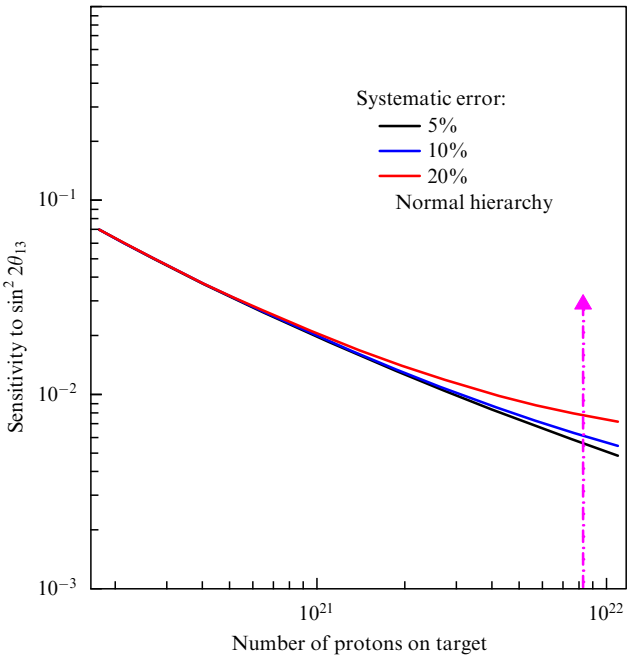

Figure 6. Dependence of the sensitivity to θ_{13} (90% CL) on the number of protons on the target. The three curves correspond to possible systematic errors of 5%, 10%, and 20%. The dashed arrow indicates the anticipated experimental sensitivity ($\sin^2 2\theta_{13} = 0.006$ at 90% CL) for 8.5×10^{21} POT.

background events rather than the result of neutrino oscillations is equal to 0.7%. Therefore, with a probability of 99.3% this result may be interpreted as an indication of $\nu_\mu \to \nu_e$ oscillations. The central value for $\sin^2 2\theta_{13}$ amounts to 0.11 for normal neutrino mass hierarchy, and to 0.14 for inverse hierarchy at $\delta = 0$.

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Isotope production at the Institute for Nuclear Research, Russian Academy of Sciences: current status and prospects

B L Zhuikov

1. Possibilities of producing radionuclides in intermediate-energy accelerators

It is likely that the idea of producing radionuclides for science and applications appeared when the Institute for Nuclear Research, USSR Academy of Sciences was founded in 1970 and it was decided to construct a linear accelerator of intermediate-energy protons — a meson factory. Beginning from the late 1980s, extensive research and development were performed aimed, first of all, at the construction of a facility for acceleration of heavy ions of radionuclides in a cyclotron specially built for this purpose [1]. It was assumed to produce radionuclides in the proton beam of a linear accelerator and to extract them expressively from irradiated targets. This project was aimed at fundamental studies in the field of nuclear physics. Simultaneously, it was planned to carry out the production of isotopes for medical and technical purposes. A similar program was accepted and is now being realized, for example, at the Legnaro National Laboratories (INFN-LNL) in Italy.

Because of a drastic reduction in financing, the program on heavy ions was not realized, and now the main focus is the

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Table 1. Main operating intermediate-energy proton beam facilities for producing radionuclides.

Institution	Location	Proton energy used for producing radionuclides, MeV	Beam current used for producing radionuclides, μA
Institute for Nuclear Research, RAS	Troitsk, Moscow region, Russia	160	120
Los Alamos National Laboratory	New Mexico, USA	100	200
Brookhaven National Laboratory	Upton, New York, USA	200	90
TRIUMF: Canada' National Laboratory for Particle and Nuclear Physics	Vancouver, Canada	110	50
iThemba Laboratory for Accelerator Based Sciences	Faure, Republic of South Africa	66	150
ARRONAX (Accelerator for Research in Radiochemistry and Oncology at Nantes Atlantic) *	Nantes, France	70	2 × 375

* Being launched.

Table 2. Radionuclides produced at INR, RAS and the possibilities of producing them during one irradiation run at a current of 120 μA.

Radionuclide	Half-life period	Target	Energy range, MeV	Exposure time, h	Produced activity, Ci
Sr-82 *	25.5 d	Rb	40—100	250	5
Na-22 **	2.6 y	Mg, Al	35—150	250	2
Cd-109 **	453 d	In	80—150	250	2
Pd-103 **	15 d	Ag	50—150	250	50
Ge-68 **	288 d	Ga, GaNi	15—50	250	1
Sn-117m **	14 d	Sb, TiSb	40—150	250	3
Se-72 ***	8.5 d	GaAs	45—60	250	3
Cu-67 ***	62 h	Zn-68	70—150	100	10
Cu-64 ***	12.7 h	Zn	40—150	15	15
Ac-225 ***	10 d	Th	40—150	250	4
Ra-223 ***	11.4 d	Th	40—150	250	13

* Regularly produced.
** Technology is developed, test samples are delivered to a customer.
*** Production methods are developed, and technology is being developed.

production of radionuclides, predominantly for medicine. In 1991–1992, based on investigations and developments with minimal expenditures, a facility for the production of radionuclides in a diverted 160-MeV proton beam in a linear accelerator was built [2, 3], which became the word's highest facility for producing isotopes at that time. This facility, upgraded several times, continues to be one of the world's largest and is so far the only one operating in Europe and Asia. Today only a few such facilities exist in the world (Table 1).

We formulated the program of radioisotope studies based on principles which are quite obvious in the field of fundamental science, but have rarely been realized in Russia in applied studies to date:

— the development of only those areas in which we have an indisputable advantage over all other analogous developments in the world;

— the maximal optimization and permanent improvement of parameters to achieve the best efficiency;

— the combination of the results of our own scientific studies with technological developments, with the aim of their broad implication;

— the close scientific collaboration, as well as production and technical cooperation with leading world centers.

The specific feature of the linear accelerator at the Institute for Nuclear Research (INR), RAS is that it would simultaneously provide comparatively high-energy (160–600 MeV) protons and a high-intensity (100–500 μA) beam in the future. In principle, it can be used for producing not only various neutron-deficient isotopes but also neutron-excess isotopes. However, the production of only a few of these isotopes is expedient in such an expensive facility to be competitive with other methods and taking into account the volume of the potential market. Table 2 lists radionuclides which we produce or produced in the accelerator at INR, RAS. The facility provides radionuclides not only for medical and technical applications, but also for important fundamental studies, such as the investigation of high-spin isomers and the search for the neutrino mass [4–7].

The development of facilities for producing radionuclides was successful due to a close collaboration with colleagues from Canada's National Laboratory TRIUMF in Vancouver, and American specialists at the Los Alamos National Laboratory (LANL) and Brookhaven National Laboratory (BNL). Our foreign colleagues took part in the formation of the isotope program. The USA made a considerable investment for the development of medical isotope production in Russia within the framework of the program for Global Initiatives for Proliferation Prevention (GIPP). On the other hand, when a crisis in the production of strontium-82 for medicine occurred in the late 1990s due to the termination of operation of the isotope facility with an 800-MeV proton beam in Los Alamos, and the danger appeared that the continuous production of this very important radionuclide would cease, it was INR that played a decisive role in the solution to this critical problem [8–10]. The Institute supplied

targets irradiated at our accelerator for processing in the USA using Russian technology. In addition, we took part in the development of a new efficient facility on a diverted 100-MeV proton beam at the accelerator in Los Alamos laboratory [11]. Today, we are involved in a number of joint investigations, which are difficult or even impossible to perform without the participation of INR. The construction of the facility at Los Alamos in six to seven years was financed by the US government. According to estimates, about 150 thousand patients have already been diagnosed using isotopes prepared only in the accelerator at INR, RAS and recovered in the USA. It should be noted that the isotope produced in Los Alamos is supplied noncommercially to Russia for pre-clinical and clinical trials. In addition, American partners support the development of the independent production of selected radionuclides and radiopharmaceutical compounds in Russia. This collaboration, which is broadly discussed in the domestic press, is presented at a Nuclear Museum in Los Alamos as an example of fruitful international peaceful cooperation.

It is important that the unique accelerator at INR, which cannot be fully engaged in other domestic problems, is regularly in operation due to this work.

The methods elaborated in collaboration with Russian scientists are also used in Canada. At present, INR is involved in the development of a new powerful ARRONAX facility in Nantes (France) for the production of medical radionuclides. The construction of this facility is financed from several governmental sources.

2. High-intensity 160-MeV proton beam target facility

An accelerator beam facility at INR, RAS was constructed specially for the production of radionuclides with maximum efficiency [2, 3]. Some new, original developments were utilized in its construction. The facility control and safety systems are reliable and correspond to the highest world standards.

The laboratory spans five rooms in the beam zone and a control room located in an adjacent building. A proton beam with an energy of up to 160 MeV is directed to a separate underground room through an ion guide equipped with systems for beam and vacuum diagnostics. Targets are mounted in ultrastrong graphite slots at the edge of a horizontal rod (Fig. 1), which is inserted into a shielding cast iron cube about 180 t in weight. The targets are intensely cooled with water circulating in a closed loop. The construction of the beam entrance window between the accelerator vacuum and cooling water (metal lithium between two stainless steel sheets) allows using the window for many years and replacing it if necessary. A system of cooled graphite collimators with thermocouples provides an accurate control of the size and position of a high-intensity proton beam directly on a target.

The accelerator facility allows irradiating simultaneously several targets of different designs at different proton energies. The technical features of the INR linac allow the extraction of a 158-MeV proton beam, as well as beams of proton energies 143, 127, 113, 100, and 94 MeV, thereby minimizing the energy scattering of the beam. Already at present the shielding and the target cooling system permit the irradiation of targets with 120–140-μA beams.

The exploitation of the facility over the entire operation period has demonstrated that it is convenient to service, all its

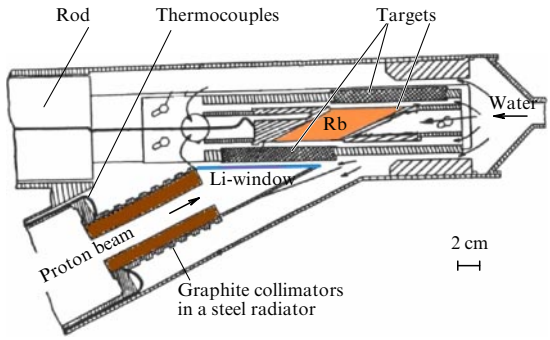

Figure 1. Target device in the proton beam of the INR, RAS accelerator.

systems operate reliably, and it can be used for fundamental studies and regular production of many important radionuclides for various applications.

3. Isotopes produced and production methods

3.1 Strontium-82

Among those isotopes for medical applications which can be produced using an intermediate-energy proton beam, strontium-82 (with the half-life period $T_{1/2} = 25.5$ days), obviously occupies the first place. This radionuclide is the most important product of all similar facilities (see Table 1). It is used in rubidium-82 medical generators applied in cardiologic diagnostics by means of positron-emission tomography (PET) (see section 3.2). At present, ^{82}Sr isotope is mainly produced in nuclear reactions Rb(p, 4n) and Rb(p, 6n) in the proton energy range from 40 to 100 MeV utilizing targets made of metallic rubidium or rubidium chloride. This radionuclide cannot be produced at small low-energy proton accelerators or in a nuclear reactor.

We use metal rubidium targets which are the most efficient for ^{82}Sr production. The targets irradiated at the INR accelerator are delivered to the LANL, where they are processed using radiochemical technology with rubidium dissolution. The extracted pure ^{82}Sr isotope is utilized in rubidium-82 generators mainly in clinics in the USA (Fig. 2).

Later on, we elaborated a new method for strontium extraction without rubidium dissolution, proceeding from ^{82}Sr sorption on different surfaces directly from melted rubidium [12]. The extraction of radionuclides from liquid metals is a complex and poorly studied physicochemical process involving the production of colloid particles in melted metal and chemical reactions on the surface. Our investigations have demonstrated the efficiency of this approach and the possibility of its application for extracting different radionuclides from the melts of other metals, for example, silver and lead. This makes the method promising for other applications, in particular, the recovery of valuable radionuclides from a lead–bismuth coolant upon transmutation of radioactive wastes.

Based on the investigations performed, a technology was developed for extracting ^{82}Sr nuclides from irradiated rubidium targets, which is utilized in hot cells at the Federal State Unitary Enterprise "State Scientific Center of the RF–Leypunsky Institute for Physics and Power Engineering" (SSC RF–IPPE) (Obninsk). It is planned in the future to built a new facility with a target made of circulating rubidium with the on-line extraction of produced ^{82}Sr, which will

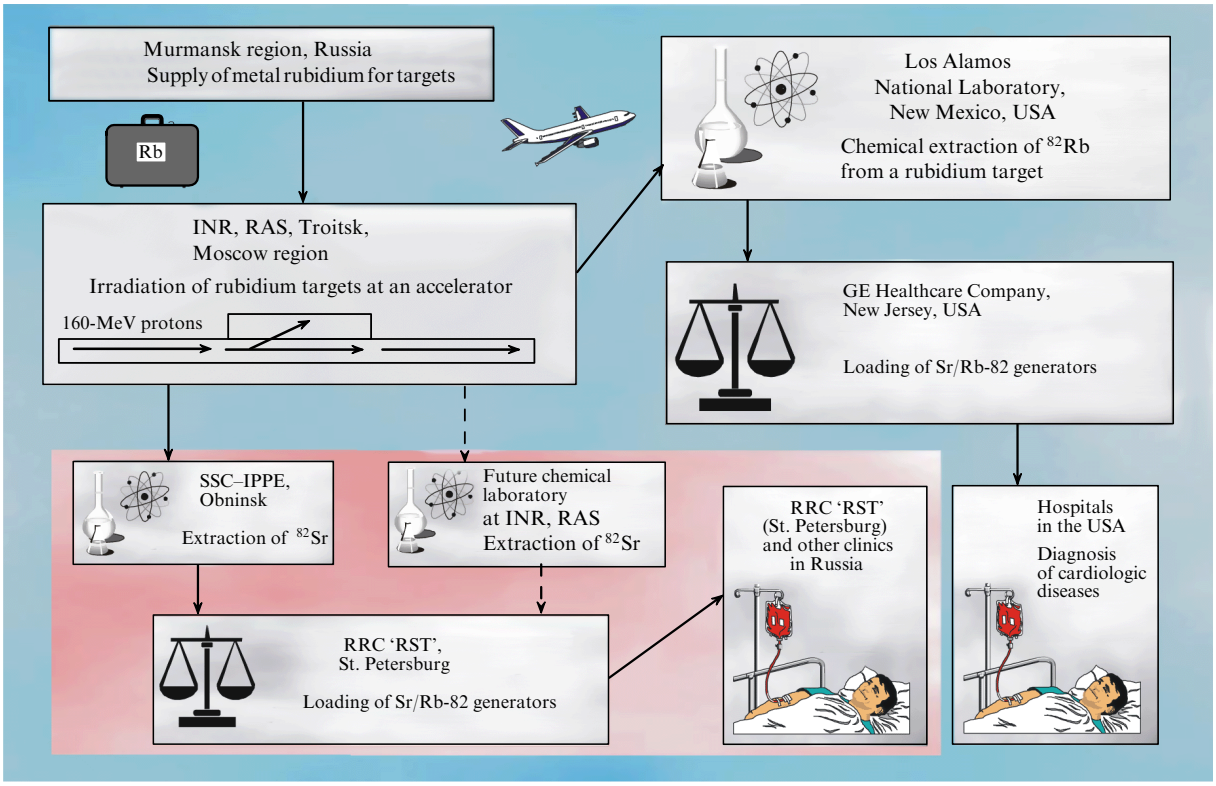

Figure 2. Production, transportation, and distribution of strontium-82.

drastically increase the efficiency. The INR, RAS holds patents on this technology [13].

The development of this new technology provided the production of proprietary pure ^{82}Sr and made it possible the fabrication of strontium/rubidium-82 generators for nuclear medicine in Russia and abroad (see Fig. 2).

3.2 Strontium/rubidium generator

The schematic of the generator's operation is illustrated in Fig. 3. Strontium-82 is absorbed on an ion-exchange column from hydrated tin dioxide. This radionuclide decays to short-lived ^{82}Rb ($T_{1/2}$ = 1.3 min). A physiological solution (0.9% NaCl) is pumped through the column with the sorbent retaining Sr^{+2} ions, while Rb^{+} ions are washed out. The high ion-exchange properties are provided by the presence of microcrystallites (of size a few nanometers) on the sorbent surface [14].

^{82}Rb isotopes eluted from the column is introduced into the circulatory system of a patient for blood flow diagnostics. The decay of this radionuclide is accompanied by the emission of positrons, which annihilate, emitting two oppositely directed 511-keV gamma quanta. The blood supply of different organs, first and foremost of the heart, is measured with a PET scanner. This provides the effective diagnosis of the ischemia of the heart and other diseases. So far, such a generator (Cardiogen®) has regularly been produced only by the companies GE Healthcare and Nordion in North America. Our generator, developed in collaboration with Canadian researchers [15, 16], has much better parameters compared with its American counterpart. At present, our generator is successfully undergoing clinical trials at a laboratory equipped according to the GMP (Good Manufacturing Practice) standards at the Russian Scientific Center of Radiology and Surgery Technologies (St. Petersburg). However, numerous bureaucratic problems during transportation, customs formalities, and the receiving of licenses of different types have severely thwarted the adaptation process.

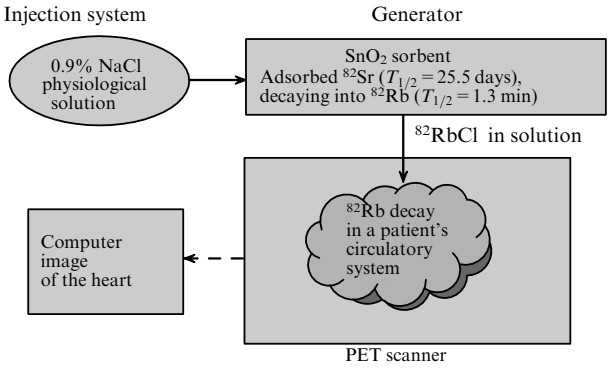

Figure 3. Operation principle of a strontium/rubidium-82 generator.

3.3 Tin-117m

This radionuclide is very promising for targeted immunotherapy in the medical treatment of atherosclerosis, bone cancer therapy, and other diseases [17]. Tin-117m emits monoenergetic Auger electrons with energies of 127 and 152 keV and fixed ranges of 0.22 and 0.29 mm, respectively, in water. This is the advantage of ^{117m}Sn over radionuclides emitting beta particles. The most efficient is a product with a high specific activity, which, unlike a product with a low specific activity, cannot be obtained by irradiation in a nuclear reactor.

^{117m}Sn with the high specific activity is produced in nuclear reactions of antimony with intermediate-energy protons: ^{121,123}Sb (p, 2p xn)^{117m}Sn. INR efficiently collaborates in this direction with BNL. This work is an example of utilizing fundamental studies in applied developments.

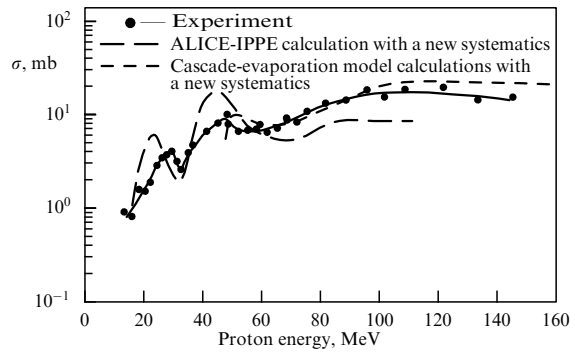

Figure 4. Calculated and experimental cross sections for ^{117m}Sn production upon irradiation of antimony by protons.

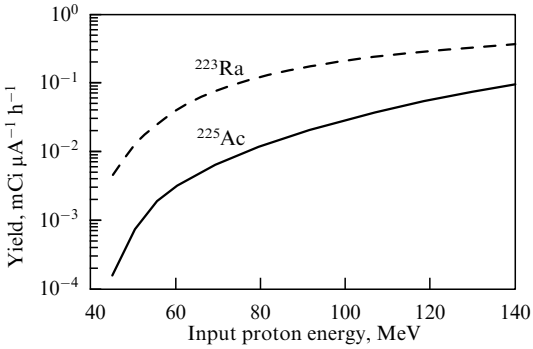

Figure 5. ^{225}Ac and ^{223}Ra yields in nuclear reactions of ^{232}Th as functions of the input proton energy in a thick target (calculations are performed for a 10-day exposure; the decay time after EOB is 10 days for ^{225}Ac, and 16 days for ^{223}Ra).

First of all, it was necessary to calculate the possible yield of ^{117m}Sn in nuclear reactions, its specific activity, and the level of radioactive impurities. The models that existed then could not provide the correct calculation of cross sections for isomeric states. We developed a new systematics which, in conjunction with the known ALICE-IPPE model (a version developed at the SSC–IPPE) and the Cascade–Evaporation–Fission (CEF) model (developed at INR, RAS), allows estimating isomeric ratios [5]:

$$\frac{\sigma_m}{\sigma_g} \approx a \exp\left[-b\,(J_m - J_t)\right],$$

where σ_m is the cross section for the isomeric nuclear state, σ_g is the ground-state cross section (it can be calculated from theoretical models), J_m and J_t are the spins of the produced isomeric nucleus and the target nucleus, respectively, and $a \approx 1.05$, and $b \approx 0.47$ are correlation coefficients. The experiments on production of high-spin isomers on different targets at different proton energies, on which a new systematics was developed, were conducted at the INR accelerator, the TRIUMF accelerator [4], and the cyclotron of the Joint Research Centre in Ispra (Italy) in collaboration with the scientists from the University of Milan.

The estimates of the ^{117m}Sn production cross sections, performed based on the developed systematics, were in good agreement with experimental cross sections [18] (Fig. 4). The specific activity in different irradiation regimes and the content of different impurities were also calculated.

We then developed technologies for manufacturing and irradiating targets containing antimony, and for the radiochemical recovery of ^{117m}Sn isotopes in hot chambers. Targets made of metal antimony in graphite or niobium shells [19] and of a TiSb intermetallic compound [20] were developed. The latter compound, which we produced for the first time in big amounts, is distinguished simultaneously by high thermal stability and high heat conduction and, therefore, constitutes a quite promising target material.

The methods for the production of ^{117m}Sn and its extraction from targets are protected by a number of Russian and foreign patents [19–22], and the technology is ready for mass production. Clinical trials are being undergone in the USA with the participation of BNL in collaboration with American commercial partners.

3.4 Actinium-225 and radium-223

Even more promising for radioimmunotherapy are alpha-active radionuclides [23]. The short ranges of alpha particles (smaller than 0.1 mm) and the high density of local energy release make alpha-emitters a rather efficient means for treating oncological diseases, which minimizes the irradiation dose of healthy organs and tissues. Alpha-radionuclides can be efficiently delivered to effected cells with the help of nanostructures based, in particular, on monoclonal antibodies [24].

Actinium-225 ($T_{1/2} = 10$ days) is one of the promising radionuclides for such a therapy, which can be used to destroy cancerous cells both directly and using daughter bismuth-213 ($T_{1/2} = 46$ min) obtained in an ^{225}Ac/^{213}Bi generator [25]. ^{223}Ra is also promising for nuclear medicine, and is already used as the drug Alpharadin® for medical treatment of the bone cancer diseases. The methods used earlier could not provide the production of ^{225}Ac and ^{223}Ra isotopes in big amounts.

Radionuclides ^{225}Ac and ^{223}Ra can be obtained irradiating thorium-232 by intermediate-energy protons [26]. Figure 5 presents the yields of ^{225}Ac and ^{223}Ra nuclides in thick thorium-232 targets as functions of the input proton energy, which were determined from the cross section measured in our experiments. Such high yields allow the production of these radionuclides in quantities of a few curies for only a week of irradiation at the accelerator. These amounts many times exceed the amounts produced by other methods. At the same time, due to nuclear spallation and fission reactions, numerous isotopes of other elements are produced in the target. We detected in the gamma and alpha spectra of irradiated Th-targets more than 80 radionuclides from which actinium and radium nuclides should be recovered by radiochemical methods. The method of actinium recovery was developed in collaboration with Moscow State University and the Frumkin Institute of Physical Chemistry and Electrochemistry, RAS by using liquid–liquid extraction and extraction chromatography, while radium was recovered by sublimation from a thorium–lanthanum melt and thermochromatographic separation in metal titanium columns (Fig. 6), followed by the additional purification of radium [27]. As a result, the opportunity opens for producing great amounts of radiochemically pure ^{225}Ac and ^{223}Ra isotopes valuable for nuclear medicine.

3.5 Other promising medical radionuclides

One of the advantages of the INR accelerator and the 160-MeV proton beam facility is the fact that several targets installed successively along the beam can be irradiated simultaneously. Thus, different targets are irradiated in

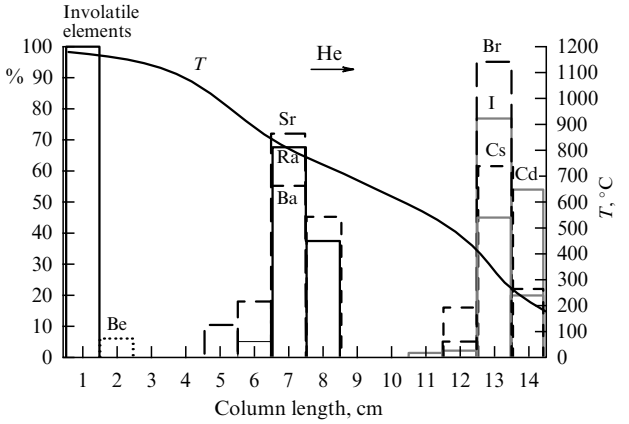

Figure 6. Thermochromatographic extraction of Ra with Sr and Ba from involatile (Th, Ac, Pa, La, Pm, Ce, Nd, Cr, Zr, Mo, Nb, Tc, Te, Sn, Sb, Ag, Ru, and Rb) and volatile elements, sublimated from a thorium–lanthanum melt, in a metal titanium column.

different proton energy ranges advantageous for the production of one isotope or another (see Table 1).

Simultaneously with a rubidium target irradiated in the energy range from 40 to 100 MeV, it is possible to irradiate metal silver at higher energies, and a gallium target at lower energies (see Table 1) to produce palladium-103 and germanium-68, respectively. These radionuclides are widely applied in medicine. ^{103}Pd is specifically tailored for prostate therapy in the form of special sources (Theragenics® seeds). Even more promising is the use of this radionuclide (as well as ^{117m}Sn) in the form of albumin microspheres [28] for the therapy of various diseases. ^{68}Ge finds use for calibration of positron-emission tomographs and manufacturing medical ^{68}Ga generators [29]. ^{103}Pd and ^{68}Ge nuclides can be produced more simply utilizing low-energy proton accelerators [30]. However, they can also be produced as by-products at the INR facility.

A new promising medical radionuclide, which cannot be obtained in low-proton energy accelerators, but can be produced in our accelerator, is selene-72 ($T_{1/2} = 8.5$ days), which serves as the generator of arsenic-72 ($T_{1/2} = 26$ h) emitting positrons and can find application in PET diagnostics. The high cross sections for the ^{75}As(p, 4n)^{72}Se nuclear reaction (which we measured for the first time) provide a high yield of ^{72}Se isotopes in targets containing arsenic. In accordance with our patent [31], a stable GaAs compound inserted into a niobium shell is utilized as a target. An efficient procedure was proposed for extracting ^{72}Se isotopes from the irradiated GaAs target by using sublimation and chemical reactions at high temperatures [3, 31]. Unfortunately, no efficient radiopharmaceutical drugs with ^{72}As radionuclides have been developed so far.

3.6 Isotopes for science and technology

Very important experiments are being carried out at INR, RAS on the search for the neutrino mass by analyzing the beta decay spectrum of tritium at the Troitsk-ν-mass installation [32]. To study volume charge effects in gaseous tritium, krypton-83m is of significance, emitting monoenergetic electrons with an energy close to the boundary electron energy in the beta decay of tritium. Krypton-83m is produced in the decay of ^{83}Rb ($T_{1/2} = 86.2$ days), which serves as the generator of ^{83m}Kr ($T_{1/2} = 1.86$ h).

We produced ^{83}Rb by irradiating strontium fluoride target with 100–120-MeV protons. Rubidium was extracted by the gas-chemical method: it was sublimated from an irradiated target at 1200 °C in a helium flow in a graphite apparatus and then deposited by a thin layer onto a metal foil. The foil was heated during experiments to evaporate ^{83m}Kr from a thin layer [6]. The use of this source contributed to the estimation of a new upper bound for the neutrino mass.

The INR accelerator can also be utilized for producing cadmium-109 from an indium target, and sodium-22 from an aluminium target (see Table 1). Both these isotopes are applied in science and technology: cadmium-109 is an important radionuclide used, in particular, in X-ray fluorescence analysis, while sodium-22 finds an application in Mössbauer spectrometry and in the physics of positronium. The experimental cumulative cross sections for the ^{109}Cd production from indium in the energy range from 80 to 140 MeV proved to be rather high. As a result, the yield of cadmium-109 upon irradiation of indium was many times higher than that in the previous method of producing this radionuclide by 800-MeV protons [33]. Both cadmium and sodium isotopes can easily be extracted from the irradiated target by the high-temperature sublimation methods [34] developed at INR, RAS.

4. New possibilities and outlook for the further development of isotope production

4.1 Modernization of the INR linear accelerator and the target irradiation facility

The linear accelerator at INR operates in the pulsed regime producing 200-μs, 14-mA pulsed beams at a pulse repetition rate of 50 Hz. The maximum admissible average beam current is determined in most cases by the target stability. The passage from a pulse repetition rate of 50 Hz to 100 Hz will provide an increase in the average current to the target by 20–30%. A beam sweeping system will ensure a more uniform distribution of pulsed thermal and radiation impacts over the target. Such systems were installed in other accelerators. As a result, the current can be approximately doubled, whereas the operational expenditures will increase insignificantly. Correspondingly, the amount of produced isotopes will increase. The target facility should also be modernized to improve the cooling of irradiated targets. Such a modernization can be performed during a short time, in one to two years.

4.2 Development of new efficient technologies and facilities for target processing

INR developed a number of techniques for the radiochemical extraction of radionuclides from different targets. Facilities based on radiochemical technologies of the ^{82}Sr and ^{117m}Sn recovery developed at INR in collaboration with SSC–IPPE operate in hot cells in Obninsk. Targets irradiated in the INR accelerator are processed in Obninsk and other institutions (LANL and BNL, Russian Scientific Center 'Applied Chemistry' in St. Petersburg, Tsiklotron Co., Ltd., Karpov Institute of Physical Chemistry in Obninsk, and Mayak Production Association in Ozersk, Chelyabinsk region). This involves large expenditures and considerable difficulties. The organization of a new production of ^{225}Ac and ^{223}Ra isotopes, which requires serious technological developments, is even more difficult.

The design of own radiochemical laboratory at INR, RAS with hot cells (an annex to operating building No. 17 with

waste processing plant) is completed. The project can be realized in four years, but this will require considerable expenditures.

4.3 Design of a new accelerator with target facilities

The INR accelerator is an efficient tool for producing various radionuclides. However, it is a complex and expensive facility which was constructed mainly for another purpose — investigations in the field of fundamental physics. In addition, facilities of this type cannot operate on a year-round basis and cannot provide the sufficient regularity of production of short-lived radioisotopes.

It is expedient to perform mass production of radionuclides at a special accelerator, probably of the cyclotron type. The ARRONAX accelerator (70 MeV, 750 μA) recently commissioned in France may cover the demand for ^{82}Sr isotopes for some time. However, the particle energy in this accelerator is too low for producing ^{225}Ac and ^{223}Ra in sufficient amounts (see Fig. 5). It is most appropriate to construct for this purpose a new H^- cyclotron with a particle energy of no less than 120 MeV, specially designed for the production of isotopes. It is assumed that such a cyclotron will have several beam lines with a total current of about 1 mA. It is reasonable to install it in the already existing building No. 25 of the experimental complex at INR, RAS.

The new accelerator can be used to realize a new technology for ^{82}Sr production from circulating rubidium with direct sorption from liquid metal. Many technical devices for systems with a liquid sodium coolant utilized in fast-neutron reactors have already been developed in Russia. As a result, it would be possible to produce ^{82}Sr isotopes in amounts of no less than 300 Ci per year, which exceeds the existing world's total ^{82}Sr consumption level. The rapidly increasing number of PET devices will provide a growing market for this radionuclide. Other beam lines in the cyclotron may serve for the regular production of ^{225}Ac, ^{117m}Sn, and other isotopes. In addition, the proton beam can find applications in proton therapy. The fulfillment of this project would make Russia a leading manufacturer of many important radionuclides, providing the diagnostics and therapy of many hundreds of thousands patients per year.

This project, including the modernization of the INR accelerator, the construction of the hot cell laboratory, the production of generators, and the construction of the new high-power cyclotron, has passed a scientific and technical expertise by the Russian Corporation of Nanotechnologies (RUSNANO)[1], and been approved. However, financing is still not allocated and when it will come through is still uncertain. The system of state regulation existing at present is becoming more complicated, hindering the development and commercialization of new technologies.

5. Conclusion

Based on our own scientific studies and technological developments, the researchers at INR, RAS have organized the production of radionuclides playing an important role for nuclear medicine in Russia and the world. To achieve further considerable progress, it is necessary to upgrade the existing facilities, to construct new facilities and buildings, and to develop new technologies. This would significantly increase the potential of nuclear medicine, most of all in the diagnosis of cardiological diseases and the medical treatment of oncological diseases. The scientific and technological problems are quite solvable. State financing all the world over always plays a great role in projects of this type; however, a considerable investment to provide progress in this field in Russia is rather problematic.

[1] On 21 March 2011, the State Corporation ROSNANO was transformed into Open joint-stock company RUSNANO (*Editor's footnote*).

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