Results of investigations of isotopes far from the β-stability band. Summary of work on the YaSNAPP Program in the Nuclear Problems Laboratory of the Joint Institute for Nuclear Research. Part I

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We summarize the results of research on isotopes far from the β-stability band, carried out at the Nuclear Problems Laboratory of the Joint Institute for Nuclear Research in 1967-1973 by the YaSNAPP program. The methods of obtaining and investigating the isotopes are briefly described, and the results are presented and analyzed for spherical and transition nuclei: $z \sim 40$ and $N \sim 50$; $Z > 50$ and $N \leq 82$; $Z = 81$ and $N \leq 116$; $Z = -84\text{-}87$ and $N \leq 126$.

INTRODUCTION

Research on the properties of atomic nuclei far from the β-stability band has attracted great interest in recent years. The problems, methods, and results of this research, carried out extensively in a number of the world's scientific centers, have been discussed many times recently at international conferences.[1,2] The importance of this investigation is frequently illustrated by the fact that, according to the theoretical estimate, there can exist in nature approximately 5000 different nuclei that are stable against prompt emission of nucleons (Fig. 1). Only a few more than 1500 nuclei have been experimentally observed and investigated to one degree or another. As a rule, these nuclei lie in the β-stability band and have relatively large half-lives. It is clear that the task of developing a nuclear theory, as well as many other pressing scientific problems, call for the investigation of the present three fundamental methods: neutron-fission reactions, reactions induced by multiply-charged ions, and reactions induced by protons accelerated to energies of several hundred MeV.

As early as 1955, reactions with protons (E_p = 660-680 MeV) were used at the Nuclear Problems Laboratory of the Joint Institute for Nuclear Research in Dubna to obtain isotopes with large neutron deficits. These studies have demonstrated for the first time that the spallation reactions offer unmatched possibilities for study of the structure of nuclei with a large neutron deficit. In the initial studies of this research (1955-1960), isotopes of rare earth elements were obtained, with deficits of six to eight neutrons in comparison with the stable isotopes. It turned out that the obtained isotopes were fully sufficient for the performance of precision nuclear-spectroscopy research (e.g., with the aid of high-resolution β spectrometers).

In investigations carried out at the Nuclear Problems Laboratory and in several participating countries of the

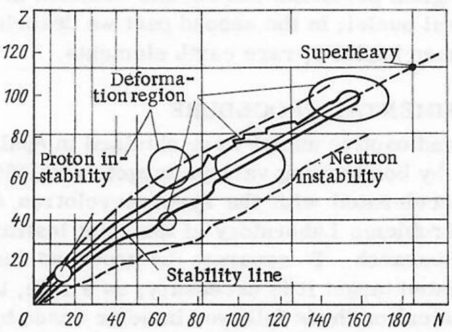

Fig. 1. Neutron-proton diagram of atomic nuclei.

TABLE 1. New Isotopes Discovered in the Nuclear Problems Laboratory in 1967-1973

Isotope	$T_{1/2}$, min	Reference	Isotope	$T_{1/2}$, min	Reference
^{77}Rb	3.9	[17]	^{156}Er	19.5	[163]
^{78g}Rb	19	[55]	^{159}Tm	11±3	[164]
^{78m}Rb	6	[55, 56]	^{161}Yb	3.0	[165]
^{86}Nb	1.4±0.2	[67]	^{163}Yb	13±3	[164]
^{87g}Nb	2.6	[67]	^{165}Lu	10	[166]
^{87m}Nb	3.8	[67]	^{166}Lu	3.3±0.2	[167]
^{88m}Nb	7.3±0.1	[12]	^{166}Hf	6.0±0.5	[167]
^{92}Ru	3.16±0.33	[22, 72]	^{167}Hf	1.9±0.2	[167]
^{128}Ce	3.5±1.0	[104]	^{169}Hf	3.2±0.1	[167]
^{129}Ce	5.5±1.0	[104]	^{167}Ta	2.9	[168]
^{132}Pr	1.6	[103]	^{168}Ta	2.5	[168]
^{133}Pr	7±3	[97]	^{169}Ta	5.0	[168]
^{134m}Pr	11	[101]	^{170}Ta	7.0	[168]
^{134}Nd	8	[97]	^{171}Ta	25	[168]
^{135}Nd	5.5; 15	[97]	^{172}W	6±2	[169]
^{136}Nd	55	[95]	^{176}Os	3.0	[170]
^{141}Sm	11±1	[77]	^{177}Os	3.5	[170]
^{141m}Sm	22.5±0.5	[75]	^{178}Ir	0.5±0.3	[23]
^{144}Gd	4.9±0.4	[74]	^{180}Ir	1.5±0.1	[23]
^{147m}Tb	1,8	[157]	^{181}Ir	5.0±0.3	[23]
^{148m}Tb	2.1±0.1	[158]	^{188}Tl	1.5	[24]
^{150m}Tb	6.0±0.1	[158]	^{189}Tl	1.4±0.4	[25]
^{148}Dy	3.5	[159]	^{190}Tl	3.5±0.4	[24, 130]
^{153}Ho	2.0	[162]	^{191}Tl	5.2±0.4	[130]

Joint Institute for Nuclear Research, where this method of obtaining the isotopes was used, more than 80 new isotopes were discovered, and abundant information was obtained on the structure of neutron-deficient nuclei. A review of this research is contained in a paper by K. A. Gromov and B. S. Dzhelepov.[3] They used the classical off-line procedure and investigated nuclei with half-lives of approximately one hour and more.

A new stage in the development of short-lived isotopes far from the β-stability band was initiated in the mid-1960's. By that time, high-grade semiconductor detectors had been developed for nuclear radiation, which made it possible to investigate rapidly, in a multichannel regime and with high resolution, complex spectra of γ rays, conversion electrons, etc. Considerable progress was made also in the technique of electromagnetic isotope separation. It was precisely at that time that several programs were proposed for investigation of short-lived isotopes far from the β-stability band. The program at the Joint Institute for Nuclear Research was named Nuclear Spectroscopy in Proton Beams (YaSNAPP). This program was started in 1966-1967 and is continuing to this day. The work done in 1967-1973 yielded abundant information on the nuclear properties of the newly discovered and already known isotopes. Table 1 lists the isotopes, in the ground and isomeric states, discovered by us during that time.

We describe here some summary results of these investigations. In the first part of the review we consider methodological problems and results obtained in the study of spherical nuclei; in the second part we describe results for deformed nuclei of rare earth elements.

1. EXPERIMENTAL PROCEDURE

The radioactive nuclei were obtained in spallation reactions by bombarding various targets with 660-MeV protons accelerated with the synchrocyclotron of the Nuclear Problems Laboratory of the Joint Institute for Nuclear Research. To separate the produced nuclei from the irradiated target it is necessary, as a rule, to use radiochemical methods followed in some cases by isotopic separation. To this end, there was completed by the end of 1969 a setup (YaSNAPP-1) operating on-line with the accelerator.[4,5] It was possible to obtain and investigate with this apparatus radioactive nuclei with half-lives of approximately one minute and longer. This limit was imposed by the relatively large distance between the YaSNAPP-1 apparatus and the accelerator, so that the targets had to be transported to the accelerator and back with the aid of a pneumatic system. On-line experiments using spallation reactions, capable of obtaining and investigating isotopes with half-lives down to 0.1 sec (the YaSNAPP-2 setup), are being planned following the reconstruction of the synchrocyclotron.[4,5] The YaSNAPP-1 apparatus (Fig. 2) consists of the following principal units, which were designed mainly at the Nuclear Problems Laboratory of the Joint Institute for Nuclear Research:

1. A system for bombarding the targets with the extracted proton beam (660 MeV, $\sim 10^{11}$ protons/sec) with remote control and search for the maximum beam density.

2. A pneumatic system for transporting targets to the accelerator for bombardment and back to the chemical laboratory (approximate distance 70 m, transport speed approximately 10 m/sec).

3. Apparatus for rapid chemical processing of the bombarded targets.

4. Electromagnetic mass separator with ion sources of various types.

5. Collector systems for the reception, transportation, and extraction of the radioactive isotopes separated in the mass separator.

6. Apparatus for spectrometry of the radioactive emissions.

7. Apparatus and programs for the reduction of the experimental data.

High-Speed Chemical Methods of Radioactive-Isotope Separation

To investigate short-lived isotopes by the YaSNAPP program it is necessary to obtain rapidly compounds with maximum possible activity and purity, in a chemical form suitable for subsequent separation of the isotopes in a mass separator. This was done by modifying and improving already existing methods[6] and by developing new ones (Table 2).

As shown by the investigations, the choice of the target plays an important role: It is necessary to take into consideration its chemical composition, its aggregate state, and other physical and chemical characteristics. For example, the choice of targets in the form of salts of rare earth element complexes of the type $(NH_4)_2$Ln (DTPA), where DTPA stands for diethylene triamine pentaacetic acid, has led to an appreciable acceleration of the separation of the microscopic quantities obtained in nuclear reactions of rare earth elements from the macroscopic quantities of the target material, on the basis of the Szilard–Chalmers method.[7] This stage, in conjunction with the subsequent improvement of the chromatographic separation of the rare earth elements by fractions (Dowex-50 resin was replaced by Aminex-5; the column dimensions were decreased to 2×60 mm), and also in conjunction with an improved variant of electrolytic preparation of the compound for introduction into the ion source[8], has led to an appreciable reduction in the time necessary to complete the entire procedure, which now takes not more

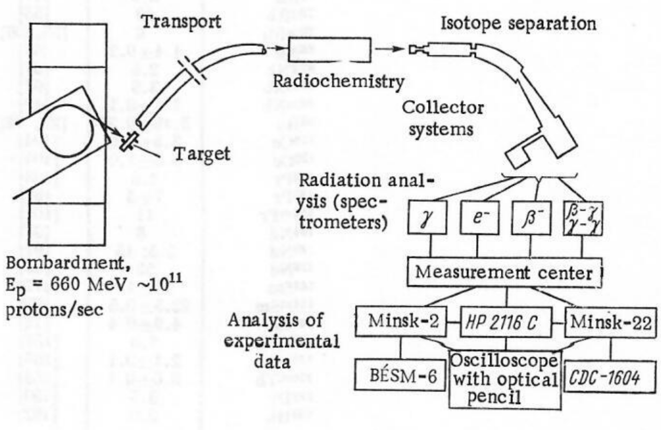

Fig. 1. Neutron-proton diagram atomic nuclei.

TABLE 2

Method	Element	Production reaction	Target	Separation condition	Time of chemical separation min	Mass separation	Investigated isotopes	Reference
Modified methods of "wet" chemistry (selective precipitation, sorption in surfaces, ion-chromatography, extraction)	Rb	Sr(p, 2pxn) Rb Y(p, 3pxn) Rb	$SrCl_2$ $Y(NO_3)_3$	Precipitation of tetraphenyl borate of Rb at pH = 3-5	4	No		[19]
	Sr	Rb(p, xn) Sr	$RbNO_3$	Precipitation of $SrCO_3$ at pH > 7	4	No		[19]
	Y	Spallation reactions: 1) Nb + p 2) Sr(p, xn)Y	Nb_{met} $SrCl_2$	Separation of fluoride, sorption in column on Dowex 50 × 8 resin	≥ 30 10	No	^{84}Y	[58]
	Nb	Mo(p, 2pxn)Nb	H_2MoO_4 Mo_{met}	Sorption of Nb on glass filter from ammonia solution	7	No	^{90}Nb	[19, 71]
	Ba	Ce(p, 3pxn)Ba	CeO_2	Collection of recoil nuclei in 0.1 M solution of HCl. Separation by column with Dowex-50 × 8	10	Yes	$^{124-127}Ba$	[107, 108, 111, 112]
	REE	Spallation reactions: 1) Ln + p	$(NH_4)_2Ln$ DTPA	Separation of recoil nuclei that form no complexes by sorption with Aminex A-5 column	10	Yes	from Pr to Dy (4 min ≤ $T_{1/2}$ ≤ 30 min	[7, 100, 101]
		2) Ta + p	Ta_2O_5	Gathering of recoil nuclei in 0.1 M solution of HNO_3. Separation by column with Aminex A-5	12	Yes	from Dy to Lu ($T_{1/2}$ ≥ ≥ 10 min	[20]
	At Rn Fr	Spallation reactions: Th + p	Th_{met}	Recovery of RN by dissolving Th. Concentration of At in column with Te_{met}. Separation of Fr in column with Dowex-50	5 ~30 ~15	Yes	$^{208-211}At$ $^{205-212}Rn$ ^{212}Fr	[26, 27] [141-147] [151-154]
	Zr Nb Mo Tc Ru	Spallation reactions: Ag + p	AgCl	From the melt at t = 625-850°C in the carrier-gas stream: $Cl_2 + O_2$ (7 : 1) or $HCl + O_2$ (1 : 1); precipitation in TX (thermochromatography) column by zones	3	No	$^{86,87,88}Nb$ $^{88}Mo \rightarrow {}^{88}Nb$ ^{92}Ru	[12, 13, 22, 67]
	W	1) Ta(p, xn) W 2) Au + p	Ta_{met} Au_{met}	Volatilization of W* by burning Ta and Au (t = 1160°C) in a stream of moist oxygen (P_{H_2O} = 414 mm Hg), precipitation in TX column	~10	No		[171]
	Re	1) W(p, xn)Re	W_{met}	Volatilization of Re* by burning W(t = 1160°C) in a stream of moist oxygen (P_{H_2O} = 430 mm Hg). Precipitation in TX column	~10	No		[172]
		2) Re(p, pxn)Re	NH_4ReO_4	Thermal decomposition of NH_4ReO_4 at t = 600-800°C. Precipitation of Re* in TX column.	3	No	^{179}Re	[10, 173]
		3) Os(p, 2pxn) Re	Os_{met}	Burning of Os (t = 850°C) in a stream of oxygen. Precipitation of Re* in TX column	3	No		[10]
	Re Os Ir Hg	Spallation reactions: Au + p	Au_{met}	From the melt at t = 1160°C in the carrier-gas stream (O_2); selective precipitation in TX column by zones	3	No	$^{178,180-182}Ir$	[14, 23]

TABLE 2 (continued)

Method	Element	Production reaction	Target	Separation condition	Time of chemical separation, min	Mass separation	Investigated isotopes	Reference
	Tl	Pb(p, 2pxn)Tl	PbF_2	From crystal powder at t = 650°C in carrier-gas stream (N_2); precipitation in TX column in the 270-170°C zone	3	Yes	$^{188-197}Tl$	[11, 24, 25]
Emanation	Kr	Sr(p, 3pxn)Kr	SrO	Emanation from crystal powder at t = 400°C, p = 10^{-2} mm Hg, absorption in trap with activated carbon at liquid-nitrogen temperature	2	Yes	^{79m}Kr	[15]
	Rn	Th(p, 5pxn) Rn	ThO_2	Same		Yes	$^{205-207}Rn$	[16, 148-150]
Reaction in ion source	Rb Sr	Zr(Nb) + p	$Zr(Nb)_{met}$	Evaporation at temperature of ion source; chemical separation of isobars after mass separation: precipitation of $RbClO_4$ and $SrSO_4$	Without chemical separation prior to mass separation	Yes	$^{77,78}Rb$	[17, 55, 56]
	REE	Spallation reactions: Ta + p	Ta_{met}	Evaporation at temperature of ion source; chemical separation of isobars after mass separation with Aminex A-5 column	Without chemical separation prior to mass separation	Yes	from La to ($T_{1/2} \geq 1$ min	Lu [18, 159-162]

than 20 min under these conditions.

Highly promising for rapid separation of radioactive isotopes is the method of gas thermochromatography, based on removing the volatile compounds, which are produced under certain conditions, from the heating zone by a carrier gas into a tube with a specified temperature gradients, on the walls of which the volatile compounds are absorbed in various temperature zones as the gas stream passes through the tube.[9,10] This method makes it possible to separate chemically the necessary isotopes from the target material and to purify them directly during the course of the bombardment on-line, so that isotopes with a half-life on the order of one minute could be investigated. Figure 3 shows a diagram of the chemical apparatus used in an experiment of this type.

In the gas thermochromatography methods the radioactive isotopes were separated by making use of the volatility of the fluorides[11] of Tl, of the chlorides[12] of Mo, of the oxychlorides[13] of Zr and Nb, of the oxides[14] of Ir, Os, Re, and Hg, and of the hydroxides[171,172] of W and Re.

The emanation property of noble gases was used to separate Kr and Rn from the oxides SrO and ThO_2, respectively.[15,16]

Procedures used in some investigations have made it possible to dispense with the chemical separation of the element from a complicated mixture of bombardment products. This was possible when the relatively volatile impurities were evaporated from high-melting-point targets directly in the ion source of the mass separator. The isotopes of the elements evaporated at high temperature were gathered on a collector belt. When necessary, one or two chemical operations have made it possible to separate the obtained isobars, as was done, e.g., in the case of rubidium and strontium[17] and for rare earth elements.[18]

Mass Separators and Ion Sources

The electromagnetic separator used in the on-line system of the Scandinavian type[28] ensures a dispersion

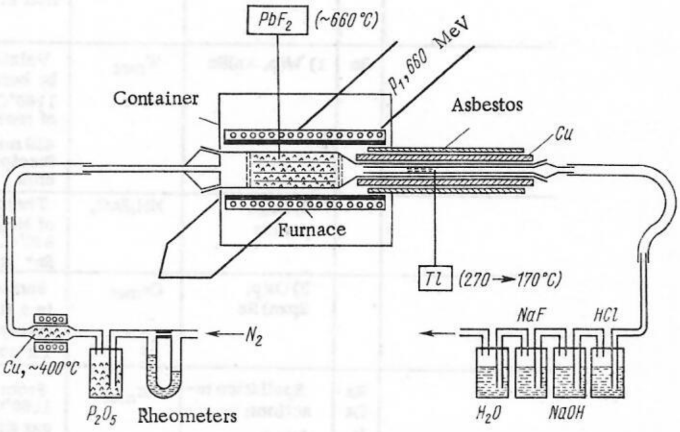

Fig. 3. Experimental arrangement for the production and gas-thermochromatographic separation of Tl isotopes from the target material during the course of bombardment.

of 15 mm at $\Delta m/m = 1/100$ and makes it possible to separate simultaneously isotopes up to M = 250 in a range of ± 15% of the average mass in the focal plane. The resolution of the mass lines reaches 2000. However, the resolution, efficiency, and operating speed of the mass separator depend mainly on the construction and operating conditions of the ion source and on the parameters of its ion-optical system. Experiments[29] have led to optimization of these parameters, so that maximum resolution could be reached and the separation efficiency could be significantly increased.

Three types of ion sources were developed and investigated for the separation of isotopes of various elements.

1. A plasma source of the magnetron type, with automatic introduction of the specimen – to separate isotopes of elements having boiling points[30] up to 1000°C. In particular, this source was used to separate the radioactive isotopes of Tl with efficiency up to 12%.

2. A unique high-temperature tubular source with surface ionization.[31] It ensures a separation efficiency up to 100% for ultrasmall amounts of radioactive isotopes at a radioactive-atom ionization potential $V_i \leq 5$ eV. The efficiency decreases with increasing V_i and amounts to 1% at $V_i = 7$ eV. This means that the separation of approximately 50 elements is possible, including lanthanides and actinides.[32]. This source was used to separate the isotopes of Nd, Pr, Yb, Tm, Ho, Dy, Ba, Rb and others. The experimental values of the isotope-separation efficiency of certain elements are given in Fig. 4. This ion source is distinguished also for its high speed (Fig. 5). The time that the reaction products stay in the source is approximately 10 msec; the time to reach operating temperature is approximately 1 minute. It should also be noted that the high temperature inside the ion source (approximately 3000°C) makes it impossible to dispense in certain cases with radiochemical processing of the bombarded targets, which consumes a certain amount of time (e.g., approximately 20 minutes for rare earth elements). It was possible to place bombarded high-melting-point targets (Ta, Zr, Nb, etc.) directly in the ion source. In this case the radioactive atoms rapidly leave the target material as a result of thermal diffusion, and then become ionized on the incandescant tungsten surface of the source. This method was successfully used to obtain short-lived isobars of alkali earth and rare earth elements.[17,18] Investigations of the mechanism of diffusion and ionization of the atoms in such a system show that the method of isobaric separation can be particularly convenient in future on-line experiments.

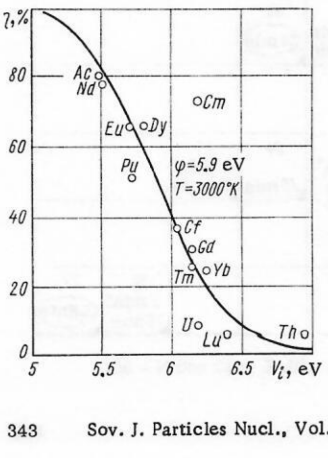

Fig. 4. Experimental efficiencies of isotope separations using a source with surface ionization on tungsten, vs the ionization potential.

3. A source with surface ionization and a gas discharge, with a hollow cathode – for the separation of isotopes of high-melting-point (Zr, Hf, Nb) and other difficult-to-ionize elements.[33] The use of atom ionization in the gas discharge on top of the surface ionization makes it possible to extend the range of investigated nuclei and to cover practically the entire periodic table of elements.

An electromagnetic mass separator for off-line experiments was developed in 1968.[34] This instrument was used to separate, for the first time in the USSR, large numbers of radioactive isotopes ($T_{1/2} \geq 10$ min), using ion sources of various types.[17,35]

Spectrometric Apparatus and Reduction of Measurement Results

Suitable measuring apparatus and methods for experiment control and computer data reduction were developed for the investigation of the emission of short-lived nuclei.

As follows from the properties of the nuclei that can presently be investigated with the YaSNAPP-1 setup, the main sources of the information are positron, γ-, and x-ray emission and conversion electrons. Their emission spectra (energies and transition intensities), and also the time and angular correlations between them must be measured as soon as possible after the mass separation of the nuclear-reaction products. This predetermines the main requirements that must be satisfied by the spectrometric apparatus, by the apparatus needed to control and monitor the experiments, and by the procedure for the reduction of the results.[36] It is necessary to ensure rapid transport of the atoms of the radioactive nuclei from the focal plane of the mass separator to the detectors, and to use the following: 1) radiation detectors with high resolution and efficiency, coupled to multichannel analyzers; 2) multidimensional analysis; 3) high-speed reduction of the results during the course of the experiment in order to monitor the course of the experiment with the aid of the intermediate data; 4) a system of programs for the final reduction of the results with the basic computers of the Joint Institute for Nuclear Research.

The transport of the radioactive nuclei from the focal plane of the mass separator to the detectors was effected in the following manner: A belt system transported the atoms of one chosen isotope within two to three seconds

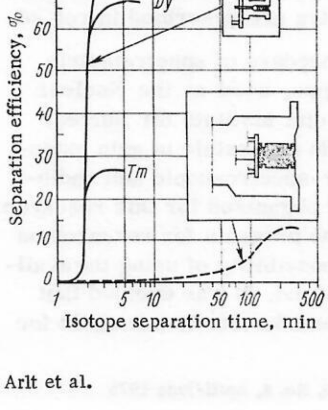

Fig. 5. Efficiency of isotope separation using a source with surface ionization and a standard gas-discharge source (dashed curve) vs the separation time.

Isotope separation time, min

after the mass separation to the detectors,[37] and the remaining isotopes were gathered on a foil extracted from the mass separator through a gate after approximately 30 seconds.

The main instruments for measurement of the characteristics of the emissions were various semiconductor detectors. For precision measurements, different spectrometric electronic blocks were developed, such as preamplifiers,[38] an amplifier, a coding device with a stabilization circuit, and a system for time measurements with semiconductor detectors.[39] The use of the concept of unipolar spectrometric pulses has made it possible to increase the counting rate in experiments with Ge(Li) detectors to several tens of thousands per second, without noticeably spoiling the resolution (by not more than 10% at counting rates up to 40,000 counts/sec). The development of a system for obtaining "fast" time signals from "slow" semiconductor detectors, by cancelling out the front and by altering the rise time of the pulses, has made it possible to obtain good temporal resolution when working with semiconductor detectors in a wide dynamic range and at high counting rates.[39] Multidimensional analysis (16 windows $\times$ 256 channels, 8×512, and 4×1024) was effected with the aid of the AI-4096 analyzer and a system of digital windows.[40]

In addition, measurements of two-dimensional coincidences were carried out with an HP-2116 computer and an AI-4096 analyzer. In this case the information was recorded on magnetic tape, and the window settings after the experiment were programmed to match the positions of a two-dimensional 4096 + 4096-channel memory field.[41]

For high-speed reduction of the data, the measurement center was then connected with the computers Minsk-2, Minsk-22, and HP-2116,[40–42] using the "light pencil" method (see Fig. 2). The ÉPOS-1 program makes it possible to determine the energies and intensities of the transitions within a short time of the experiment, after several tens of seconds, with sufficient accuracy, so that the control of the experiment is greatly facilitated.[41,43] For the subsequent reduction one can use the programs ÉPOS-2[43,44] or KATOK.[45] The final reduction of the spectrum was carried out with the aid of the programs SIMP-3 and GAMMA with the SDS 1604A computer[46,47] and with the aid of the GAMMA program with the BÉSM-6 computer.[46]

The use of semiconductor detectors with high resolution, and the use of a modified GAMMA program made it possible to determine the energies of the γ rays of the short-lived isotopes with an error[48] of several tens of electron volts. The programs used to reduce the positron and conversion-electron spectra are described in ref. 46.

The classical off-line procedure of spectrometric research on radioactive isotopes, used at the Nuclear Problems Laboratory of the Joint Institute for Nuclear Research since 1958, has made it possible to gain extensive experience in the nuclear-spectroscopic and radiochemical laboratory specially organized for this research.[3] Therefore, when developing the program for research on the short-lived isotopes, the possibility of using the available equipment was first assessed. It was decided that the use of these instruments and devices is advisable for the study of the short-lived isotopes. Thus, the large magnetic α spectrograph[49] was used to investigate the short-lived isotopes of Rn (up to ^{206}Rn with $T_{1/2} = 6$ min), and the magnetic β spectrographs were used to investigate the spectra of the conversion electrons of ^{165}Yb ($T_{1/2} =$ 10 min) and ^{160}Tm ($T_{1/2} = 9$ min).

To investigate the short-lived isotopes we used semiconductor γ, x-ray, and β spectrometers, installations for the measurement of $\gamma\gamma$ coincidences and of angular correlations, etc.[42,50,51] In 1972, operation was started of an iron-free toroidal β spectrometer [of the "Appel'sin" (orange) type] with hitherto unmatched characteristics: resolution 1% and transmission 20% or else resolution 0.4% and a transmission[52] of 7%. The use of this apparatus provides great possibilities in the investigation of short-lived isotopes.

A microphotometer for automatic reduction of the information obtained from photographic plates exposed in the β spectrographs was specially developed and produced;[53] an automatic unit is being developed for the scanning of photographic plates from α spectrographs, with provisions for the reduction of the obtained information with the aid of a computer.

INVESTIGATION OF SPHERICAL AND TRANSITION NUCLEI

Nuclei with $Z \approx 40$ and $N \approx 50$

In this region, the decays of the following isotopes and isomers were investigated: ^{77}Rb, ^{78g,m}Rb, ^{85m}Sr, ^{83g,m}Y, ^{84}Y, ^{85g,m}Y, ^{86}Y, ^{87g,m}Y, ^{87g,m}Zr, ^{89g,m}Zr, ^{86}Nb, ^{88g,m}Nb, ^{89g,m}Nb, ^{90}Nb, ^{92}Ru (Fig. 6). All these nuclides were obtained by bombarding the appropriate targets ($SrCl_2$, Y_2O_3, Zr_{met}, Nb_{met}, Mo_{met}, AgCl) with high-energy protons. In all cases except Rb there was no mass separation of the isotopes.

The γ spectra of the chemically separated compounds of the radioactive isotopes were measured, and in some cases also the $\gamma\gamma$ coincidences and the conversion-electron spectra. The γ transitions were identified with definite isotopes by means of the rate of decrease of their intensity and by their genetic relation with the parent and daughter isotopes.

Z \ N	49	48	47	46	45	44	41	40
$_{44}$Ru		92 3.16 min						
$_{41}$Nb	90 14.6 h	89 1.18 h* 1.9 h	88 7.3 min 14 min	87 3.8 min 2.6 min	86 1.4 min			
$_{40}$Zr	89 4.18 min* 78.4 h		87 14 sec* 94 min					
$_{39}$Y		87 14 h* 80 h	86 14.6 h	85 2.68 h* 5 h	84 39 min	83 7.4 min* 2.6 min		
$_{38}$Zr			85 70 min* 64 d					
$_{37}$Rb							78 6 min* 19 min	77 3.9 min

Fig. 6. Diagram of nuclides with $Z \approx 40$ and $N = 50$.

Results of experiments. ^{77}Rb. This isotope was discovered in 1972. Its half-life and total decay energy were determined, eight γ transitions were observed, and a decay scheme was proposed.[17,54]

^{78g,m}Rb. The ground and isomeric states were identified[55] and an isomeric transition was observed.[56]

^{83g,m}Y. The decays of the isomers ^{83g}Y and ^{83m}Y were investigated for the first time. Nine γ transitions that follow the decay of the ground state, and also three γ transitions produced upon decay of the isomeric state were found. The decay scheme of the ^{83}Y isomers was constructed: Eight excited states of ^{83}Sr were introduced and their spins and parities were determined.[57]

^{84}Y. A total of 24 γ transitions were observed, of which 14 were observed for the first time. The decay scheme was supplemented and refined, and the quantum numbers were proposed for most levels.[58]

^{85g,m}Y, ^{85m}Sr. In the γ spectrum of the ^{85}Y isomer with $T_{1/2}$ = 5 h, assumed to be ^{85g}Y, there were found 30 γ transitions, of which nine were observed for the first time. Three γ transitions were observed in the decay of ^{85m}Y. The isomer decay schemes were constructed. The spins and parities of the excited states of ^{85m}Sr were determined. The intensity ratio of the γ decay and of the isomeric transition was determined[59–61] for ^{85m}Sr.

^{86}Y. More than 80 γ transitions were observed, 50 of them for the first time. The decay scheme was constructed. The spins and parities of the excited states of ^{86}Y were proposed.[62,63]

^{87g,m}Y. The decay scheme was confirmed and refined. It was shown that the ^{87g}Y (1/2−) → ^{87m}Sr (1/2−) β transition has an anomalous value[64] of log ft.

^{87}Zr. Fifteen γ transitions were observed in the spectrum of ^{87}Zr, most of them for the first time. The decay scheme was constructed and the spins and parities of the ^{87}Y levels were determined.[65,66]

^{89}Zr. Six γ transitions were obtained and a decay scheme was proposed.[66]

^{86}Nb. This isotope was discovered in 1973. The half-life was determined, two γ transitions were observed, and a decay scheme was proposed.[62]

^{87g,m}Nb. Several new γ transitions were observed, a decay scheme was proposed, and the spins and parities of the levels were determined.[67]

^{88g,m}Nb. A total of 95 transitions, more than 80 of them found for the first time, were observed in the γ spectrum of ^{88}Nb. The decay of the ^{88g}Nb ground state was investigated. The quantum numbers of the excited states of ^{88}Zr were determined.[12,68]

^{89g,m}Nb. Out of the 75 γ transitions obtained, 30 were observed for the first time. The end-point energy of the positron spectrum was determined. The decay scheme of the ^{89}Nb isomers was constructed. The spins and parities of the proposed levels were determined.[60,61,69,70]

^{90}Nb. The decay scheme was refined and supplemented. The spins and parities of the ^{90}Zr levels were determined.[60,61,71]

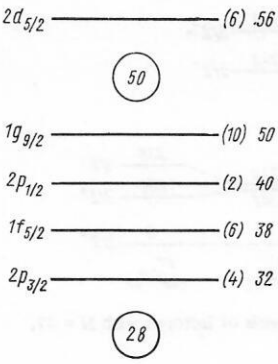

Fig. 7. Fragment of shell scheme.

^{92}Ru. This isotope was discovered in 1971. Its half-life was determined, and three γ transitions were found. A decay scheme was proposed, and the spins and parities of the levels of the daughter ^{92}Tc were determined.[22,72]

Conclusions. On the basis of the results, and also by using data by others, mainly the results of spectrometric investigations of the nuclear reactions, one can draw certain general conclusions. It should be noted first of all that all the nuclei considered are spherical, and consequently many of their levels should be adequately described by the shell model. The numbers of protons and neutrons in all these nuclei lie between the magic values 28 and 50.

Isotopes with odd A. The properties of the low levels in these nuclei are determined by the position of the odd nucleon (or hole) in the subshells $1g_{9/2}$, $2p_{1/2}$, $1f_{5/2}$, and $2p_{3/2}$ (Fig. 7). This gives rise to single-particle levels with spin and parity $9/2^+$, $1/2^-$, $5/2^-$, $3/2^-$ (Figs. 8-10).[73] We see that the energy spacing between the levels with $I^\pi = -1/2^-$ and $9/2^+$ decreases with decreasing Z for all the isotones, and for the isotones with N = 47 and 45 it becomes even negative at Z = 34. The reason is that the ratio of the neutron binding energies in the $g_{9/2}$ and $p_{1/2}$ orbits increases with decreasing Z. The space between the 3/2 and 1/2 levels, to the contrary, is practically constant for all the isotopes and isotones. The spacing between the $5/2^-$ and $1/2^-$ levels is approximately constant for nuclei with equal numbers of neutrons, but decreases with decreasing N at constant Z. For N = 45, the $5/2^-$ levels lie lower than the $3/2^-$ levels (Fig. 11).

For the isotones with N = 47 there appears an "anom-

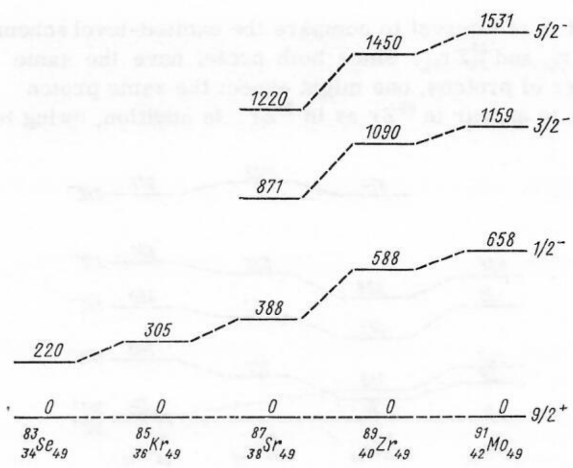

Fig. 8. Systematics of low-lying levels of isotones with N = 49.

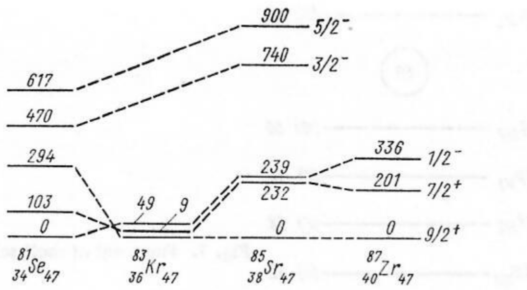

Fig. 9. Systematics of low-lying levels of isotones with N = 47.

alous" level with $I^{\pi} = 7/2^{+}$, which becomes the ground state for the isotones with N = 45. It is usually interpreted as a configuration state of the type $(g_{9/2})^{-3}_{7/2^+}$ for N = 47 and $(g_{9/2})^{-5}_{7/2^+}$ for N = 45, with seniority $\nu = 3$ and 5 respectively. It is not excluded, however, that we are dealing here with a more complicated interaction between the particles (holes) and the phonons.

A second level with $I^{\pi} = 3/2^{-}$ appears for ^{85}Sr and the isotones with N = 45. It can be assumed that the dominant part of the neutron configuration of these levels is of the form $(p_{3/2})^{-1}(p_{1/2})^{-2}(g_{9/2})^{10}$ for ^{85}Sr and $(p_{3/2})^{-1}(p_{1/2})^{-2}(g_{9/2})^{8}$ for N = 45.

As to the higher levels, their interpretation is not so clear and is apparently not so simple. Some states can be explained on the basis of the interaction of the odd neutron (hole) with the excited core [e.g., $2^{+}(g_{9/2})^{2n+1}$]. The nuclei with N = 47 and 45 can acquire states with configuration $(g_{9/2})^{-3}$ ($\nu = 3$) and $(g_{9/2})^{5}$ and ($\nu = 5$), respectively. Some states that differ from others in having a lower log ft value can be interpreted as three-particle states of the type $\pi(g_{9/2})^{2n+1}\,\pi(p_{3/2})^{-1}\,\nu\,(p_{1/2})^{+1}$ or $\pi(p_{3/2})^{-1}\nu\,(p_{1/2})^{1}\,\nu\,(g_{9/2})^{2n+1}$. Some nuclei, however, e.g., ^{89}Zr, were found to have too many levels to be able to explain them on the basis of the indicated concepts.

Even – even nuclei. The lower levels of the doubly magic nucleus $^{90}_{40}\mathrm{Zr}_{50}$ can be explained on the basis of the shell model as being proton two-particle levels with configurations indicated in Fig. 12. It is to be expected that the states that become populated among the higher-energy levels in the decay of $^{90}_{41}\mathrm{Nb}_{49}$ are those of the type $\pi(g_{9/2})^{1}\,\pi(p_{3/2})^{-1}\,\nu(g_{9/2})^{-1}\,\nu(p_{1/2})^{-1}\,\nu(d_{5/2})^{2}$ (see ref. 71).

It is of interest to compare the excited-level schemes of $^{90}_{40}\mathrm{Zr}_{50}$ and $^{88}_{40}\mathrm{Zr}_{48}$. Since both nuclei have the same number of protons, one might expect the same proton states to appear in ^{88}Zr as in ^{90}Zr. In addition, owing to the presence of two holes in the $g_{9/2}$ neutron shell one might expect an analogous neutron-type level system. Actually, a band of states with $I^{\pi} = 0^{+}, 2^{+}, 4^{+}, 6^{+}$, and 8^{+} is observed both in ^{88}Zr and in ^{90}Zr. These levels, however, are well excited in the (p, t) reaction and also appear quite distinctly for the isotope $^{86}_{38}\mathrm{Sr}_{48}$, where neutron states should preferably arise. They must therefore be interpreted as neutron two-hole states. To be sure, still other levels with $I^{\pi} = 2^{+}$ (1818 keV) and $I^{\pi} = 8^{+}, 9^{+}$ (3390 keV) appear in ^{88}Zr, but the terms with $I^{\pi} = 4^{+}$ and 6^{+} are missing from the possible band. In addition, a deexcitation of the 2^{+} level takes place, as is usual for vibrational two-phonon states of spherical nuclei. One can therefore conclude either that ^{88}Zr does not have the proton-state band observed in the ^{90}Zr nucleus, or that the probability of its excitation in the decay of ^{88}Nb is much lower.

In the ^{88}Zr nucleus there are also observed two states with $I^{\pi} = 3^{-}$ (2456 and 3032 keV). The state 3_1^- is probably collective and octupole–vibrational, decaying predominantly to the vibrational level 2_2^+, while the state 3_2^- is a particle state that decays to the neutron level 2_1^+.

A band of neutron levels with $I^{\pi} = 2^{+}, 4^{+}, 6^{+}$, and 8^{+} is observed also for the nucleus $^{84}_{38}$Sr (only the 2^{+} and 4^{+} levels are shown in Fig. 12). There exists a level 2_2^+ (1456 keV) with symptoms of two-phonon vibrational states. As in the case of the isotone $^{82}_{36}\mathrm{Kr}_{46}$, a 3^{+} level is observed, decaying predominantly to the 2_2^+ level (the parentheses at the transitions indicate the decay probabilities). This decay mode agrees with the assumption that the 3^{+} level belongs to a quasirotational band based on the 2_2^+ level. All these facts

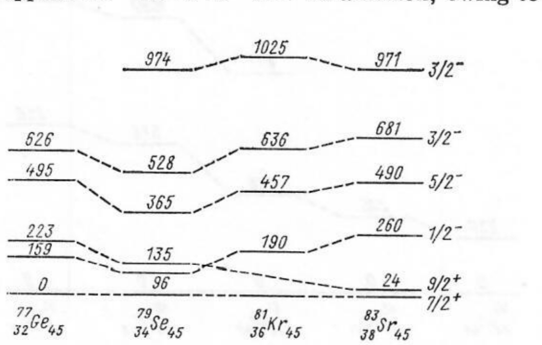

Fig. 10. Systematics of low-lying levels of isotones with N = 45.

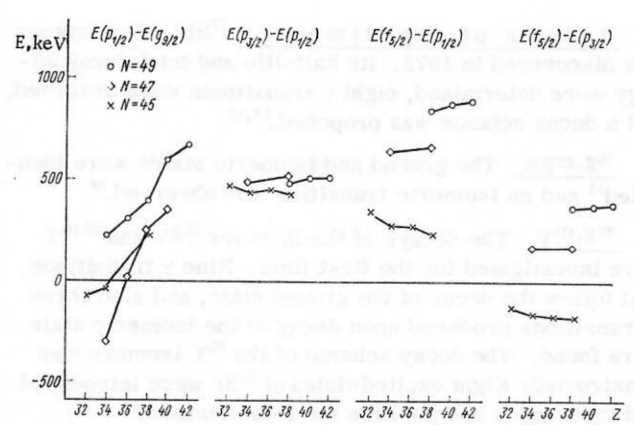

Fig. 11. Energy spacings of certain states of isotopes with N = 49, 47, and 45.

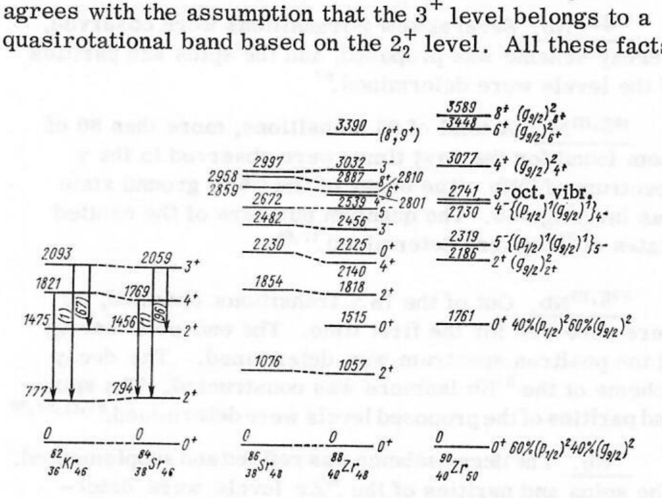

Fig. 12. Low-lying levels of certain even–even nuclei.

allow us to draw the general conclusion that the role of the collective effects increases when the number of neutrons decreases from the magic value N = 50 (or the subshell $g_{9/2}$).

Odd – odd nuclei. Investigation of the odd–odd nuclei is important from the point of view of study of the residual proton–neutron interaction, since most levels result here from the interaction of the odd proton with the odd neutron.

${}^{93}_{43}Tc_{49}$. Studies were made of the levels of this nucleus, which are excited upon decay of the isotope ^{92}Ru discovered by us. An analogy with the isotone ${}^{90}_{41}Nb_{49}$ has been revealed.

${}^{86}_{39}Y_{47}$, ${}^{84}_{39}Y_{45}$. The ground level 4^- and the isomeric level of the ^{86}Y nucleus result from the interaction of the $g_{9/2}$ neutron with a proton located on the $p_{1/2}$ and $g_{9/2}$ orbits respectively. The ground and isomeric states of the neighboring odd isotopes ${}^{85}_{39}Y_{46}$ and ${}^{87}_{38}Y_{48}$ are likewise decided by the position of the proton in the orbits $p_{1/2}$ and $g_{9/2}$, respectively. This sequence seems to be violated in the nucleus ${}^{83}_{39}Y_{44}$ (see Fig. 9). In addition, the ground states of the nuclei with N = 45 and with even Z have $I^\pi = 7/2^+$. Thus, in accordance with the Brennan–Bernstein rules as generalized by L. K. Peker, one should expect a value $I^\pi = 7^+$ for ${}^{84}_{39}Y_{45}$. This agrees with the fact that the 6^+ level (2808 keV) in ^{84}Sr is populated in the decay of ^{84}Y.

The magic character of Z = 40. It is very important to ascertain whether a certain number of neutrons or protons is magic. In this case the higher orbits are separated by a large energy gap. Consequently, the wave functions are relatively pure and the admixtures of the higher orbits can be neglected in the first approximation. These nuclei, together with the neighboring ones that differ by one nucleon, lend themselves readily to a theoretical analysis. It is of interest to consider the magic character of the number 40, i.e., the number of particles when all the subshells, including $2p_{1/2}$, are filled.

We shall analyze one of the several attributes of a magic number, namely the position of the 2_1^+ level in even–even nuclei. It is known that in magic nuclei the 2_1^+ level lies much higher than that of the neighboring nuclei.

It follows from the described systematics (Fig. 13) that N = 40 is not magic. As to Z = 40, it is patently magic

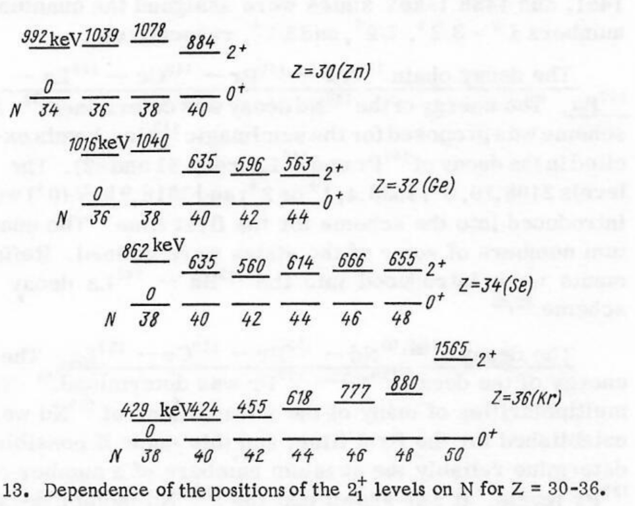

Fig. 13. Dependence of the positions of the 2_1^+ levels on N for Z = 30-36.

for N = 50 (${}^{90}_{40}Zr_{50}$) and also for N = 56 (${}^{96}_{40}Zr_{56}$), but not for other N (Fig. 14). In other words, its magic character is a function of N. It becomes magic when the neutrons completely fill the shell and even the subshell, but when the neutron shell (subshell) is incompletely filled, it is no longer magic. One can therefore expect Z = 40 to be magic also for N = 40 (${}^{80}_{40}Zr_{40}$).

Results of Investigations in the Region of Neutron-Deficient Isotopes with Z > 50, N ≤ 82

The investigation of the properties of nuclei close to magic with N = 82 is of special interest, first, from the point of view of observing in them levels of collective nature, and, second, from the point of view of experimentally verifying certain consequences of the "semimicroscopic" description of the properties of these nuclei, which can be carried out because their neutron system is closed.

The particular interest in the nuclei Ba, Cs, La, and Pr, which are strongly neutron-deficient, is the result of experiments that have discovered the existence of a "new" deformation region near Z ~ 56, N ~ 70. In the theoretical calculations of many groups, this circumstance was confirmed qualitatively, although the quantitative explanation of the properties of these nuclei is still unsatisfactory. We have therefore carried out experiments on the β decay of the short-lived nuclei Ba, Pr, and Nd in order to supplement the experimental material obtained mainly by the in-beam spectroscopy method with heavy-ion beams. Our investigations were carried out in three

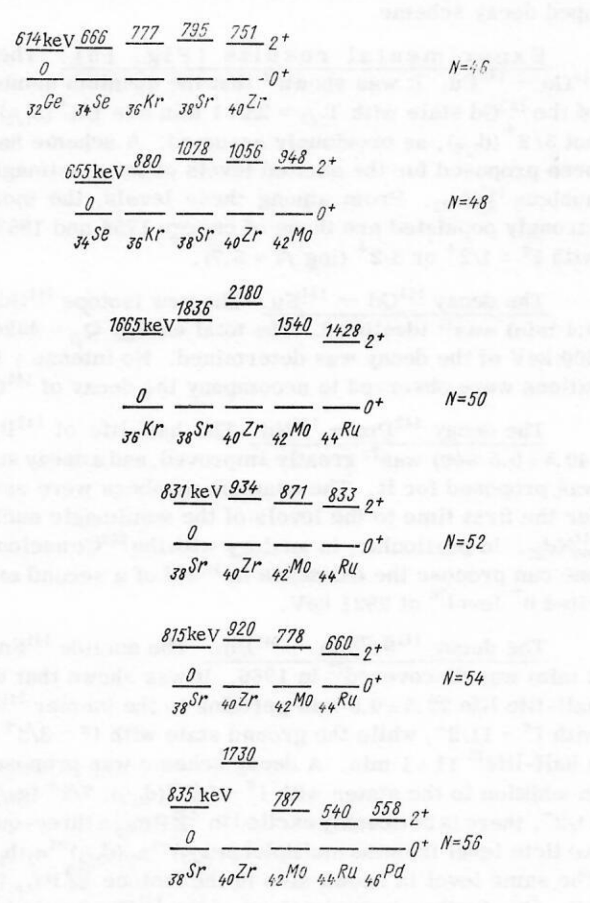

Fig. 14. Dependence of the positions of the 2_1^+ levels on Z for N = 46-56.

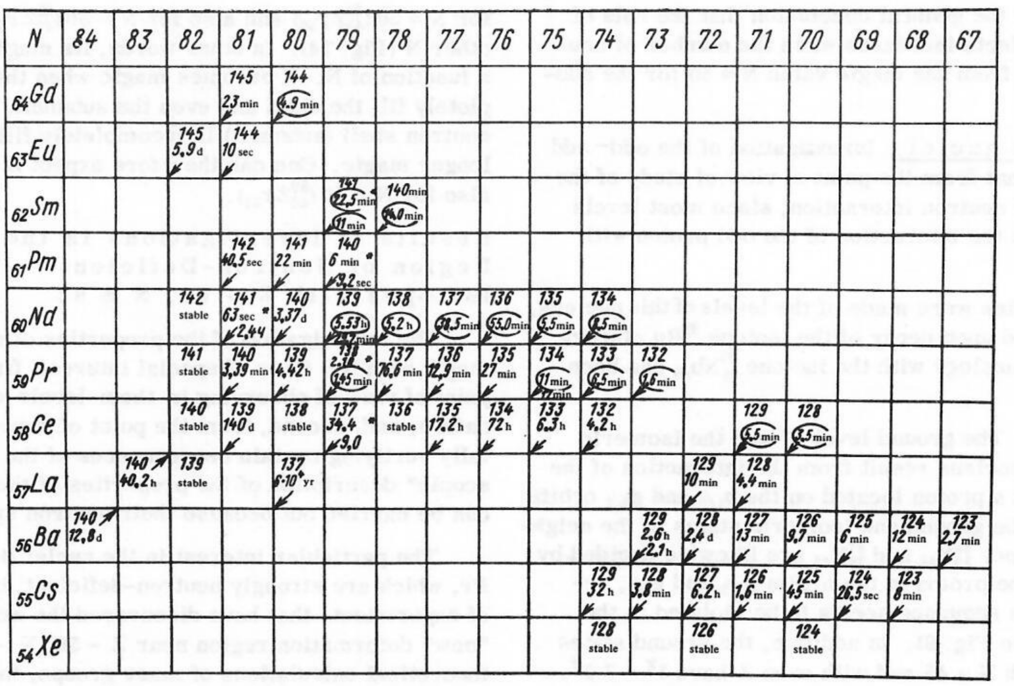

Fig. 15. Diagram of nuclides: Z = 54-64, N = 70-83.

stages: The first consisted of identifying new short-lived nuclides; the second was the measurement of their characteristics for the purpose of developing a preliminary decay scheme; the third was a detailed investigation of the structure of the excited states on the basis of the developed decay scheme.

Experimental results (Fig. 15). The decay $^{145}Gd \to {}^{145}Eu$. It was shown[74] that the quantum numbers of the ^{145}Gd state with $T_{1/2} = 23 \pm 1$ min are $1/2^+ (s_{1/2})$ and not $3/2^+ (d_{3/2})$, as previously assumed. A scheme has been proposed for the excited levels of the semimagic nucleus $^{145}_{63}Eu_{82}$. From among these levels, the most strongly populated are those of energy 1758 and 1881 keV with $I^\pi = 1/2^+$ or $3/2^+$ (log $ft = 5.7$).

The decay $^{144}Gd \to {}^{144}Eu$. The new isotope ^{144}Gd (4.9 ± 0.4 min) was[74] identified. The total energy $Q_\beta = 4320 \pm 400$ keV of the decay was determined. No intense γ transitions were observed to accompany the decay of ^{144}Gd.

The decay $^{142}Pm \to {}^{142}Nd$. The half-life of ^{142}Pm (40.5 ± 0.5 sec) was[75] greatly improved, and a decay scheme was proposed for it. The quantum numbers were assigned for the first time to the levels of the semimagic nucleus $^{142}_{60}Nd_{82}$. In particular, in analogy with the ^{140}Ce nucleus[81,82], one can propose the existence in ^{142}Nd of a second excited 0^+ level[76] at 2921 keV.

The decay $^{141g,m}Sm \to {}^{141}Pm$. The nuclide ^{141}Sm(21 ± 2 min) was discovered[77] in 1966. It was shown that the half-life life 22.5 ± 0.5 min pertains to the isomer ^{141m}Sm with $I^\pi = 11/2^-$, while the ground state with $I^\pi = 3/2^+$ has a half-life[75] 11 ± 1 min. A decay scheme was proposed. In addition to the states with $I^\pi = 5/2^+ (d_{5/2})$, $7/2^+ (g_{7/2})$, $11/2^-$, there is noticeably excited in $^{141}_{61}Pm_{80}$ a three-quasiparticle level from the multiplet $p(d_{5/2})^{-1} n_1 (d_{3/2})^{-1} n_2 (h_{11/2})^{-1}$ The same level is known also in the isotone $^{139}_{59}Pr_{80}$ (ref. 84). Our further investigations of the ^{141}Pm levels by the method of delayed coincidences and angular $\gamma\gamma$ correlations[78] have made it possible to analyze the nature of some of these levels. The 629 keV $(11/2^-)$ state was found to have an isomeric character. The properties of the 196.5-keV transition are typical of transitions of the $g_{7/2} \rightleftharpoons d_{5/2}$ type.

The decay $^{140}Sm \to {}^{140}Pm \to {}^{140}Nd$. The nuclide ^{140}Sm was discovered[77] in 1966. Its half-life, according to the latest data,[75] is 14.0 ± 0.5 min. It was shown that the decay of ^{140}Sm populates predominantly the ground state of ^{140}Pm with $I^\pi = 1^+$, $T_{1/2} = 9.2$ sec. Quantum numbers 8^- were assigned to the isomer ^{140}Pm with $T_{1/2} = 5.8$ min. The ^{140g}Pm decay energy was established to be $Q_\beta = 5900 \pm 400$ keV.

The decay $^{141g,m}Nd \to {}^{141}Pr$ was comprehensively investigated in ref. 79. New levels 1434.7 and 1456.1 keV were introduced into the decay scheme. Combination of the multipolarities of a number of γ transitions has made it possible to determine the quantum numbers of the levels 1126.9, $3/2^+$; 1292.6, $5/2^+$; 1298.6 keV, $1/2^+$. The 1434.7, 1451, and 1456.1-keV states were assigned the quantum numbers $I^\pi = 3/2^+$, $7/2^+$, and $5/2^+$, respectively.

The decay chain $^{140}Nd \to {}^{140}Pr \to {}^{140}Ce \leftarrow {}^{140}La \leftarrow {}^{140}Ba$. The energy of the ^{140}Nd decay was determined.[80] A scheme was proposed for the semimagic $^{140}_{58}Ce_{82}$ levels excited in the decay of ^{140}Pr and ^{140}La (refs. 81 and 82). The levels 2108.10, 6^+; 2533.4, 1^+ or 2^+; and 3016.9 keV (0^+) were introduced into the scheme for the first time. The quantum numbers of some of the states were refined. Refinements were introduced into the $^{140}Ba \to {}^{140}La$ decay scheme.[82,83]

The decay $^{139g,m}Nd \to {}^{139}Pr \to {}^{139}Ce \to {}^{139}La$. The energy of the decay $^{139}Nd \to {}^{139}Pr$ was determined.[84] The multipolarities of many of the γ transitions of ^{139}Nd were established for the first time, and this made it possible to determine reliably the quantum numbers of a number of ^{139}Pr levels. It was shown that the ^{139m}Nd isomer decays via an M4 transition in only 14.7% of the cases, and in the remaining 85.3% it undergoes an $\varepsilon + \beta^+$ decay. The energy of the ^{139}Pr → ^{139}Ce decay was improved.[85] The intensities of the γ decay were established. This has made it possible to determine the intensity balance of the ^{139}Pr transitions with high accuracy and to draw conclusions concerning the quantum numbers of the ^{139}Ce levels. The energy of the ^{139}Ce → ^{139}La decay was refined.[85]

The decay chain ^{138}Nd → ^{138g,m}Pr → ^{138}Ce. The nuclides ^{138}Nd and ^{138}Pr ($T_{1/2}$ = 1.5 min) were discovered earlier.[86,87] A level scheme was proposed for the first time for the ^{138}Nd → ^{138}Pr decay.[88] It was shown that the decay of ^{138}Nd results in excitation of several levels with $I^\pi = 1^+$. The ^{138g,m}Pr decay schemes were supplemented with many new ^{138}Ce levels. Quantum numbers were assigned for the first time to a number of levels.[88,89]

The decay ^{137}Nd → ^{137}Pr → ^{137}Ce → ^{137}La. The nuclide ^{137}Nd was discovered in 1965 (ref. 90). Its half-life[91,92] is 38.5 ± 1.5 min. A level scheme was proposed for the first time for the ^{137}Nd → ^{137}Pr decay, and 37 new levels were introduced into it. The lifetimes of the states 75.4 ($T_{1/2}$ = 0.38 ± 0.03 nsec) and 306.4 keV (0.5 ± 0.2 nsec) were measured. The ^{137}Pr → ^{137}Ce decay scheme was greatly supplemented[93] and the multipolarities of a number of γ transitions were established. Ten previously unknown states were introduced into the level scheme of ^{137}Ce. The lifetime of the 160.3 keV state was measured ($T_{1/2}$ = 0.79 ± 0.14 nsec). It was shown that in the decay of ^{137}Ce (Q_β = 1455 ± 30 keV, $I^\pi = 11/2^-$) the β transition to the $11/2^-$, 1004-keV level of ^{137}La is strongly suppressed[94] (log ft = 7.3).

The decay chains ^{136}Nd → ^{136}Pr → ^{136}Ce. The nuclide ^{136}Nd ($T_{1/2}$ = 55 min) was discovered by us in[104] 1969. Subsequent investigations of the γ rays, internal-conversion electrons, and positron decay have established its decay scheme.[96] Just as in the case of ^{138}Nd, a number of levels with $I^\pi = 1^+$ are excited in the decay of ^{136}Nd. It was established that the ^{136}Pr state with $T_{1/2}$ = 13 min has quantum numbers $I^\pi = 2^+$. It was shown that the isomer ^{136}Pr with $T_{1/2} \approx 1$ h (ref. 129), if it exists at all, is not excited in spallation reactions of Ta, Er, and Gd, nor in reactions induced by heavy ions. The level scheme of the ^{136}Pr → ^{136}Ce decay was supplemented with a number of new levels. In particular, the ground-state band 0 (0^+), 522 (2^+), 1313 (4^+), and the bands 1092 (2^+), 1553 kev (3^+) were introduced for the first time.

The decay chain ^{135}Nd → ^{135}Pr → ^{135}Ce. The nuclide ^{135}Nd was first identified radiochemically from the genetic connection of the isobars.[97] Investigations with mass-separated sources yielded $T_{1/2}$ = 15 min. More than 40 γ transitions were observed. Its decay scheme was constructed. From a comparison of the results obtained in refs. 98 and 99 one can conclude that the observed β decay comes from a ^{135}Nd state with $I^\pi = 9/2^-$. The decay ^{135}Pr → ^{135}Ce was investigated in detail. In particular, the lifetimes of some of the excited states were measured. A decay scheme was proposed.[100]

The decay chain ^{134}Nd → ^{134}Pr → ^{134}Ce. The nuclide ^{134}Nd ($T_{1/2}$ = 8.5 min) was discovered in ref. 97. The half-life value was confirmed in later measurements of mass-separated sources. Results of the measurement of the γ spectrum do not make it possible at present to construct the decay scheme. The ^{134m}Pr ($T_{1/2}$ = 11 min) and ^{134g}Pr ($T_{1/2}$ = 17 min) decays were investigated in ref. 101. A new isomeric state of ^{134m}Pr with $T_{1/2}$ = 11 min was identified. A level scheme of the γ decay was constructed on the basis of measurements of the γ spectra and the $\gamma\gamma$ coincidence spectra.

The decay ^{133}Pr → ^{133}Ce. The nuclide ^{133}Pr was discovered in ref. 97 and investigated in greater detail in ref. 102. The half-life is 6.5 min. A decay scheme was proposed.

The decay ^{132}Pr → ^{132}Ce. The nuclide ^{132}Pr was discovered recently.[103] Its half life is 1.6 min. No detailed investigations were carried out.

The decays of ^{129}Ce and ^{128}Ce. These nuclides were discovered in[104] 1969. Their half-lives are 3.5 and 5.5 min, respectively. The identification was by a radiochemical method on the basis of the genetic connection between the isobars. No detailed investigations have been carried out so far.

The decay ^{129}Ba → ^{129}Cs was investigated in order to supplement the systematics of the probabilities of transitions of the $5/2^+ \rightleftharpoons 1/2^+$ type in odd isotopes of Cs (Fig. 16). A measurement was made of the lifetime of the first excited state in the ^{129}Cs nucleus,[105] E_{1ev} = 6.545 keV, $T_{1/2}$ = 72 nsec.

The decay chains ^{127}Ba → ^{127}Cs; ^{125}Ba → ^{125}Cs; ^{123}Ba → ^{123}Cs. The decay schemes of the odd barium isotopes were studied as part of an investigation of the decay of isomeric states in the nuclei ^{127}Ba and ^{125}Ba, which were observed in ref. 121 and were interpreted by its authors as a state with negative deformation. In addition, systematic investigations were made of the probabilities of transitions of the type $5/2 \rightleftharpoons 1/2^+$ in odd Cs nuclei. The results of refs. 106-109 did not confirm the conclusions drawn in refs. 121 and 110 (see the discussion that follows).

The decay of the even isotopes ^{128,126,124}Ba. Investigations were made of the decay of these isotopes and of the isotopes of Cs and Xe with corresponding masses.[111,112]

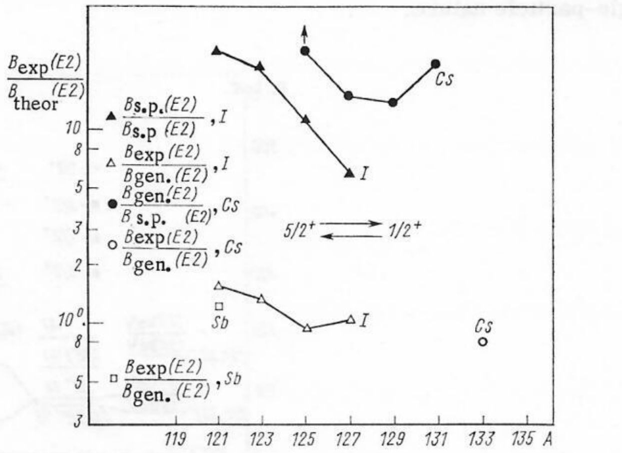

Fig. 16. Comparison of the reduced probabilities of E2 transitions of the type $5/2^+ \rightleftharpoons 1/2^+$ in odd nuclei of Sb, I, and Cs with single-particle estimates and with calculations based on the weak-coupling model.[113]

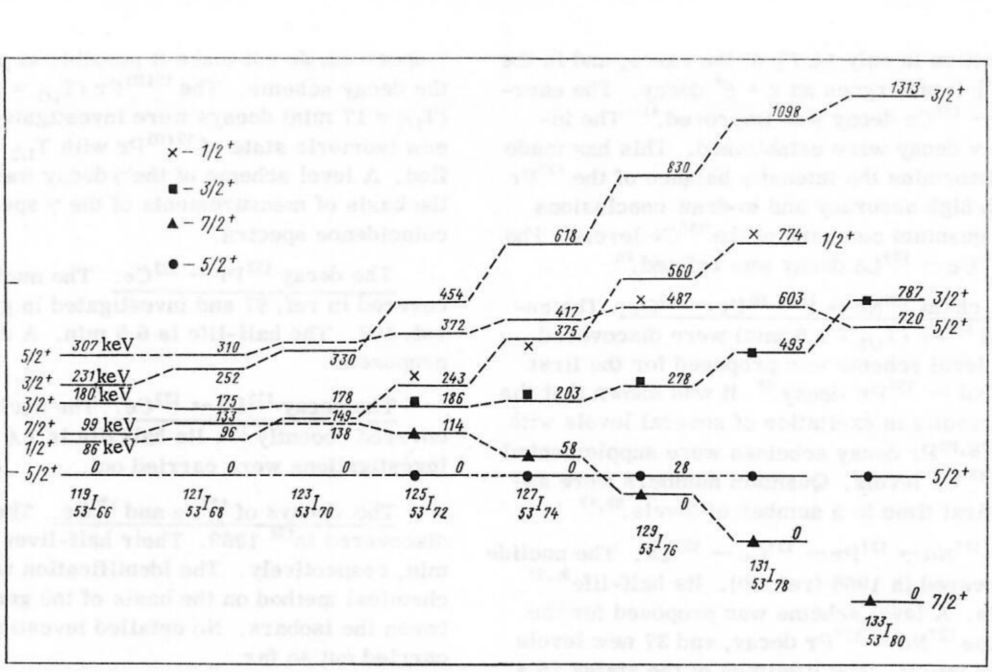

Fig. 17. Systematics of low-energy states in odd iodine nuclei (in addition to the experimental levels, the figure shows also those calculated from ref. 114).

The energy of the positron decay of ^{126}Ba and ^{128}Ba was measured and decay schemes were proposed for these barium isotopes.

General conclusions and discussion. Nuclei with odd A. The systematics of low-energy states of nuclei with Z = 51 to 59, $N_{even} \leq 82$, are shown in Figs. 17-20. Account was taken of both the experimental results obtained with the aid of the YaSNAPP setup and of the results of other investigations. An analysis of the properties of the nuclei in this region of Z and N leads to the following general conclusions:

1. Near the magic N = 82, the level density in the energy range $\lessdot$ 1 MeV is low; the observed quantum numbers of the levels ($I^\pi = 7/2^+, 5/2^+, 3/2^+, 1/2^+, 11/2^-$) correspond to the odd-proton states expected from the Mayer scheme for Z = 50 to 82. The observed large values of the spectroscopic factors in the nucleon transfer or pickup reactions and the reduced probabilities of the γ transitions between these states indicate that these levels have a single-particle nature.

2. With increasing distance from the magic number N = 82, a strong lowering of the levels with $I^\pi = 3/2^+, 1/2^+$, and $11/2^-$ is observed, particularly in the Pr, La, and Cs nuclei. In the isotopes $^{125-129}Cs$, $^{129,131}La$, and ^{135}Pr, the levels with $I^\pi = 1/2^+, 3/2^+$ are the ground states.

3. In certain Pr and Cs nuclei, and especially I nuclei, a second level with $I^\pi = 5/2^+$ appears systematically at an energy of several hundred keV.

4. Accelerated E2 transitions, e.g., between the levels with $I^\pi = 5/2^+ \rightleftharpoons 1/2^+$, are observed regularly in certain isotopes of Sb, I, and Cs (Fig. 16).

5. In I, La, and Pr isotopes there appear systematically, at 500-1000 keV, states with large values of the spin (e.g., $I^\pi = 9/2^+, 11/2^+$).

Even–even nuclei. There are several deviations from the predictions of the simple vibrational model. For example, in the decay of ^{136}Pr (2^+), the rate of β transition to the 1092-keV 2_2^+ level ($\log ft = 5.6$) is much larger than to the single-phonon 552 keV 2_1^+ level ($\log ft = 6.8$).

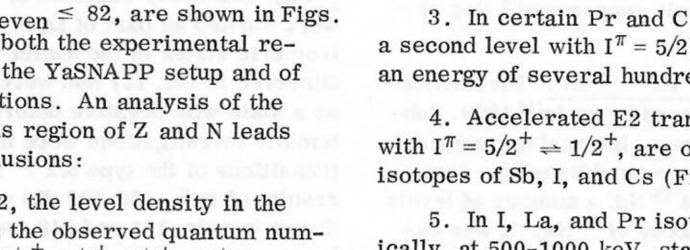

Fig. 18. Systematics of low-energy states in odd nuclei of Cs.

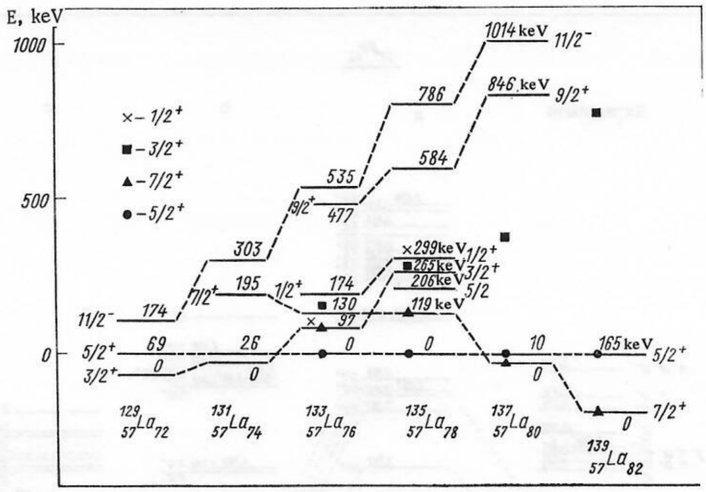

Fig. 19. Systematics of low-energy states in odd La nuclei.

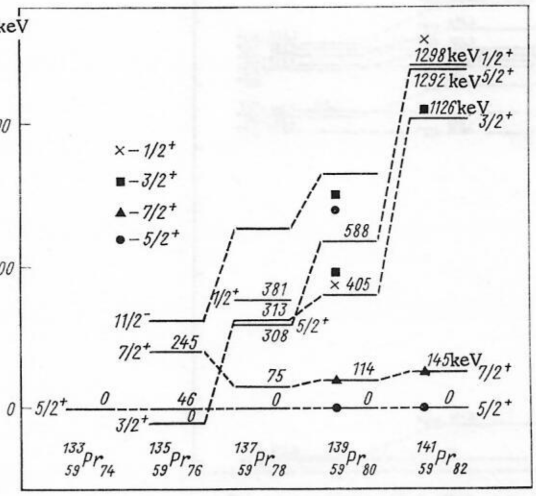

Fig. 20. Systematics of low-energy states in odd Pr nuclei.

Odd–odd nuclei. The level density in the range ≲ 1 MeV is quite high. Levels with $I^\pi = 1^+$ are encountered among them with anomalously high frequency.

At the present time there is no model describing all the characteristic properties of the nuclei in this region. For nuclei with an N = 82 closed shell, calculations were performed successfully within the framework of a model that takes into account the interaction of the particles above the "inert" core Z = 50, N = 82. Using the quasiparticle description, the authors of refs. 113 and 123-128 chose a residual interaction inthe form of a Gaussian,[113,125,137] of surface δ forces,[123,126,128] in the form of an Elliot potential,[124] etc. The obtained interaction matrices of the "active" (in excess of Z = 50) protons on the orbitals $g_{7/2}$, $d_{5/2}$, $d_{3/2}$, $s_{1/2}$, $h_{11/2}$ were diagonalized to obtain a set of single-and three-quasiparticle states for nuclei with odd A and two-quasiparticle state for even–even nuclei.

Figure 21 compares the experimental spectrum of the excited levels of ^{141}Pr (E_{exc} < 2.1 MeV) with those calculated in accordance with the models of refs. 113, 123, and 124. The agreement between the calculations and experiment is satisfactory when it comes to describing the energies, spins, and parities of the levels of ^{141}Pr. The radiation characteristics of the levels and their spectroscopic factors, obtained from photon transfer and pick-up reactions, are also adequately described.

A comparison of the spectrum of energy levels of ^{140}Ce, obtained experimentally in refs. 81 and 82 and in different nuclear reactions, with the calculated spectra[125-128] is shown in Fig. 22. Besides the energies and the level sequences, the models account adequately for the probability of the γ transition $4_1^+ \rightarrow 2_1^+$, for the magnetic moment of the 4_1^+ level, for the reduced matrix element of the $0^+ \rightarrow 0^+$ transition, etc.

It can be noted that the calculated characteristics of the semimagic nuclei are quite sensitive to the choice of the type of the residual interaction and to the choice of the energy eigenvalues of the single-quasiproton orbitals $g_{7/2}$, $d_{5/2}$, $d_{3/2}$, $s_{1/2}$, and $h_{11/2}$. A comprehensive study of the nuclei with N = 82 by various methods will undoubtedly yield abundant material with which to improve the model concepts.

It should be noted that the peculiarities listed in subsections 2-5 cannot be explained within the framework of the shell model, primarily because of the strong enhancement of the E2 transitions, which indicates that collective effects play a significant role in these nuclei. For example, the 306.4-keV level with $I^\pi = 5/2^+$ of ^{137}Pr relaxes to the ground state ($5/2^+$) and to the first excited level ($7/2^+$) via strongly enhanced (by 25 and 7 times, respectively) E2 transitions. An analysis of the probabilities of the M2 and E3 transitions that deexcite the $I^\pi = 11/2^-$ level in the isotones with N = 80 (Table 3) shows that the E3 transitions are also enhanced.

It is therefore understandable that some progress was made in the description of the nuclei in the considered region with the aid of a model representation that takes into account the connection between the single-particle states of the nuclei with collective excitation of the even–even core.[114-116] The Hamiltonian of this model consists of three parts $H = H_c + H_p + H_{int}$, which take into account the collective excitation of the core H_c, the excitation of the individual nucleons H_p, and the interaction between them H_{int}. Three parameters are used in the calculations: The parameter ξ serves to obtain the correct sequence of the levels and the connection between the col-

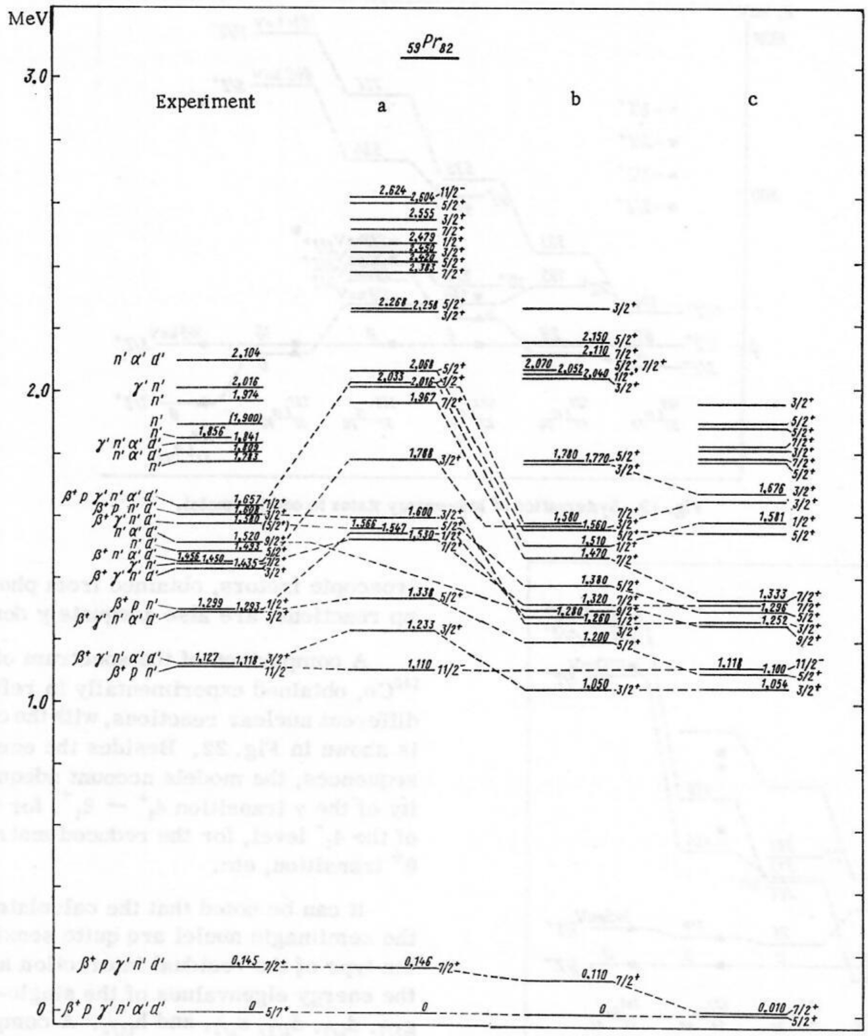

Fig. 21. Comparison of the ^{141}Pr excitation expectrum observed in different reactions and in β^+ decay with the theoretical calculations:[113,123,124] Each level is labeled by the method of its excitation: β^+) decay of ^{141}Nd; d', α', n', and γ') inelastic scattering of deuterons, α particles, neutrons, and γ rays, respectively; proton pickup and transfer reactions. a) The calculations of Waroquier and Heyde;[113] b) calculations of Widenthal;[123] c) calculations of Freed et al.;[124] the residual interaction was chosen in the form of a Gaussian, surface δ forces, and Elliot potential, respectively.

lective and single-particle excitations; the parameter $\hbar\omega$ characterizes the excitation of the core and is usually taken from the neighboring even–even nucleus, and the parameter E_i is the energy of the single-particle states.

Figures 17-20 compare the calculations based on such a model[114] with the experimental data. We see that the energy of the first states with $I^\pi = 5/2^+$, $7/2^+$, $1/2^+$, $3/2^+$ and certain other peculiarities of the nuclei considered (see subsections 2, 4, 5) can be well accounted for.

Certain difficulties are also encountered. The second level with $I^\pi = 5/2^+$, which appears regularly (subsection 3), is not encountered in the calculations at all. It is possible that this state is due to the loss of coupling between two $g_{7/2}$ protons of the core, which leads to the appearance of states with $I^\pi = 5/2^+ (= J - 1)$ at low excitation energies.[114] Another limitation of the model is the weak coupling between the single-particle excitation and the collective motion of the core, and this casts doubts

TABLE 3. Analysis of the Probabilities of M2 and E3 Transitions that Deexcite the $I^\pi = 11/2^-$ Levels in the Isotones ^{137}La, ^{139}Pr, and ^{141}Pm (N = 80)

Nucleus	$^{137}_{57}La_{80}$		$^{139}_{59}Pr_{60}$		$^{141}_{61}Pm_{80}$	
E_{lev}, keV	1004		822		628	
$T_{1/2}$, sec	$(4.1\pm0,7)\cdot10^{-10}$		$(3.68\pm0.20)\cdot10^{-8}$		$(2.18\pm0.09)\cdot10^{-7}$	
E_γ, keV	994	1004	708	822	432	628
$I_i^\pi \to I_f^\pi$	$11/2^-$—$5/2^+$	$11/2^-$—$7/2^+$	$11/2^-$—$7/2^+$	$11/2^-$—$5/2^+$	$11/2^-$—$7/2^+$	$11/2^-$—$5/2^+$
σL	$E3$	$M2$	$M2$ | $E3$	$E3$	$M2$	$E3$
δ^2	∞	0	$0.005\pm0,005$	∞	0	∞
$\frac{T_{1/2}\text{ s. p.}}{T_{1/2}\text{ exp}}$	$\geqslant 7.82$	$\geqslant 0.112$	$(2,66\pm0.45)\cdot10^{-2}$ | $\leqslant 22$	4.2 ± 0.9	$(5.2\pm1.6)\cdot10^{-2}$	$5.8\pm1,8$

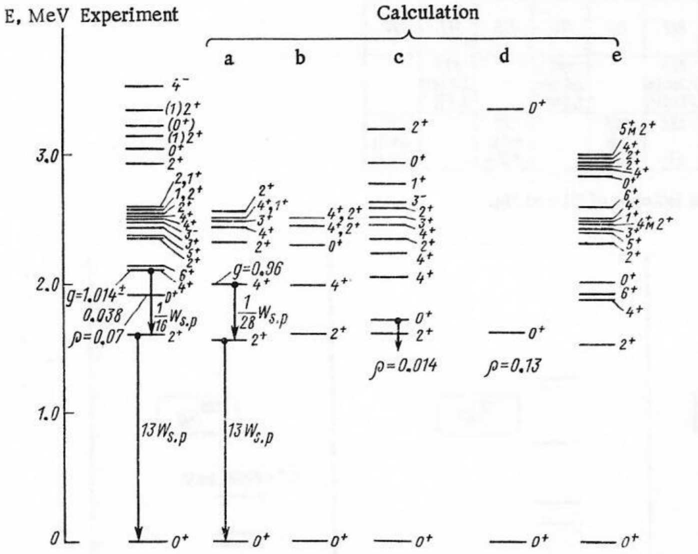

Fig. 22. Comparison of the experimentally known spectrum of the excited levels of ^{140}Ce with the spectra calculated in accordance with the models given in ref. 125-128: a) calculations of Rho;[125] b) Plastino et al.;[126] c) Lombard;[127] d) Bes, performed within the framework of the pair-vibration model; e) Wildenthal;[128] the residual interaction is chosen in the form of the Gaussian[125,127] and surface δ forces,[126,128] respectively.

on the applicability of this model when the "new" deformation region (the strongly neutron-deficient isotopes of Cs, La, and Pr) is approached. For the lightest isotopes of these elements, a more adequate description is afforded by calculations based on the model representations of deformed nuclei.[117-120] A characteristic result of the calculations for strongly neutron-deficient nuclei in this region consists in the appearance of states with negative as well as positive values of the deformation parameter. A hypothesis was therefore advanced that shape isomerism exists in this region of nuclei.[119] Experiments on β decay of short-lived barium isotopes, however, have revealed no indications of this phenomenon. In particular, our experiments did not confirm the presence in the light nuclei ^{125,127}Ba of the isomeric states observed in ref. 121. They were interpreted on the basis of the existence, among the states with positive parity, of a state^{505} $9/2^-$ (the Nilsson state) that agrees with the calculation. Nor did our studies confirm the hypothesis of shape isomerism in the ^{127}Cs nucleus, which was advanced in ref. 110 in connection with the proposed hindrance of the γ transition with 65.9-keV energy.

The experimental energies of the states of the light odd Cs isotopes are compared with the calculated Nilsson energies[107] in Fig. 23. It is interesting that the low-en-

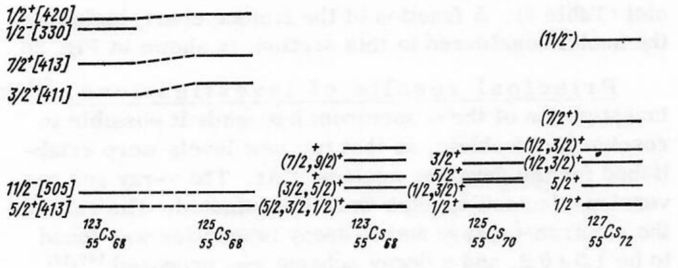

Fig. 23. Comparison of the energies of the calculated levels in odd Cs nuclei[177] with the experimental values.

ergy state with $I^\pi = 1/2^+$ is not accounted for by the calculations. It is possible that the isomeric state observed in the ^{127}Cs nucleus[110] is connected with[105] the $11/2^-$ level. It should be noted that some of the characteristic properties of the nuclei with Z ~ 51-63 are predicted by the calculations of Kisslinger and Sorensen[122] on the basis of the pair and quadrupole interactions. The lowering of the energies of the states with $I^\pi = 1/2^+$ and $3/2^+$ in the Cs, La, and Pr nuclei and the strong enhancement of the E2 transition $5/2^+ \rightleftharpoons 1/2^+$ are predicted correctly. Within the framework of the Kisslinger and Sorensen model, this is due to the phonon character of these states.

Neutron-Deficient Isotopes of Tl

Nuclear-spectroscopy investigations of the neutron-deficient isotopes of Tl (Fig. 24) were among the first problems solved with the YaSNAPP-1 setup using electromagnetic mass separation of the isotopes. An ion source of the magnetron type[30] was used to separate the Tl isotopes in the mass separator.

Principal results of experiments. The investigations have led to observation of new isotopes and isomeric states of Tl (see Table 1 and Fig. 24).[24,25,130,131]

In the investigation of the emission spectra of the light isotopes of Tl, a total of approximately 250 γ transitions were observed, of which 220 were new. The multipolarities were determined approximately for one third of the γ transitions.

Odd isotopes. ^{197}Tl, ^{195}Tl, ^{193}Tl (refs. 130, 132-134). The measured half-lives agree with the previously known values.[129] Decay schemes were constructed. The intensity ratios of electron capture and positron decay were determined on the basis of the intensity ratios of the x-ray and annihilation radiations.

^{197}Tl and ^{195}Tl. The values of log ft were estimated for many levels in the decay of these isotopes. The known spins and parities of several low-lying levels, the transition multipolarities, and the values of log ft have made it possible to determine the spins and parities of many levels.

^{191}Tl and ^{189}Tl (refs. 130, 25). The half-lives of ^{191}Tl and ^{189}Tl were determined. From the investigations of the γ spectrum of ^{191}Hg it can be concluded that in the ^{191}Hg nucleus, besides the known $13/2^+$ state ($T_{1/2}$ = 51 min) there exists also another state, probably $3/2^-$, with $T_{1/2}$ = 49 ± 10 min.

The results obtained on the properties of the excited states of the odd Hg isotopes were compared with the calculations of Kisslinger and Sorensen[122] and Dzholos.[174] As seen from Fig. 25, the calculations describe correctly certain properties of the level system.

Even isotopes. ^{192}Tl and ^{190}Tl (refs. 131, 135). The half-lives of the ground (2^-) and isomeric (7^+) states of ^{192}Tl and ^{190}Tl were determined and their decay schemes were constructed. The proposed decay scheme of ^{192}Tl agrees well with the scheme in ref. 136.

^{188}Tl. By observation in the γ spectrum of the Tl isotopes of the transitions $4_1^+ \to 2_1^+$ and $2_1^+ \to 0_1^+$ between known levels of the ^{188}Ag nucleus, excited by heavy ions,[137] we identified a new isotope ^{188}Tl ($T_{1/2}$ = 1.6 ± 0.5 min).

N	107	108	109	110	111	112	113	114	115	116	117
$_{81}$Tl	188 1.6 min	189 1.4 min	190 3.2 min 3.5 min	191 5.2 min	192 11 min 11 min	193 2.1 min 21 min		195 3.6 sec 1.2 h		197 0.5 sec 2.8 h	
$_{80}$Hg		188 13.3 min	189 8.7 min 7.7 min	190 120 min	191 51 h 49 h	192 5 h	193 11 h 3.5 h		195 40 h 9.5 h		197 24 h 64 h

Fig. 24. Diagram of the isotopes of Tl and Hg.

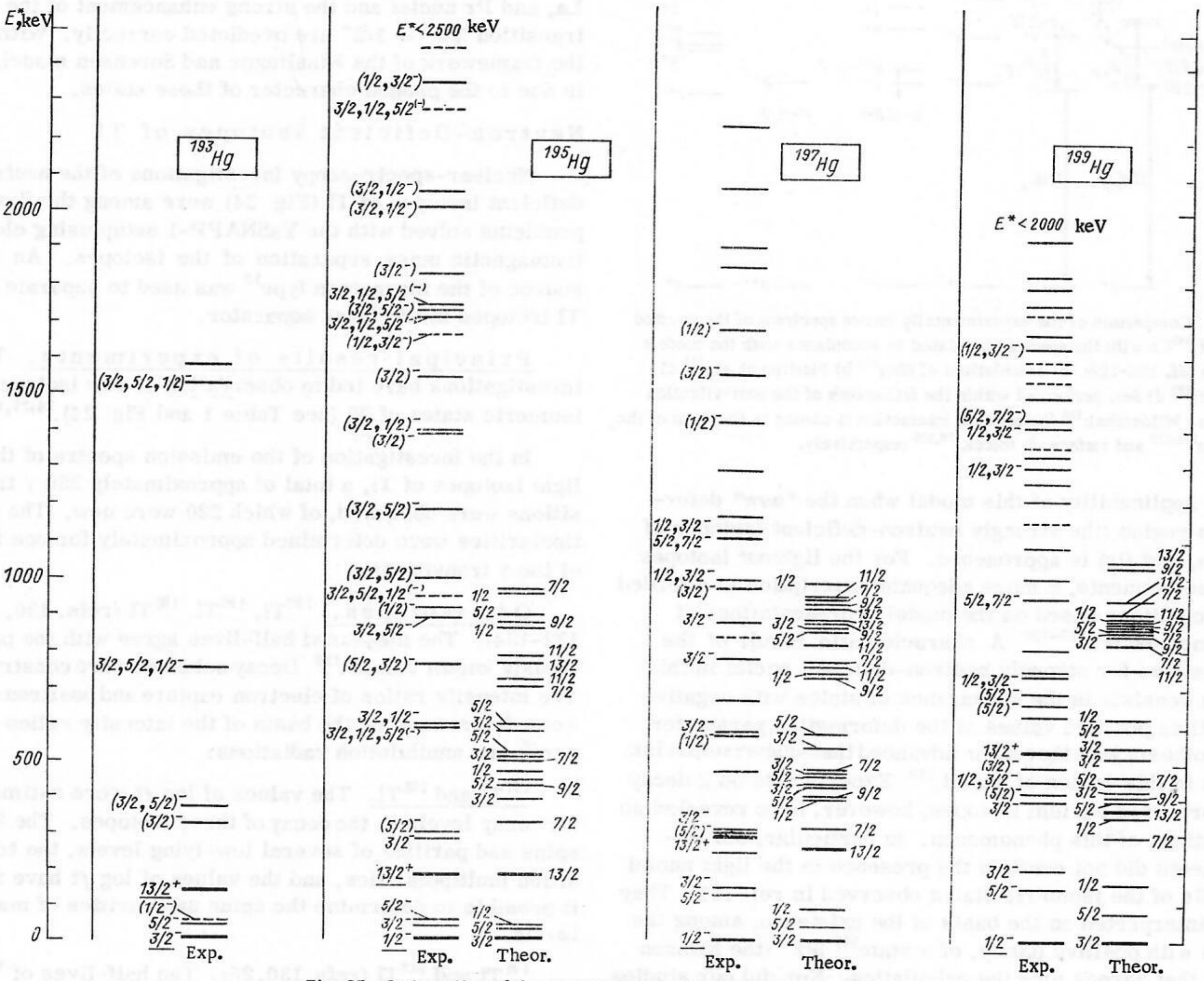

Fig. 25. Systematics of the energy levels of the odd isotopes of Hg.

A comparison of the experimental and theoretical results for even Hg isotopes shows that the anharmonic vibrational models of Covello and Sartoris[138] and of Alaga and Ialongo[139] describe correctly many experimental facts and serve as a firm basis for further research.

Investigation of the Decay of Nuclei in the Region Z = 84 to 87 and N ≤ 126

The experimental investigations of the emission spectra produced in radioactive decay of neutron-deficient isotopes of Po, At, Rn, and Fr were started in 1967. The radioactive isotopes of these elements were obtained by fission of thorium by 660-MeV protons from either the internal ($I_p = 2\ \mu A$) or the external ($I_p = 0.3\ \mu A$) beam of the JINR synchrocyclotron. The isotope mass separation was carried out for the relatively long-lived isotopes ($T_{1/2}$ = 20 min and longer) in the off-line regime.[34] The short-lived isotopes ($T_{1/2} \leq 20$ min) were investigated with the YaSNAPP-1 setup.

Investigations of the spectra of γ rays and internal-conversion electrons were carried out with the aid of instruments and apparatus described above, while the α particles were investigated with the aid of a large magnetic α spectrograph.[49] The high resolution (up to 2 keV) of this instrument with its low background and relatively large aperture (~ 0.05% of 4π) has made it possible to observe new α transitions to excited states of daughter nuclei (Table 4). A fraction of the isotope chart, including the nuclei considered in this section, is shown in Fig. 26.

Principal results of investigations. ^{212}Fr. Investigation of the α spectrum has made it possible to resolve two doublets, so that two new levels were established for the daughter nucleus ^{208}At. The γ-ray and conversion-electron spectra were investigated. The ratio of the electron-capture and α-decay intensities was found to be 1.3 ± 0.2, and a decay scheme was proposed.[140,141]

^{212}Rn is a β-stable isotope. Investigation of the α

TABLE 4. Results of Investigations of the α-particle Spectra from the Isotopes of At and Rn

Isotope, $T_{1/2}$, α, per cent per decay	$E_\alpha + \Delta E_\alpha$ keV	E of daughter-nucleus level, keV	$I_\alpha \pm \Delta I_\alpha$
^{208}At (1.8 ± 0.3) h $\sim 0.5\%$	5640 ± 3 5626 ± 3 5586 ± 3 5507 ± 3	0 15 56 136	100* 2.2 0.9 0.2
^{209}At $(5.3\pm0,3)$ h $(4.1\pm0,5)\%$	5647 ± 2	0	100*
^{210}At (7.9 ± 0.5) h $(0.18\pm0.02)\%$	5524 ± 1.5 5465 ± 1.5 5442 ± 1.5 5386 ± 1 5361 ± 1 5131 ± 2	0 59.9 82.9 140 167 398.3	100* 26 ± 2 95 ± 6* 14 ± 2 83 ± 6* $1.2\pm0,4$
^{211}At (7.1 ± 0.2) h $(41\pm1)\%$	5866 ± 2 5210 ± 1.5 5141 ± 2	0 669.5 742.5	100* $(1.3\pm0.2)\cdot10^{-2}$ $(4\pm2)\cdot10^{-3}$
^{206}Rn ~ 6 min	6260 ± 3 ~ 6600	0 ~ 680 (2+)	100* $<0,1$
^{207}Rn (10 ± 1) min $(23\pm7)\%$	6126 ± 3 6068 ± 3 5995 ± 4	0 59 133	100* (0.66 ± 0.02) 0.10 ± 0.03
^{208}Rn (23.5 ± 0.5) min $(67\pm3)\%$	6139 ± 3 5470 ± 4	0 682	100* $(4.7\pm0.4)\cdot10^{-3}$
^{209}Rn (28.5 ± 1.0) min $(17\pm2)\%$	6039 ± 3 5898 ± 3 5887 ± 3 5660 ± 3	0 144 155 386	100* (0.14 ± 0.02) (0.22 ± 0.02) $(2.4\pm0.2)\cdot10^{-2}$
^{210}Rn (2.4 ± 0.1) h $(96\pm1)\%$	6038 ± 3 5351 ± 3	0 700	100* $(5,6\pm0,3)\cdot10^{-2}$
^{211}Rn (15 ± 0.5) h $(26\pm1)\%$	5850 ± 2 5783 ± 2 5616 ± 3 5466 ± 3 5276 ± 3 5179 ± 3 5055 ± 4	0 68.3 238.5 391.4 585 684 812	100* 186 ± 3* 0.79 ± 0.07* $(4.1\pm0,3)\cdot10^{-2}$ $(4.4\pm0.3)\cdot10^{-2}$ $(7.6\pm0.7)\cdot10^{-3}$ $(1.8\pm0.6)\cdot10^{-3}$
^{212}Rn (22 ± 1) min 100%	6262 ± 3 5588 ± 3	0 687	100* $(5.0\pm0.5)\cdot10^{-2}$
^{212}Fr (20.6 ± 0.03) min $43\pm3)\%$	6405 ± 3 6383 ± 3 6342 ± 3 6335 ± 3 6262 ± 3 6183 ± 3 6173 ± 3 6127 ± 3 6076 ± 3 5983 ± 4	0 23.5 63.6 71.7 147.7 227 237 284 336 431	100* 107* 14 46* 170 5.9* 5.0 5,4* 1.9* 0.3*

Note: The asterisks mark groups of α particles known prior to the present investigations.

spectrum has revealed, for the first time, α decay to the 687-keV 2^+ level of ^{208}Po, with intensity $5\cdot10^{-4}$ per decay of ^{212}Rn (ref. 142).

$\underline{^{211}\text{Rn.}}$ In addition to the three previously known groups,[129] we observed four new groups with intensity from 10^{-5} to 10^{-6} per decay of ^{211}Rn. This has established in the ^{207}Po nucleus four new levels:[142] 391.4, 585, 684, and 812 keV.

$\underline{^{210}\text{Rn.}}$ In addition to the principal α transition, we observed for the first time an α decay to the 700-keV 2^+ level of ^{206}Po, with intensity $5\cdot10^{-4}$ per decay.[142] The spectra of the conversion electrons and γ rays were investigated and a scheme was proposed for the $^{210}\text{Rn}\to{}^{210}\text{At}$ decay.[143]

$\underline{^{209}\text{Rn.}}$ Investigation of the α decay has established the existence of 144-, 155-, and 386-keV levels in ^{205}Po (ref. 142). Thorough investigations of the conversion-electron and γ-ray spectra and of the coincidence spectra have made it possible to develop a detailed scheme for the decay $^{209}\text{Rn}\to{}^{209}\text{At}$ (refs. 144, 145).

$\underline{^{208}\text{Rn.}}$ Alpha decay to the 682-keV 2^+ level of ^{204}Po was observed for the first time.[142] The γ rays and conversion electrons were investigated, and the lower excited states of ^{208}At produced in the decay of ^{208}Rn were introduced.[146,147]

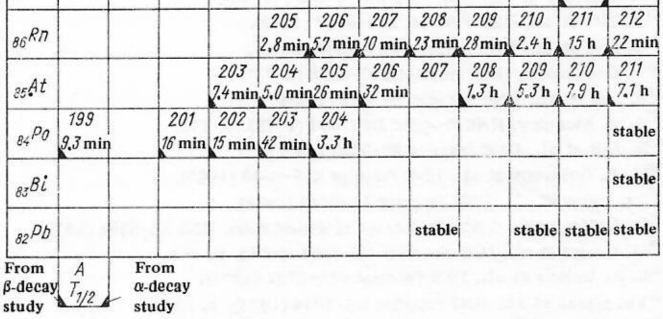

Fig. 26. Diagram of investigated isotopes of Po, At, Rn, and Fr.

$\underline{^{207}\text{Rn.}}$ Alpha decay to excited levels of ^{203}Po with energies 59 and 133 keV was observed.[142] It was established that 14 levels are excited in the $^{207}\text{Rn}\to{}^{207}\text{At}$ decay, of which 11 are new.[148,149]

$\underline{^{206}\text{Rn.}}$ No fine-structure lines were observed in investigation of the α decay of ^{206}Rn. It was shown that the intensity of α decay to the 2^+ level of ^{202}Po with approximate energy 680 keV is less than 10^{-3} of the intensity of α decay to the ground state. The γ-ray spectra of ^{206}Rn were investigated for the first time. A fragment of the scheme of the $^{206}\text{Rn}\to{}^{206}\text{At}$ decay was proposed.[150]

$\underline{^{205}\text{Rn.}}$ The γ-ray spectrum produced in the decay of ^{205}Rn was studied. Excited states of ^{205}At with energies 264.9, 620.0, and 729.5 keV were introduced.[148]

$\underline{^{211}\text{At.}}$ For the first time, α decay was observed to the 670- and 743-keV levels of ^{207}Bi, which are known from investigations of β decay of ^{207}Po (ref. 151).

$\underline{^{210}\text{At.}}$ The high resolution of the spectrograph employed has made it possible to find three new fine-structure lines (see Table 4). Thus, α decay was observed to

TABLE 5. Exact Measurements of the Energies of the Principal α Groups of Isotopes of At and Po (refs. 151, 154, 156)

Isotope	$T_{1/2}$, min	E_α,keV	Isotope	$T_{1/2}$, min	E_α,keV
^{207}At	1.8 h	5759 ± 3	^{206}Po	8.83 days	5223 ± 1.5
^{206}At	29.5	5703 ± 2	^{204}Po	3.6 h	5377 ± 1.5
^{205}At	25.0	5903 ± 2	^{203}Po	29	5384 ± 3
^{204}At	7.9	5952 ± 2	^{202}Po	42	5588 ± 2
^{203}At	7.4	6087 ± 2	^{201}Po	15,5	5684 ± 2
^{209}Po	103 year	4883 ± 3	^{201m}Po	9,0	5787 ± 2
^{208}Po	2.93 year	5116 ± 2	^{199}Po	5,0	5952 ± 2
^{207}Po	5.7	5115 ± 2.5	^{199m}Po	4,1	6058 ± 3

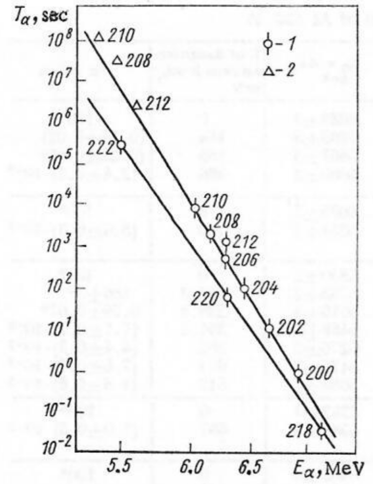

Fig. 27. Dependence of the partial α-decay periods of even–even Rn nuclei on the α-particle energy: energy scale $1/\sqrt{E_\alpha}$: 1) partial periods for ground-state α transition; 2) for transitions to first excited 2^+ levels of the daughter nuclei.

all the four lower levels of ^{206}Bi, which are known from ^{206}Po decay. Decay to the 140- and 398-keV levels was also observed.[151]

^{209}At. Alpha decay was observed to the 541-keV excited state of ^{205}Bi (ref. 151). A scheme for the decay γ was constructed [152] from the results of the study of the spectra of the γ rays, conversion electrons, and $\gamma\gamma$ coincidences.

^{208}At. The existence of 15-, 56-, and 136-keV levels in the daughter nucleus ^{204}Bi was established as a result of an investigation of the α-particle spectrum.[153]

Exact measurements of total α-decay energies of the short-lived isotopes $^{199-209}$Po and $^{203-208}$At were performed with the large magnetic α spectrograph (Table 5). The investigations of the α spectra of the isotopes of Rn and At have made it possible to establish reliably the existence of a number of excited levels in the daughter nuclei (see Table 4). The accurate data obtained on the energies and intensities of the α decay will undoubtedly be of importance for a comparison of these data with the new theoretical concepts of α decay, which are presently being developed, and also for the systematics of the experimental data concerning this decay. It is indicated in ref. 142 that the data obtained on the α decay of the even–even isotopes of Rn make it possible to draw certain conclusions concerning the dependence of the partial half-lives of the α decay of even–even Rn isotopes on the decay energy. It is seen from Fig. 27 that log T_α is proportional to $1/E_\alpha$ for all the even–even Rn isotopes, but the straight line for the isotopes with $N > 128$ neutrons has a slope different from that of the line for $N < 128$. The systematics include the known cases of α decay to excited 2^+ states of the daughter nuclei.

Since the spin and parity selections rules for α decay are not as rigorous as for β decay and γ radiation, investigations of α decay seldom make it possible to establish the spins and parities of the nuclear levels. These problems are best solved by investigating the β and γ spectra. We investigated most thoroughly the β decay of the chain ^{209}Rn → ^{209}At → ^{209}Po. Investigations of the β decay of the other nuclei considered above are continuing. The presently available data make it possible to conclude that modern shell models[155] explain the observed properties of the excited states of the nuclei up to excitation energies ~3.5 MeV.

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