PROTON DECAY OF RADIOACTIVE NUCLEI

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Experiments on proton decay of radioactive nuclei are described. Data for two proton emitters obtained by irradiating Ni with Ne^{20} and O^{16} beams are presented. The first (one of the lighter Ne or Mg isotopes) has a half-life $(85 \pm 15) \times 10^{-3}$ sec and emits 5 ± 0.2 MeV protons. The half-life of the second emitter is 23 ± 4 sec, it emits 2.5 ± 0.2 MeV protons. On the basis of a number of experiments it is concluded that the second emitter is a light Br or Kr isotope, that is, under-the-barrier protons are emitted in this case (the height of the Coulomb barrier is ~ 8.5 MeV).

The protons are most probably ejected from the daughter nucleus following the positron transition with which the measured half-life is connected. Emission of the 5-MeV protons resembles the emission of delayed neutrons. The mechanism of emission of the 2.5-MeV sub-barrier protons is similar to that of the long range α particles from heavy nuclei. The possibility of proton decay of configurational isomers, which may hold for the 2.5-MeV proton emitter, is also considered.

1. INTRODUCTION

THE possibility of a new type of radioactive transformation of nuclei—proton decay—was considered in the literature many times. More than 10 years ago Alvarez, Birge, et al. made the first attempt to detect proton emitters [1-5]. At the same time A. B. Migdal and B. T. Geĭlikman (Report, Joint Institute for Nuclear Research, BI-1542) and B. Dzhelepov [6] analyzed theoretically the possible mechanisms of proton decay and several ways for the synthesis of proton-active nuclei. It was clear that radioactive nuclei with sufficiently large proton excess will experience proton decay of one type or another. The calculations published later [7-11] dealt with refinements of the assumed characteristics of p-decay, a more detailed examination of the range of occurrence of the phenomenon, and ways of obtaining the corresponding isotopes.

The energetic feasibility of proton decay is a consequence of the decrease in the proton binding energy with decreasing number of neutrons in the nucleus. This change in the proton binding energy is due to the dependence of the nuclear interaction on the isotopic number and to the increased role of the Coulomb repulsion. Several mechanisms were considered for proton decay. First, nuclei with negative proton binding energy can become fused. Such nuclei are stable against proton emission from the ground state. In this case the picture of the p-decay will be analogous to decay from the ground state of nuclei. Second, a two-stage proton decay mechanism is possible: during the first stage we have positron decay with high energy, and during the second—emission of the proton from the excited state of the daughter nucleus (and in some cases also from the ground state). If the proton energy is lower than the Coulomb barrier, the proton will leave the nucleus by quantum-mechanical penetration through the barrier. The picture of the decay is similar in this case to the emission of long-range α particles. If the nucleus emits an over-the-barrier proton, then we can speak of an analogy with "delayed" neutrons.

It seems to us that a third proton decay mechanism—an isomer mechanism—is also possible (see Sec. 4).

It is quite probable that some isotopes of even Z with an excess of protons will experience radioactive decay of a different type—two-proton decay. The assumed existence of such a decay is a direct consequence of the effect of pair interaction of the nucleons in the nucleus. Zel'dovich [12] was the first to point out the possible instability of O^{12}, Ne^{16}, and Mg^{19} against the emission of two protons simultaneously. Gol'danskiĭ [9,13] presented a detailed analysis of the possibility of two-proton decay, and considered the main features of this phenomenon and ways of its observation.

Great advantages for the synthesis of isotopes with an excess of protons are afforded by nuclear reactions with heavy ions. A few years ago we started experiments on the radio-active products of reactions induced in nickel by accelerated Ne^{20} ions ($E \approx 130$ MeV). According to the calculation one could hope that these would include isotopes close to the limit of the nuclear p-instability. Special apparatus was used in the experiments, including a telescope made up of two proportional counters (to measure the energy and the per unit ionization). By registering the radioactive decay by means of this instrument, the type of radiation could be unambiguously established.

In the summer of 1962 we obtained results that made it possible to conclude that radioactive isotopes that experience proton decay are produced in the reaction Ni + Ne^{20}. The lifetimes of these proton emitters ranged between 0.1 sec and 5 min[14]. The presence of half-lives 0.5—1 sec and longer was established subsequently[15].

These results were soon confirmed and refined by us[16]. It turned out that the "long-lived" proton activity had a half-life ~ 25 sec and a proton energy 2.5—3 MeV. Measurements of the range and cross section for the production of this emitter indicated that it does not appear as a result of a compound nucleus in the Ni + Ne^{20} reaction, i.e., we have in this case an emitter of deep under-the-barrier protons. In addition, a proton activity with energy ~ 5 MeV and with half life ~ 0.1 sec was observed. It was established that this emitter had a mass close to that of Ne^{20}. In both cases the emission of the proton was probably preceded by β decay.

In 1963 a group of Canadian physicists reported observation of "delayed" proton radioactivity[17]. A beam of 97-MeV protons was used in the experiments. Simple recording apparatus was used, including only a surface-barrier detector for the measurement of the particle energy. The particles were identified by investigating their slowing down in aluminum. The high background level did not enable the Canadian physicists to operate at energies below 2.5 MeV, and at 3.5 MeV the background was approximately equal to the effect. Nonetheless they succeeded in identifying several proton emitters. The most detailed investigation was made on Si^{25} ($T_{1/2} = 0.3^{+0.2}_{-0.1}$ sec), and less detailed data are given for other proton emitters (Mg^{21}, Ne^{17}, O^{13}). It seems to us, however, that the authors of this work overestimate the accuracy with which the proton energies were determined; their decay schemes can more likely be regarded as tentative.

Searches for proton emitters in reactions with heavy protons are now being made at Yale University. In[26] is reported an observation of "delayed" 4.0—5.5 MeV protons, produced in the decay of Ne^{17} (half life ~ 0.7 sec). The same nucleus was investigated by Braid, Fink, and Friedman [ANL-6879 (1964)][1)] in experiments in which lithium beams were used.

The present paper is devoted to a more detailed exposition of the previously presented results[16]. In addition, it contains new data on the observed proton emitters.

2. EXPERIMENTAL PROCEDURE

The experiments were carried out on the internal beam of the heavy-ion cyclotron of the Joint Institute for Nuclear Research. In the development of the procedure we started from the need of having apparatus capable of recording protons with energy on the order of 1 MeV against a background of more intense (by a factor 10^6) β and γ radiation. The particle detector must satisfy also the following requirements: it should have spectrometric qualities, permit identification of the particle, and operate in a strong magnetic field and under a high level of electromagnetic noise. We present below a description of such a procedure.

Sampler. Figure 1 shows the diagram of the equipment placed between the dees of the cyclotron. The accelerated-ion beam 1 was incident on the target 2. The nuclei produced by the reactions were emitted from the target and were stopped by a collector 3 comprising a rotating aluminum-foil disc 8 cm in diameter. This collector transported the radioactive nuclei to the charged-particle spectrometer.

The spectrometer consisted of a proportional counter 6 (8 mm. thick) placed under two surface-barrier detectors made of high-resistance silicon 7. The use of such a "telescope" made it possible

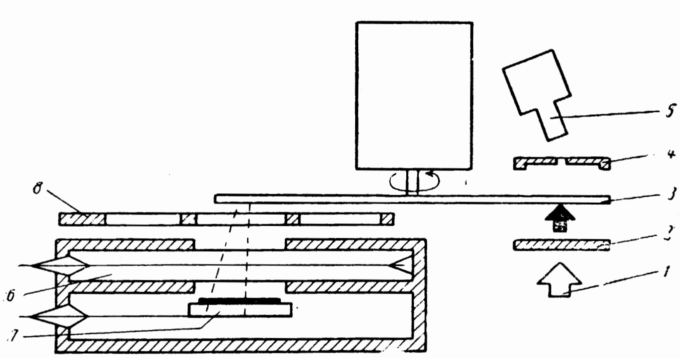

FIG. 1. Diagram of experimental apparatus.

[1)]The group of Canadian physicists obtained for the half life of Ne^{17} a different value — 103 milliseconds (private communication from Professor R. Bell, May 1964).

to measure the per-unit ionization and the particle energy simultaneously. Comparison of these quantities makes it possible to determine the type of the particle and to separate reliably the protons from the electrons and α particles. (In preparing for the experiments, we took precautions against the background due to the appearance of unknown α-active nuclei of medium atomic weight).

The entrance window of the telescope was sealed hermetically either with aluminum foil (8 microns) or with a "lavsan" film (5 μ) sputtered with a layer of copper ($\sim 200\ \mu g/cm^2$). The volume of the proportional counter was shielded against the semiconductor detectors by a lavsan film (3μ), also sputtered with copper. The counter was filled with a mixture of Ar(95%) + CH_4(5%) at a pressure of 200 mm Hg.

Under good geometry conditions, the proportional counter had outside the magnetic field a resolution $\sim 3\%$ for 5.5-MeV α particles, while the semiconductor detectors had a resolution 1—1.5%. However, to increase the efficiency, the entrance window of the telescope was made large (2×5 cm). Two silicon detectors were used simultaneously, with sensitive area 1.5—2 cm^2 each. This spread the registered particles over a large angle and worsened the resolution. In the case of the gas counter, an additional spread in amplitude was produced by the cyclotron magnetic field.

Figure 2 shows the spectra obtained for the calibration α particles under operating conditions.

The disc (10—20 revolutions per second) was rotated by an electric motor which made use of the cyclotron magnetic field. In many experiments a motor with a coil "polarized" in the cyclotron field was used. Continuous rotation of the collector was replaced by a rapid 180° reversal, produced by application of a current pulse of definite polarity. Under such conditions, the products of the reactions were gathered in a fixed section of the collector, and were then rapidly transported to the spectrometer for counting. The efficiency of registration was in this case several times higher than in the case of continuous rotation.

To measure the particle range, aluminum absorbers, secured to a remotely-controlled moving frame 8 (Fig. 1), were placed in front of the entrance window of the telescope. The same frame carried the α source. The ion collector 4, connected with the current meter, made it possible to follow the beam intensity during the time of irradiation. The ion energy was measured with a silicon detector 5, which received part of the beam, scattered by a gold foil, through a special collimator.

The apparatus shown in Fig. 1 was placed in a water-cooled copper jacket. The entrance window of the jacket was sealed with aluminum foil (8μ). The jacket was filled with helium (to 40 mm Hg) to cool the target, collector, and disc.

Electronic apparatus. The electronic apparatus employed was able to establish the type of decay, to effect a pulse-height analysis, and to measure the half life for the given energy group.

Figure 3 shows a block diagram of the apparatus. Pulses from the gas counter and the silicon detectors were amplified by cascode preamplifiers. Each preamplifier had one external tube, which was placed in the magnetic field in the immediate vicinity of the counter. The remainder of the circuit was outside the magnetic field. The external tube was a triode of rigid construction with an electrode geometry that ensured normal operation of the tube in a strong magnetic field.

The pulse from the gas counter was further am-

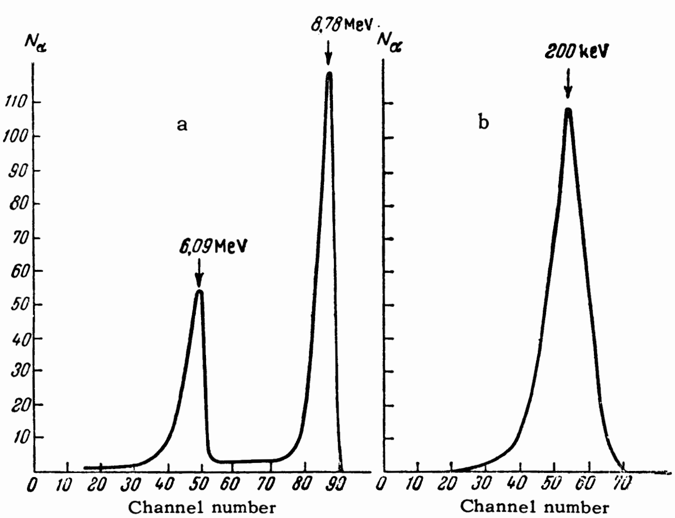

FIG. 2. Calibration curves obtained under working conditions: a – spectrum of α particle from ThC′, source placed on the disc; amount of matter between source and detector equivalent to 13μ of aluminum; b – pulse spectrum of gas counter for a 5.5-MeV α source located 3 cm from the entrance window.

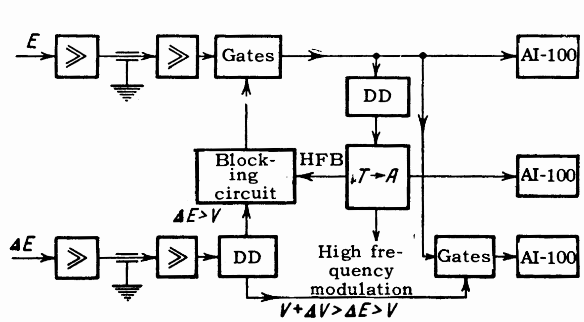

FIG. 3. Block diagram of electronic apparatus.

plified after passing through the preamplifier, shaped in duration (to 1.6×10^{-6} sec), and applied to the input of a discriminator. The pulse from the integral output of the discriminator was applied through a blocking circuit to a linear gating circuit, which received also an amplified and time-shaped (to 4×10^{-6} sec) pulse from the silicon detectors. The signal from the output of the gates was applied to two pulse-height analyzers, one of which was controlled by the differential output of the discriminator of the proportional counter. The two spectra of the pulses from the semiconductor counters were recorded simultaneously. The first spectrum included all the particles that passed through the gas counter and lost in it an energy greater than 13 keV. The second spectrum included only those particles for which the gas-counter pulse corresponded to an energy loss from 13 to 45 keV. This interval corresponds to protons with energy 1—5 MeV. The 5.5-MeV calibration α particles lost ~ 200 keV in the gas counter. It was established that only 1.5% of the total intensity of the calibration α particles were registered in the "proton range" of the per unit ionizations[2)]. Thus, the first spectrum yielded the complete picture of the energies of all the heavy particles produced by the radioactive decay, while the second spectrum included essentially the protons. Comparison of both spectra made it possible for us to separate the protons and to establish the intensity of the α radiation. The measurements were made in the intervals between the pulses that modulated the high frequency voltage on the dees (a blocking circuit was provided).

Figure 3 shows also the part of the circuit intended for the time analysis. The time analyzer consisted of a sawtooth voltage generator, a gating circuit, and an AI-100 pulse-height analyzer. The linearly increasing voltage was applied to the closed gate, which was opened for 4 microseconds by the analyzed signal that had passed through the differential discriminator. The magnitude of the pulse at the output of the gate was thus proportional to the time elapsed from the start of the triggering of the sawtooth to the instant of arrival of the pulse from the detector. The instant of triggering of the sawtooth voltage corresponded to the instant when the cyclotron was turned off; when the high-frequency voltage was turned on, the circuit was blocked. The voltage on the dees was modulated at a frequency chosen such as to make the "silence" time of the cyclotron several times larger than the measured half-life.

3. RESULTS OF EXPERIMENTS

In the investigation of the decay of radioactive products of the reactions, the emission of heavy singly-charged particles was unambiguously established. Simultaneous measurements of the energies of these particles, their per unit ionization, and their slowing down in the medium led to the conclusion that these were protons. The most clearly observed were two groups of protons with energies 5 and 2.5 MeV.

1. Group of protons with energy ~ 5.0 MeV.

a) Ne^{20} ions with energy 140 MeV were used to bombard a nickel target 10 μ thick. The collector used was aluminum 50 microns thick. This thickness is sufficient to absorb the reaction products with the longest ranges. The disc had openings through which a definite fraction of the beam passed on to the current collector. The thickness of the sensitive layer of the silicon detectors was $\sim 200\ \mu$. A 15-micron aluminum absorber was placed in front of the entrance window of the telescope. To determine the β and γ radiation background, experiments were made with an aluminum absorber 200 microns thick in front of the telescope. (In the experiments with the stopped discs, we determined also the background that could result from the presence of a residual ion beam in the cyclotron chamber during the intervals between the voltage pulses on the dees. There was practically no such background.)

b) Figure 4 shows one of the obtained spectra. In spite of the fact that the spectrum contained pulses due to particles with ionization losses greater than 13 KeV in the gas counter, the β and γ radiation background was sufficiently large up to channel 30. This is connected with the fact that the electrons have helical trajectories in the magnetic field and can lose a considerable fraction of their energy in the gas counter. In the region of channel 64, one can see clearly in the spectrum a maximum that belongs to protons with energy 5.0 ± 0.2 MeV.[3)]

The deduction that these particles are protons is based on the following.

It is seen from Table I that 92% of the particles of this group lose from 13 to 45 keV in the gas counter. The average energy loss, for protons

[2)]The entry of the α particles in the proton interval of per unit ionizations is connected with the fact that the spectrum of the gas-counter pulses has a "tail" in the region of small amplitudes, due to the influence of the magnetic field on the electron gathering.

[3)]In determining the proton energy, account was taken of the "knock-in" of the emitter in the collector and the energy lost by the protons prior to entering the silicon detector.

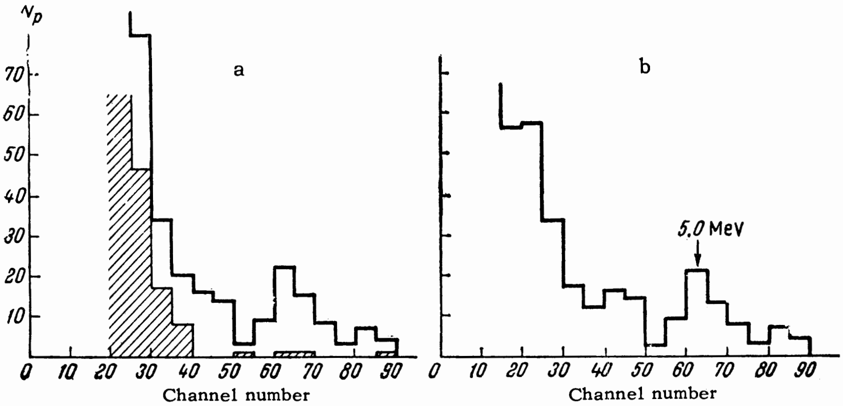

FIG. 4. a – Energy spectrum of protons for nickel bombarded with Ne^{20} ions. The spectrum of the β and γ background is shaded. (Disc – 50 μ of aluminum; sensitive layer of silicon detectors $\approx$ 200 μ); b – the same spectrum with the β and γ background subtracted. In determining the energy (5 MeV) of the proton group, account was taken of absorption in the material between the disc and the silicon detectors, and also absorption in the disc itself (due to knock-out of nuclei).

Table I. Intensity of two groups of protons for different values of the pulse ΔE from the gas counter.

Particles	I $\Delta E > 13$ keV	II 13 keV $< \Delta E < 45$ keV	II/I
Protons $E_p = 2.5$ MeV	302	279	0.92
Protons $E_p = 5.0$ MeV	1343	914	0.69
α-particles $E_\alpha = 5.5$ MeV	2648	40	0.015

Remark: the results were obtained for nickel bombarded with neon ions. The bottom line pertains to the calibration particles.

with E = 5 MeV, should be ~ 25 keV according to the estimate (with allowance for the geometrical factor).

Very instructive results were obtained in the experiments in which the slowing down of the particles in the medium was determined. One of the spectra on Fig. 5 was obtained in an experiment in which only the gas counter (equivalent to 20 μ of aluminum) was located between the semiconductor detectors and the disc. The other spectrum was obtained by placing a 30-micron aluminum absorber in front of the entrance window of the telescope. The shift of the peak corresponds to the calculated slowing down of 5-MeV protons. We note that the ~ 8.4-MeV α particles are completely absorbed in 50 μ of aluminum.

Figure 6 shows one of the decay curves of an emitter of 5-MeV protons. The half-life is 0.085 ± 0.015 sec. Apparently the spectrum contains also a less intense group of protons with energy near 5.6 MeV. Attention was focused subsequently on the group with 5 MeV energy. Several experiments were made in order to identify this proton emitter. The natural way chosen was to attempt to establish the type of the isotope-production reaction. Reactions between complex nuclei are divided into two classes. In the case of edgewise collisions of nuclei, nucleon transfer takes place and products that are close in mass to the bombarding particle are produced. Their ranges in aluminum amount to several tens of microns, and the yield depends relatively little on the type of

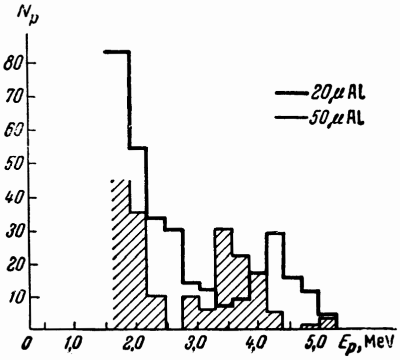

FIG. 5. Spectra of 5.0-MeV proton group, obtained in experiments with different absorbers between the disc and the detectors (20 and 50 μ of aluminum). The thickness of the absorber, with allowance for the average angle of entrance of the protons into the telescope (30°), is 23 and 58 μ of aluminum.

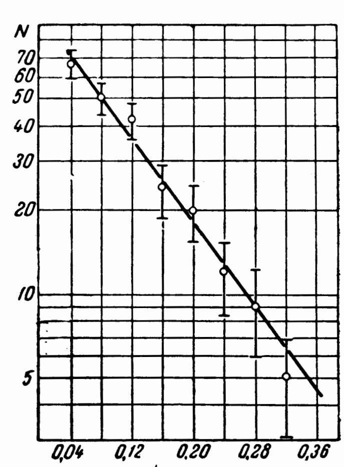

FIG. 6. Decay curve of emitter of 5.0-MeV protons.

target. The second class includes reactions which proceed via formation of a compound nucleus. The range of the products of such reactions is several microns.

In this connection, we estimated the range of the 5-MeV proton emitter. The range turned out to be appreciably larger than 9 microns of aluminum, for replacement of the 50 micron collector by an aluminum disc 9.3 μ thick decreased the effect by a factor 5—10.

Bombardment of targets made of tantalum, copper, and aluminum also led to registration of a proton activity of energy ~ 5 MeV. Its yield was 2, 3, and 5 times smaller, respectively, than from nickel. The cross section for the production of the investigated isotope in the reaction Ni + Ne^{20} amounts to several tenths of a microbarn for a neon-nucleus energy 120 MeV. One can state with assurance that this isotope is produced from Ne^{20} as a result of a nucleon-transfer reaction. Favoring this conclusion is the fact that this nucleus is produced by bombardments of targets with a large range of atomic numbers and has a large range. Both factors are typical characteristics of transfer reaction products [18]. An analysis of the properties of the possible products of such reactions leads to the most probable conclusion that ~ 5-MeV protons are emitted following decay of one of the light isotopes of neon or magnesium (Ne^{17}, Mg^{20-21}).

2. Group of protons with energy ~ 2.5 MeV.

a) A series of experiments was made to investigate the decay of the products of reactions with small ranges. In these experiments, a target of nickel 2 μ thick was used, and the aluminum disc was 9.3 μ thick. The very first experiments have shown that the emission spectrum contains no protons with energy larger than 3.5 MeV, and therefore the thickness of the sensitive layer of the silicon detectors was reduced to 80 μ. This greatly reduced the β and γ background.

Figure 7 shows the pulse-height spectrum corresponding to particles losing 13—45 keV in the gas counter. This spectrum was obtained by summing the results of six independent measurements. Each of the six experiments was accompanied by a measurement of the background. Figure 7 shows the total background. A group with a maximum in channel 32 is clearly seen.

The results of experiments to determine the per unit ionization of the particles of this group and their slowing down in aluminum indicates that these are protons. Indeed, the energy lost by these particles in the gas counter was found to be 25—60 keV, which coincides with the calculated value for protons with energy 2.5—3 MeV. This is in accord with the data listed in Table I, from which it follows that 70% of the particles of the group leave an energy of 13—45 keV in the gas counter.

The experiments on the slowing down of the particles of interest to us are illustrated by Fig. 8, which shows the energy spectrum of these particles after passing through matter equivalent to 13 and 28 μ of aluminum. The shift in the peak on going

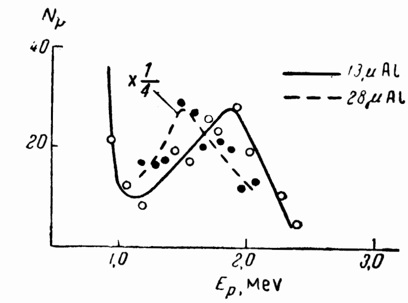

FIG. 8. Spectra of 2.5-MeV proton group. Thickness of absorber between the disc and the silicon detectors is equivalent to 13 and 28 μ of aluminum. When the average angle of entry of the protons into the telescope (30°) is taken into account, the absorber thicknesses are 15 and 32.5 μ of aluminum.

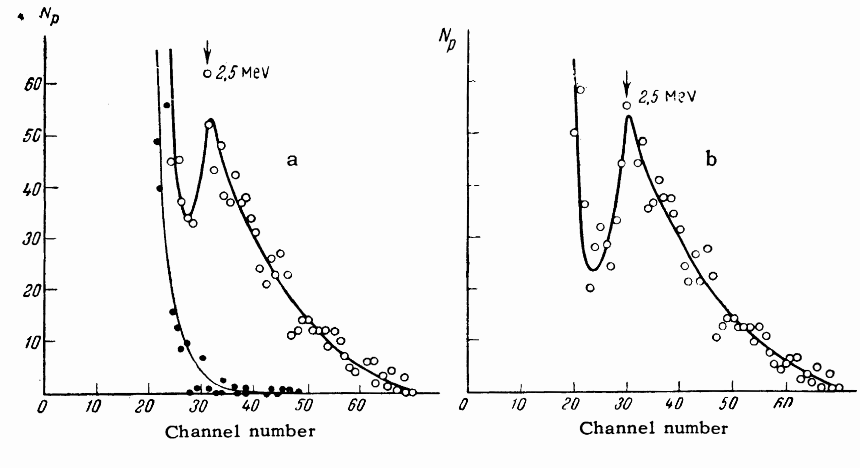

FIG. 7. a – Energy spectrum of protons from nickel bombarded with Ne^{20} ions. The spectrum of the β and γ background is indicated by black dots. b – The same spectrum with the β and γ background subtracted. The energy of the proton group (2.5-MeV) was determined with allowance for absorption.

over from one absorber to the other is in accordance with what is expected for protons.

The maximum in the spectrum of Fig. 7 corresponds to an energy 2.5 ± 0.2 MeV (the error is due essentially to the inaccuracy in accounting for the slowing down of the protons prior to entering the telescope). The spectrum contains also protons of higher energy (up to 3.3 MeV). To the left of the maximum there is still another group of protons, but this section of the spectrum has not yet been investigated because of the large background.

A time-amplitude converter was used to measure the half-life of the proton group with maximum at 2.5 MeV. One of the decay curves is given in Fig. 9. The half-life of the emitter is 23 ± 4 sec.

b) Several experiments were made to identify the obtained isotope.

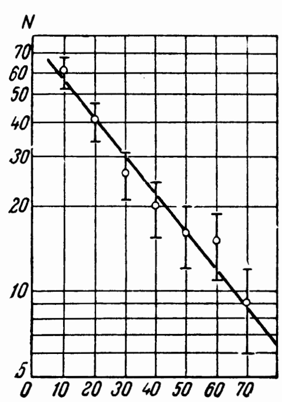

FIG. 9. Decay curve of 2.5-MeV proton emitter; reaction Ni + Ne^{20}.

To estimate the range of the nuclei, a nickel target (2 microns) was bombarded with Ne^{20} ions having an energy of 105 MeV; a 9.3 μ aluminum absorber was placed between the target and the rotating disc. The insertion of such an absorber practically eliminated the effect: the intensity of the investigated group dropped by not less than 20 times. This means that the range of the emitters of 2.5-MeV protons is less than 9 μ of aluminum.

We then bombarded Ni and Fe^{54} (target made of separated isotope, 1.6 mg/cm^2, on a substrate of aluminum 6 μ thick) with different ions. When Ni was bombarded with O^{16} ions (70—100 MeV), a group of protons with maximum near ~2.5 MeV was also observed. The curve showing the decrease of this activity with time is shown in Fig. 10. Within the limits of experimental error, the half life agrees with the 23 ± 4 sec value obtained in the analysis of the curve of Fig. 9. This gives

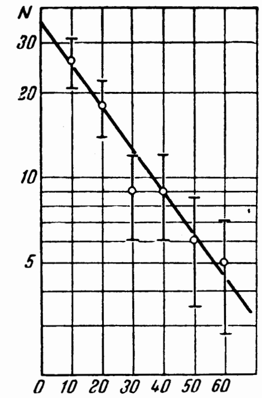

FIG. 10. Decay curve of 2.5-MeV proton emitter; reaction Ni + O^{16}.

grounds for assuming that the same proton emitter is produced in the reactions Ni + Ne^{20} and Ni + O^{16}.

No 2.5-MeV proton activity was observed when Ni (2 μ) was bombarded with B^{11} ions (65 MeV) and when Fe^{54} was bombarded by O^{16} ions. We show below the relative yield of the investigated group of protons in the various reactions:

	Ni+Ne^{20}	Ni+O^{16}	Ni + B^{11}	Fe^{54} + O^{16}
Relative yield of emitter with E_p = 2.5 MeV and $T_{1/2} \approx 23$ sec:	100	~30	<3	<1

The absolute cross sections for the production of the proton emitter in the reaction Ni + Ne^{20} is of the order of 1 microbarn. It depends little on the energy in the 100—140 MeV region [16].

The small value of the range of the proton emitter indicates that its mass number is equal to several times ten. This deduction does not depend on the assumptions concerning the mechanism of the reaction [19]. Such an isotope, which is supersaturated with protons, may be the result of the decay of an excited compound nucleus produced by coalescence of the target nucleus and the bombarding particle. We observed the effect following irradiation of nickel with Ne^{20} and O^{16} ions, but did not observe it for the reaction Fe^{54} + O^{16}. This result can be explained by assuming that the atomic number of the 23-second proton emitter is 35—36 (Br, Kr) but the mass is 70—72. This assumption is not contradicted by the excitation function for the formation of this nucleus in the Ni + Ne^{20} reaction [16]. One can raise the question whether this proton emitter is produced from nickel by a transfer reaction. Such a variant is possible, although it is less probable. Indeed, in this case one would expect the effect to be observed when nickel is bombarded with boron and Fe^{54} with oxygen.

4. DISCUSSION OF RESULTS

1. Table II shows the main characteristics of the observed proton emitters[4)], as well as the Coulomb barriers V_p for protons.

The last line of Table II contains τ_p—the calculated lifetime of a nucleus emitting a proton having the indicated energy (relative to the characteristic nuclear time τ_0). Only the Coulomb barrier is taken into account in the calculation, so that values of τ_p/τ_0 listed in the table should be regarded as lower limits. If the angular momentum carried away by the proton (l_p) differs from zero, then τ_p will be larger. This quantity increases by a factor of several times ten even when $l_p = 2$.

Table II

Isotope	(Br, Kr)$^{70-72}$	$Mg^{20,21}$, Ne^{17}
E_p, MeV	$2{,}5 \pm 0.2$	5.0 ± 0.2
$T_{1/2}$, sec	23 ± 4	$0.085 \pm 0{,}015$
V_p, MeV	8.5	4
τ_p/τ_0	$>10^4$	~ 1

It is clear that the observed delay in the appearance of the proton emission cannot be due to the Coulomb barrier. It is most likely that it is connected with positron decay. The nuclear reaction gives rise to an isotope that experiences positron decay with large energy. The daughter nucleus has low stability against the emission of a proton. Some excitation following the β^+ transition is sufficient to cause emission of a proton from the nucleus. In the case of the decay of the first isotope (Br, Kr) the proton leaves the confines of the nucleus, via the tunnel mechanism, at a level ~ 0.3 of the height of the Coulomb barrier. In this case the decay pattern is similar to the emission of long-range α particles by heavy nuclei. Protons with energy ~ 5 MeV pass over the barrier; in this case there is a complete analogy with "delayed" neutrons.

The described type of proton decay should be a rather prevalent phenomenon near the boundary of proton instability of the nuclei ($B_p = 0$), primarily for even elements. Naturally, for such a decay to exist the energy of the positron transition should exceed the proton binding energy. Moreover, the quantity E*—the excitation energy of the nucleus following the β^+ decay—should be such that the competition on the part of the radiation transition not be overwhelming. This is essentially the condition imposed on the energy of the emitted protons, $E_p = E^* - B_p$. According to our estimates, the competition on the part of the γ radiation will be insignificant when $E_p > E_{p0}$, with E_{p0} varying from ~ 0.7 to 2 MeV as Z varies from 20 to 50. Thus, for proton radiation to appear following β^+ decay, it is necessary to have $E - (E_{p0} + B_p) > 0$. The probability of the process will obviously increase with increase in this difference. Some estimates of this probability, in accordance with the statistical model, are given in[11]. The condition advanced by Gol'danskii[9], that a super-allowed β^+ transition should occur at the proton-unstable level, is completely unnecessary. The proton decay can be observable if it occurs after the ordinary β^+ transition and even if the super-allowed transition without p-decay competes with the β^+ transition. Everything is governed by the cross section for the production of the isotope and by the sensitivity of the apparatus. It must be stated that in none of the observed cases of emission of "delayed protons" is there a super-allowed β^+ transition to a proton-unstable level.

2. There is another possible mechanism of p-decay with large half-life, namely the isomer mechanism. It is known that in nuclear reactions with heavy ions, configuration isomers appear with a large probability. These nuclei are in a high-spin state produced as a result of the excitation of several nucleons. For a nucleus that is supersaturated with protons, such a state may turn out to be proton-unstable if $E^* > B_p$.

The high spin of the state leads to a suppression of the radiative transition, causing the nucleus to decay and emit a proton with energy $E_p = E^* - B_p$. On the other hand, the joint action of the Coulomb and centrifugal barriers gives rise to a large lifetime relative to proton decay. In the region of heavy nuclei, α-active configuration isomers with hindrance coefficients up to 10^{14} were observed[20-22]. Sliv and Kharitonov[23-24] attributes the appearance of high-spin isomer states to the influence of a residual np interaction. It is indicated in[24] that configuration isomers can appear in the region of nuclei with medium atomic weights.

The probability of proton decay of an isomer is approximately $W = \delta_l P_l$, where P_l—quantum mechanical penetrability of the barrier for the proton with angular momentum l, and δ_l—reduced probability of the process, which depends on the

4)Table II does not include the proton emitter with $T_{1/2} = 0.5 - 1$ sec, which we observed elsewhere[15]. It is produced from Ne^{20} as a result of transfer reactions. This emitter was not investigated here. It obviously makes a contribution to the spectrum of Fig. 4 in the region $E_p \sim 4.5$ MeV.

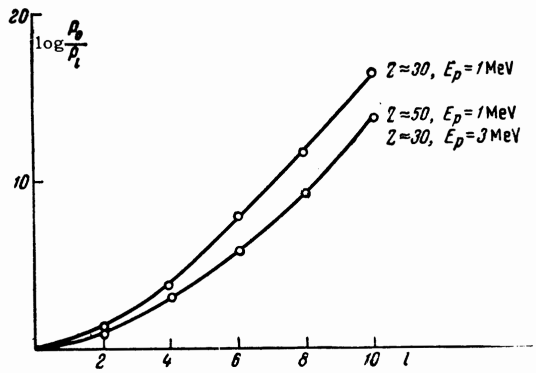

FIG. 11. Plot illustrating the effect of the centrifugal barrier on the proton emission probability, P_0/P_l – ratio of the barrier penetrabilities for protons with angular momenta zero and l.

structure of the state. Figure 11 shows the calculated hindrance coefficient of p-decay as a function of the angular momentum (we use the formula from[25]) for nuclei with Z = 30 and 50. The hindrance due to the structural factor calls for detailed calculations. For α-active isomers this hindrance component reaches 10^6.

One cannot exclude the possibility that the proton emitter which we observed, with half-life ~ 23 sec, is a proton-active isomer with spin 8–10 $\hbar$.

Further investigation of p-decay of radioactive nuclei is presently continuing in our laboratory. The purpose of these investigations is an experimental determination of the mechanism of the observed proton decay and a more exact identification of the obtained protons.

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