. B. S. Neganov, 1975.

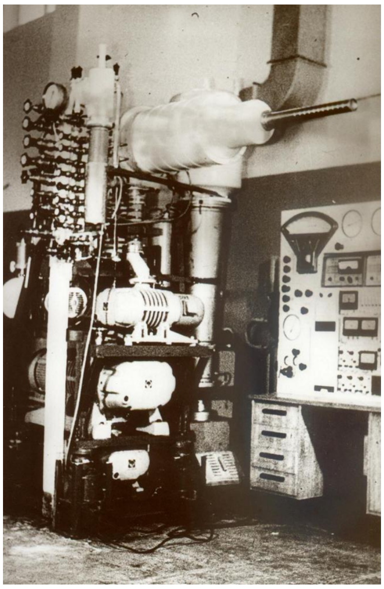

Figure 5. Full view of the second polarized target before delivery to IHEP, August 1978.

In those years, several large experiments (PROZA, HYPERON, RISK) were simultaneously carried out at our Department of Hadron Physics (DHP). Also, each year, our scientists participated in experiments at the U-70 accelerator, which usually took two to three months. By that time, the physics program with beams and the first frozen polarized target had been finished, and the setup was moved to the Sector building.

Soon physicists of the Leningrad Institute of Nuclear Physics (LINP) (including V. G. Vovchenko) and the head of our Department Yu. M. Kazarinov proposed a polarization research program to be carried out at LINP, which required delivering the polarized target to Gatchina. This dramatic transport of such a delicate experimental setup as the polarized target was the first in our experience, and extraordinary safety measures were taken. They justified themselves, and two or three months later experiments were started at the LINP accelerator. And considering that in mid-August 1978 experiments with the new polarized target began at IHEP, it becomes clear how tough the schedule of the Sector staff was at that time.

The staff members of the Sector were constantly busy participating in polarized target runs both in Protvino and in Gatchina. Over time, they established their own group for polarized target studies in Gatchina, and our participation in that work almost stopped. At IHEP, nothing of the kind has happened, and our participation has been going on with a few interruptions up to now.

Moreover, this long work has resulted in a renewed SPASCHARM project (SPin ASymmetries in CHARMonium production) (Abramov et al., 2023). The project is aimed at investigating the nucleon spin structure and the spin dependence of the strong interaction between antimatter and matter at energies of up to 50 GeV.

It is intended to produce polarized proton and antiproton beams, which will allow spin-related challenges to be solved at the SPASCHARM facility. Apart from polarized beams, it is planned to create a polarized solid target with frozen nucleon spins for this project. Also, it is supposed that the JINR team (Sector of Low Temperatures) with its unique experience (Usov, 2015) and achievements in this field (similar operating facilities in Gatchina, Protvino, Prague, and Mainz) will play a leading part in these activities.

Undoubtedly, it is necessary that IHEP specialists and Germain colleagues (from Universities of Mainz and Bonn) take an active part in the SPASCHARM project. The use of the already manufactured units and general technologies for the main detectors will contribute to higher fruitfulness and efficiency of this cooperation.

Now a special team of theoretical physicists is being established for theoretical support of the SPASCHARM experiment. This is important for searching for spin effects in certain kinematic regions where theoretical models developed by this team will predict their existence. Thus, the experiments will not be carried out blindly.

The future polarized-beam facility has no analogues in the world. The expected period of its being unique is at least 15 years. If implemented, this research will allow the participants to have a world lead in spin physics.

The real international collaboration began for us with the proposal of Czechoslovakian scientists and physicists from Yu. M. Kazarinov's sector to develop a frozen polarized target (**Figure 6**) especially for experiments at low energies of —15 MeV. That was the energy of the polarized neutron beam from the Van de Graaff (VdG) accelerator at Charles University in Prague.

We could never imagine how many problems would arise from our decision to take part in the project. With our experience of creating the experimental facilities operating in Gatchina and Protvino, serious problems in implementation of our plans in Prague were hardly expectable.

First, we had to come to Prague with a "half-made" facility and complete the work on it under quite different conditions using quite different resources. All this seriously hampered our further work, which resulted in that the polarized target was put into operation at the VdG accelerator only in 1994 (Borisov et al., 1994).

Among the difficulties we encountered in Prague was a radical change in the political system (in 1989) and, accordingly, in the attitude to us as representatives of the USSR, the country that suddenly turned to be to blame for everything. But our relations with the nearest colleagues remained, and still are, very good, which allowed us to jointly establish a precedent of organizing the only beam experiment in a JINR Member State (see **Figure 7**).

Paradoxically, JINR scientists participate in accelerator experiments all over the world but not in JINR Member States. These "precedents" serve the purpose of one of the main clauses of the JINR Charter—development of the relevant fields of physics in Member States. To carry on with the adopted experimental polarization program, the work on increasing neutron beam polarization (proposal of SLT researcher Yu. A. Plis) is underway at the VdG accelerator in Prague, and preliminary encouraging results have already been obtained.

Here it is worthwhile to mention another serious work done by the SLT researchers in 1994-1996. In December 1993, a message came from INTAS to notify about a financial support (60,000 ECU) of our project "Upgrading of the movable polarized target (MPT)". Participants in the project were specialists from France, Ukraine, and Russia (INR, PINP, JINR LHE) with the leading role of the LNP SLT researchers (**Figure 8**).

The work was divided into two stages. The first stage started in 1994 with assembling and full commissioning of the MPT under the laboratory conditions at the LNP site (**Figure 9**). This stage was successfully completed on 14 December 1994, that is, just a day before the deadline. The activities were detailed in publication (Lehar & de Lesquen, 1995).

In 1995, the Plenipotentiary of the Russian Federation at JINR B. G. Saltykov and the JINR Directorate visited the constructed facility and expressed support for the reported activities and JINR as a whole.

The second stage was associated with the second grant received from INTAS in 1995 for polarization investigations with the MPT using the neutron beam of the Synchrophasotron at the Laboratory of High Energies, JINR. The investigations were also successfully performed, of which a documentary was made and later shown by the French TV channel TF5.

It is worth noting that those investigations were carried out in the hard after-reform time and that it was the first time that JINR received a grant like this (Bazhanov et al., 1996).

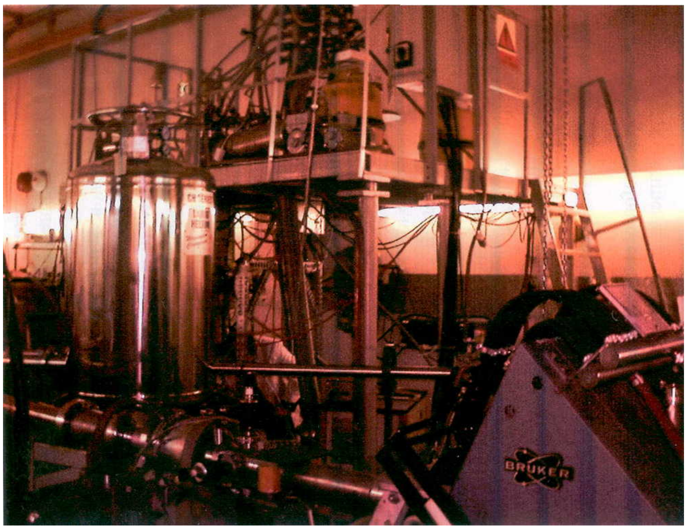

Figure 6. General view of the experimental in the beam line of the VdG accelerator at Charles University in Prague.

Figure 7. Discussing the plan of joint activities at the VdG accelerator of Charles University in Prague, 1994. Left to right l. Wilhelm, rector of Charles University in Prague; Yu. A. Usov, LNP researcher, V. P. Dzhelepov, Honorary Director of LNP; N. A. Rusakovich, Director of LNP; R. Mach, Plenipotentiary of the Czech Republic; M. Finger, Head of Department of LNP.

Figure 8. Left to right: Gilles Durand (Saclay, France), Yu. A. Usov (LNP, JINR), B. G. Saltykov (Vice-Premier, Minister of Science and Education, Plenipotentiary of RF at JINR), and A. M. Baldin (Academician, Director of LHE, JINR), 1995, LHE, JINR.

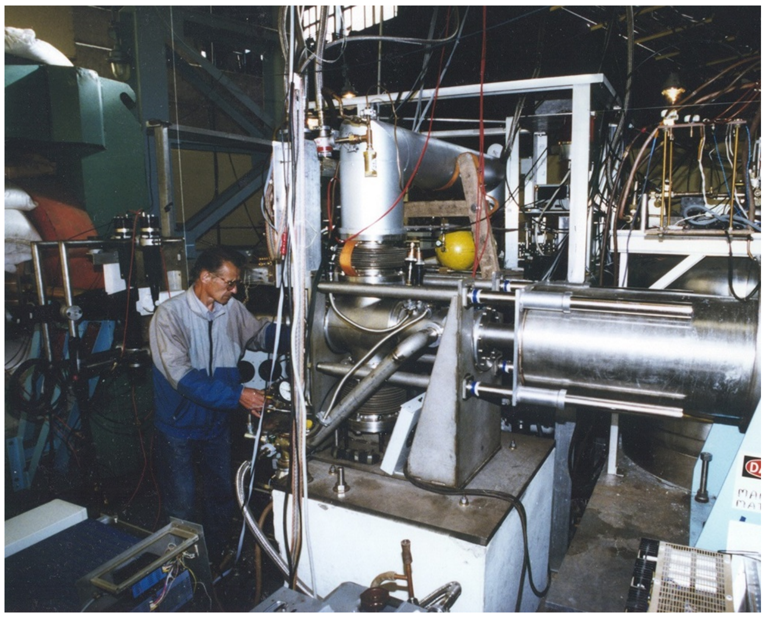

Figure 9. Movable polarized target, N. S. Borisov, 1995 LHE, JINR.

3. International Cooperation

In 1999-2001, the researchers of the Sector also took an active part in the development of the ATLAS liquid-argon calorimeter at CERN. At that period a necessity arose to calibrate platinum thermistors for precision temperature measurement of facility elements immersed in liquid argon. Scientists from JINR (LNP and LHE) prepared and signed a contract with CERN on precision calibration of 1800 platinum thermistors, which was done in compliance with the relevant plans. Most of these calibrated thermistors were mounted by the JINR specialists directly on the ATLAS detectors.

A particular story is collaboration with the University of Mainz and the University of Bonn. It began as far back as 2003, when the LNP SLT scientists got occupied with development and construction of a polarized target cryostat under the agreement with the University of Mainz. Since the cryostat was a key element dictating the main parameters of these experimental facilities, development and construction of the cryostat was a serious methodological problem that the SLT specialists successfully solved by the end of 2007. Later, at various international specialized conferences, such as PSTP (Polarized Sources, Targets and Polarimetry), experts acknowledged it to be the world's best polarized target (Thomas et al., 2013)!

A specific feature of the physics research performed with this polarized target in Mainz was the use of ideas earlier put forward by S. B. Gerasimov from the Laboratory of Theoretical Physics (LTP), JINR. This polarized target on the MAMI C accelerator of the University of Mainz (**Figure 10**, **Figure 11**) was successfully employed by a large international collaboration A2 until 2015.

At approximately the same time, the question came up before the University of Bonn as to the shutdown of its ELSA accelerator, since polarization investigations, dominant for that machine, had not been carried out there for more than ten years. It turned out that for some reasons they could not develop a new cryostat for the experimental facility over a long time (some 15 years). In view of this, the SLT specialists proposed to not simply transfer the polarized target from Mainz to Bonn for implementing the experimental program delayed for many years, as was initially intended, but to make a new cryostat in Dubna for the University of Bonn.

It took about four years of determined effort by specialists not only from LNP but also from other departments of JINR to manufacture a ^{3}He/^{4}He dilution refrigerator for the new polarized target to be used in joint experiments at the accelerator of the University of Bonn.

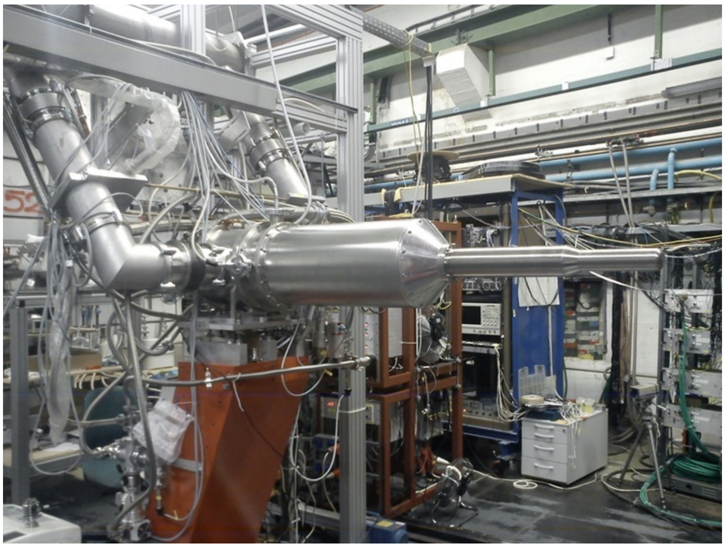

Figure 10. General view of the polarized target in the accelerator beamline (MAMI C, Mainz).

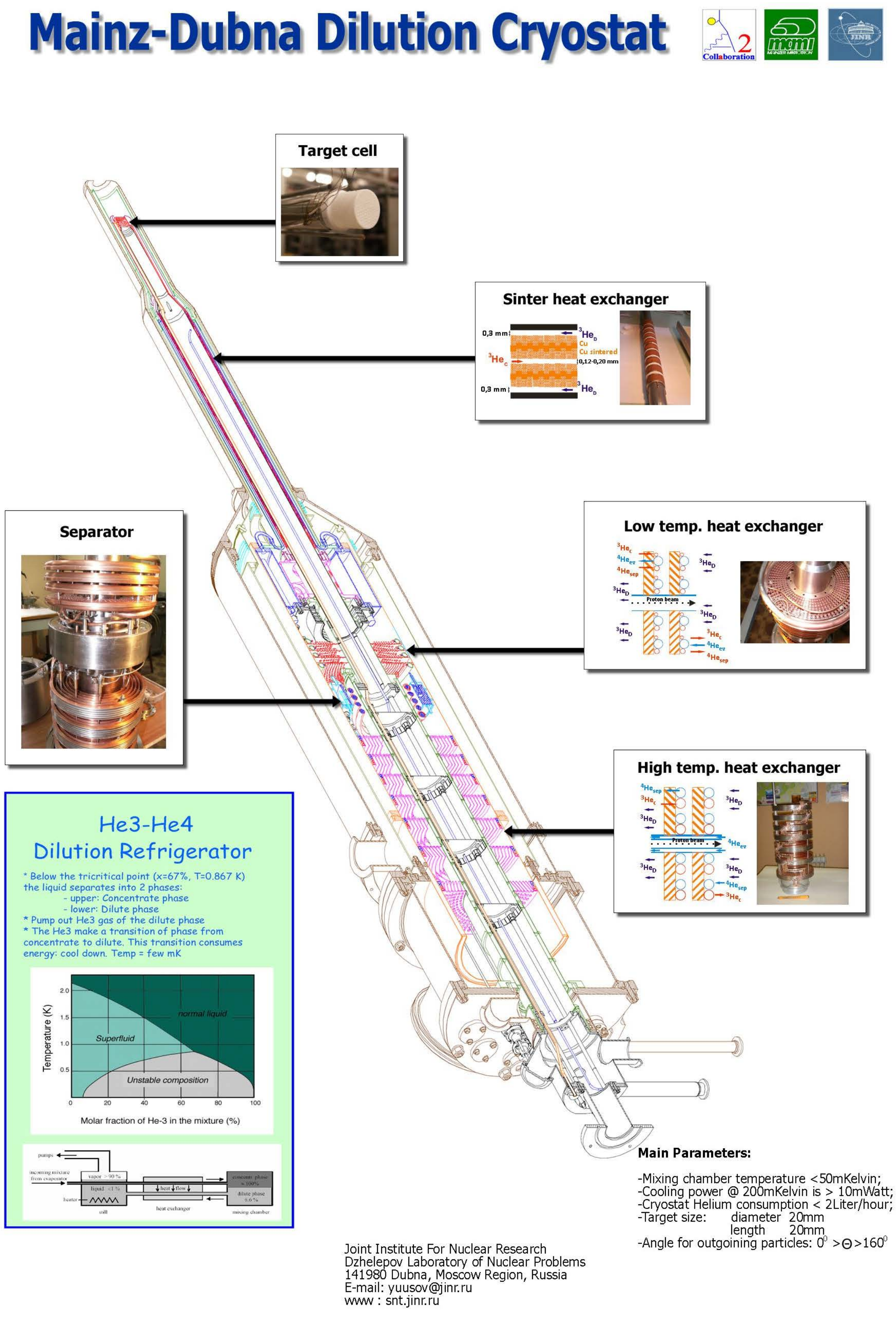

Figure 11. Main units and parameters of the polarized target cryostat in Mainz.

The cost of a cryostat for a frozen polarized target is usually more than 300 thousand euros.

The upgraded Crystal Barrel facility on the ELSA accelerator at the University of Bonn allows measuring double polarization observables for reactions of neutral meson photoproduction. It is these measurements that are crucial for searching for "missing" resonances in investigations of meson and hyperon production on protons. In June-July 2021, SLT specialists carried out final tests of the new cryostat in Bonn together with the last beam run at ELSA (Figure 12, Figure 13).

Figure 12. Cryostat for Bonn is almost completed. A. B. Lazarev.

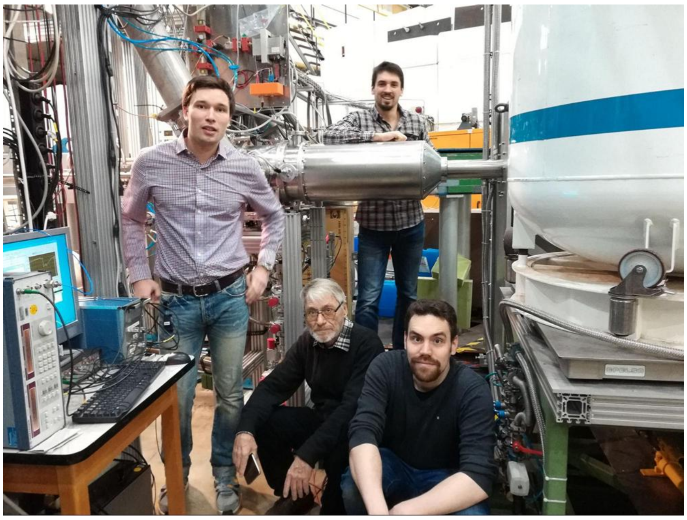

Figure 13. Launching the facility at ELSA: A. S. Dolzhikov, A. B. Neganov, l. S. Gorodnov, and S. Runkel (Bonn).

Now about the main and new among our scientific activities: the SLT researchers currently participate in development of the precision Möller polarimeter for MESA, the new superconducting accelerator of polarized electrons at the University of Mainz. There will have to face highly sophisticated problems of precision measurement of the electron beam polarization. The main part of this polarimeter is a powerful $^3He/^4He$ dilution refrigerator, and this is just the area of the SLT's unique experience and best methodological practices. A team of experts from the Laboratory of High-Energy Physics (former Laboratory of High Energies) led by V. V. Fimushkin is also engaged in the development of the polarimeter for MESA.

Activities of JINR, LNP team are presented in **Table 1** and at **Figure 14**.

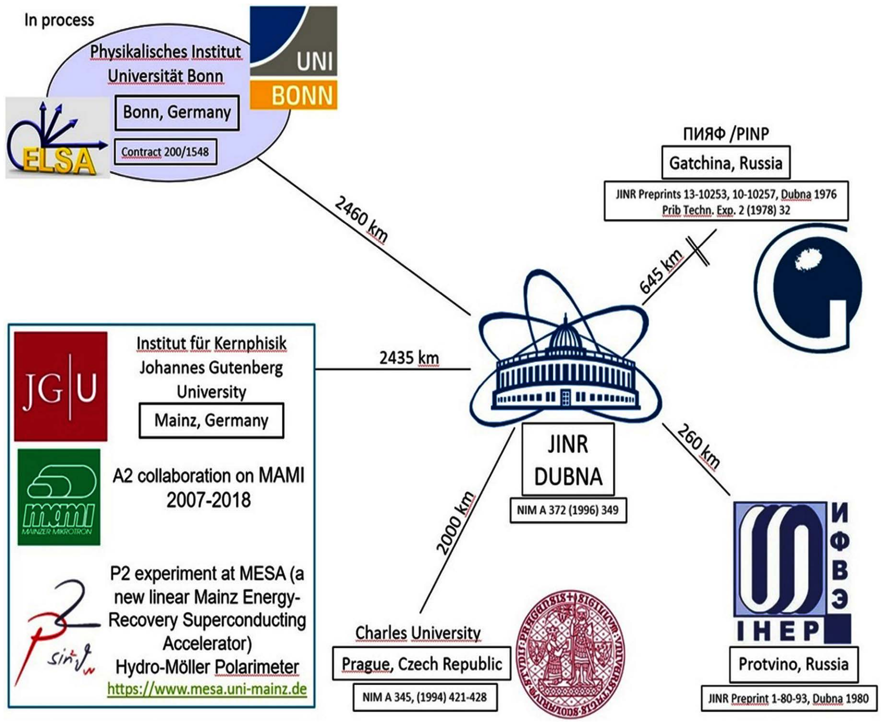

Figure 14. The main activities of the Sector to create polarized targets.

Table 1. The parameters of polarized targets developed in Dubna.

Year of first publ.	Volume cm³	Material	Magnetic field, T dynamic/frozen mode	Accelerator (place)	Maximum polarization, %	T_{min}, mK
1976	15	$C_3H_6(OH)_2$ 1,2-propanediol with Cr(V)	2.69/2.69	Dubna, Gatchina (in use)	$P_{\pm} = 98 \pm 2$	36
1980	60	$C_3H_6(OH)_2$ 1,2-propanediol with Cr(V)	2.06/0.45	Protvino (in use)	$P_{\pm} = 87 \pm 3$	20
1985	60	$(CD_2OD)_2$ deuterated ethanediol with Cr(V)	2.06/0.45	Protvino (in use)	$P_{\pm} = 37 \pm 3$	
1994	20	$C_3H_6(OH)_2$ 1,2-propanediol with Cr(V)	2.7/0.37	Prague (in use)	$P_+ = 93 \pm 3$ $P_- = 98 \pm 2$	20
1995	140	$C_3H_6(OH)_2$ 1,2-propanediol with Cr(V)	2.7/2.7	Dubna (in use)	$P_+ = 84 \pm 3$ $P_- = 91 \pm 3$	50
2013	10	H/D butanol	2.5/0.5	Mainz (in use)	$P_{H/D} = 85/75$	25

4. Conclusion

In order to carry out polarization studies it is necessary to create beams of polarized particles and/ or to use the technique of polarized targets. In recent years, there has been noticeable progress in the experimental study of spin effects. However, today there is **no theory** claiming a complete description of all the observed polarization effects. New experimental results are important for the development of a theory for describing all the spin effects.

In conclusion, it should be said that at present in experimental physics, ultra-low temperatures are used not only in the creation of traditional polarized targets of the "frozen" type, but also in new areas of experimental research: as Project "PTOLEMY"—detection of the relic neutrino; measurement of the magnetic moment of neutrino and coherent scattering on ^{4}He atoms; detection of the dark matter particles on the liquid ^{4}He at mK temperatures. Currently, our group is considering the possibility of participating in such experiments.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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