INVESTIGATION OF SOME RADIOACTIVE NUCLEI IN THE REGION OF THE FILLED $1f_{7/2}$ SHELL

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Radiation from the radioactive nuclei Ni^{65}, Co^{55}, Mn^{51}, V^{47}, and Se^{83} is investigated with a thin-lens magnetic β-spectrometer and with a scintillation γ-spectrometer. Coincidence spectra between β^- particles and γ-quanta with energies 1490 and 1120 keV are obtained for Ni^{65}. The separated partial β-spectra possess end-point energies at 620 and 1020 keV respectively. The Co^{55} β^+ transition with an end point energy of 1500 keV is to an excited level, with subsequent emission of 940-keV γ-rays. In addition, β^+(1040 keV)—γ(1410 keV) coincidences were observed for Co^{55}. The Mn^{51} β spectrum consists of two components with end-point energies 600 and 2170 keV. Weak γ transitions with energies 1560 and 2030 keV were observed. The V^{47} β^+ spectrum is simple with an end-point energy 1890 keV, and 1800- and 2160-keV γ quanta are detected in V^{47}. Besides the previously known components, a hard 3300-keV component with an intensity of the order of 2% is separated from the Se^{83} β^- spectrum.

Gamma transitions with energies 220, 355, 1850, and 2300 keV are observed in Se^{83}. The 530-, 780-, 1060-, and 1300-keV γ transitions heretofore ascribed to Se^{83} should be assigned to Br^{82}. Some of the low lying excited states of odd nuclei containing 29 (or 27) protons or neutrons are classified.

THE excited states of atomic nuclei have not yet been investigated in sufficient detail, in spite of the large number of different already-discovered characteristics of atomic nuclei. Of great interest in this connection is a systematic investigation of certain groups of nuclei having distinct features, for this greatly facilitates the interpretation of the results.

Thus, for example, in the case of odd nuclei we can single out a group with the following features. It follows from the general premises of the shell model that the $1f_{7/2}$ level, filled with 28 protons or neutrons, is shifted by the strong spin-orbit interaction and is isolated from the neighboring levels. We can consequently expect a relatively simple interpretation of the experimental data for the odd nuclei which have one "hole" in the $1f_{7/2}$ shell or one particle in excess of the filled shell. [1]

The present paper is devoted to β and γ spectrometric investigations of the radioactive isotopes Ni^{65}, Co^{55}, Mn^{51}, V^{47}, and Se^{83}. Study of the radiation from these radioactive isotopes entails an additional difficulty because of the short half-life (minutes or hours), particularly in the investigation of the β spectra of coincidences between β particles and γ quanta of selected energy.

A study of the radioactive isotopes Ni^{65}, Co^{55}, and Mn^{51} is of interest because their daughter nuclei are odd, containing 29 (or 27) protons or neutrons.

The radioactive sources were obtained by bombarding enriched-isotope targets with protons or deuterons in the 120-cm polepiece cyclotron of the Nuclear Physics Research Institute of the Moscow State University.

The β spectra were investigated with a thin-lens magnetic β spectrometer. The β sources were prepared by depositing radioactive powder on an aluminum substrate 0.27 mg/cm^2 thick. The thickness of the β sources was determined by weighing, and amounted to approximately 1 mg/cm^2 in all cases.

The magnetic β spectrometer could be connected to a coincidence circuit with single-channel scintillation γ spectrometer for the measurement of $\beta\gamma$ correlations. This made possible the separation of the partial β spectra correlated with γ quanta of definite energy. The resolution time of the coincidence circuit was periodically determined during the course of the measurement and found to be 0.25 μsec. A block diagram of the setup is shown in Fig. 1.

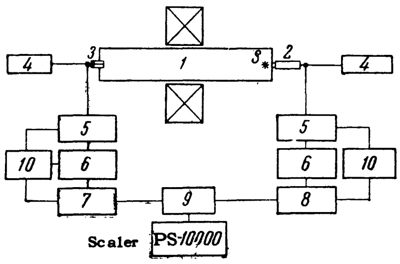

FIG. 1. Block diagram of setup for measuring $\beta\gamma$ coincidences: 1 – magnetic spectrometer, 2–photomultiplier, 3–end-window counter, 4 – high-voltage source, 5 – cathode follower, 6 – amplifier, 7 – delay block, 8 – differential analyzer, 9 – coincidence circuit, 10 – rectifier (200 V), S–radio-active source.

The γ spectra were investigated with a scintillation γ spectrometer with a 100-channel pulse-height analyzer of the "Raduga" type. The resolution of the scintillation γ spectrometer was 8.7% for Cs^{137} 662-keV γ rays.

Ni^{65} (T = 2.5 hours)

Radioactive Ni^{65} was obtained from the reaction Ni^{64}(d, p)Ni^{65}. The target was nickel enriched to 77.8% Ni^{64}. The β^- spectrum of Ni^{65} was investigated using two independent sources, and both series of measurements gave satisfactory agreement within the limits of experimental accuracy.

Analysis of the Fermi plot of the Ni^{65} β^- spectrum has shown the presence of three partial β^- transitions with end-point energies 2120 ± 40, 1050, and 620 keV, in agreement with the data of Siegbahn et al.[2] The intensities of these partial β^- transitions were 57, 14, and 29% respectively. It was impossible to separate the β^- transitions with end-point energies 375 and 477 keV, deduced in [3,4] from γ-spectrum measurements, owing to the low intensity of these transitions (on the order of 0.4%). The Ni^{65} γ spectrum measured with the scintillation γ spectrometer disclosed the presence of the previously known γ transitions with energies 370, 1120, 1490, 1630, and 1720 keV.

In the earlier measurements of the $\beta\gamma$ coincidences the partial β spectra were not separated. We therefore considered this measurement to be of great interest. The Fermi plot of the resultant β^- spectrum, for which coincidence with 1490-keV γ quanta is observed, is shown in Fig. 2, where the end-point energy is found to be 620 ± 40 keV. This is in good agreement with the β^- spectrum end-point energy obtained by resolution into partial β spectra.

Coincidences of the β^- radiation with the 1120-keV γ quanta were also observed. In this case the single-channel γ spectrometer registered Compton electrons from the harder γ quanta in addition to the photo electrons from the 1120-keV γ quanta. Since the 1490-keV γ quanta coincide only with the 620-keV β^- transition, it follows that the partial β^- spectrum with end-point energy 1020 keV (Fig. 3) is time-correlated with the 1120-keV γ quanta.

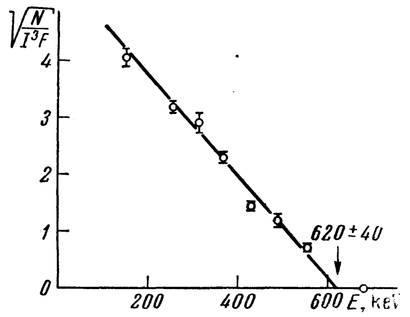

FIG. 2. Fermi plot for the coincidences between β^- particles and 1490-keV γ quanta in Ni^{65}.

The bend in the Fermi plot is apparently due to the increased number of $\beta\gamma$ coincidences produced by the Compton electrons from the 1490-keV γ quanta, and also to the additional contribution from the coincidences between the β^- transition with 620 keV end-point energy and the 1120-keV γ quanta. The latter may be connected with the fact that the 1120-keV γ radiation follows the 370-keV γ radiation. γ(370 keV)—γ(1120 keV) coincidences were observed by Wiedling and Carlson[5] and also by Hartman and Asplund.[6]

Figure 4 shows the Ni^{65} decay scheme given by Jambunathan.[4] The double lines denote the $\beta\gamma$ coincidences obtained in the present investigation.

Co^{55} (T = 18 hours)

The radioactive Co^{55} was obtained from the reaction Fe^{54}(d, n)Co^{55}. As in no other investiga-

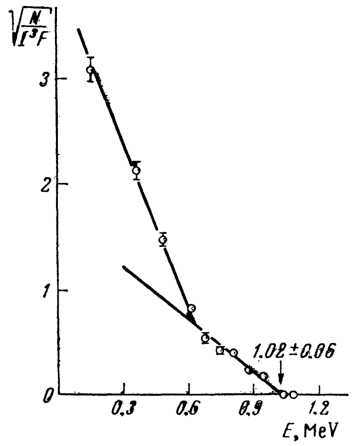

FIG. 3. Fermi plot for the spectrum of coincidences between β^- particles and γ quanta with energy $E_\gamma \geq 1120$ keV in Ni^{65}.

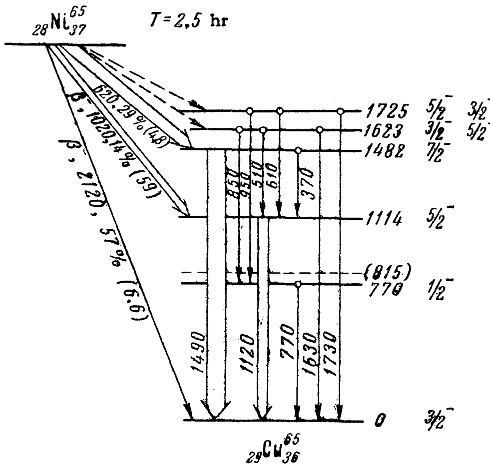

FIG. 4. Level scheme for the decay of Ni^{65}, from[4].

tion, the target this time was iron enriched to 77.4% Fe^{54}. The targets were irradiated with 10-MeV deuterons for 10 hours.

Measurements have shown that Co^{55} has a complex β^- spectrum with three components having end-point energies 1500 ± 30, 1040, and 550 keV with respective intensities 56, 41, and 3%.

The γ spectrum measured with a scintillation γ spectrometer shows clearly the γ peaks with energies 940 and 1410 keV (Fig. 5). To investigate the low-intensity hard γ transitions, a lead filter 25 mm thick was used. The observed 1800- and 2180-keV γ peaks confirmed the data first obtained by Caird and Mitchell. [7]

The presence of γ transitions with energies 250 and 477 keV is mentioned in the literature. [7,8] Since the 250-keV γ transition is of very low intensity and the 477-keV γ transition is expected at the location of the annihilation peak, these transitions are difficult to determine by direct measurement with the scintillation γ spectrometer. We therefore had to reduce the intensity of the annihilation peak and carried out the measurements for this purpose with a conical lead collimator. [9]

Figure 6 shows the γ spectrum of Co^{55} (upper curve) and the γ spectrum of the annihilation radiation of Cu^{64} (lower curve), measured with a conical lead collimator. As can be seen from Fig. 6, the annihilation line is much narrower and is shifted towards higher energies compared with the Co^{55} γ line. This is apparently due to the presence of a 477-keV γ transition; the 250-keV γ line did not occur at all in this case.

Measurements were also made of the β spectrum of the coincidences between the β^- particles and γ quanta with energies 1410 and 940 keV. Figure 7 shows the Fermi plot for the β^+ spectrum of coincidences between the β^+ particles and the 1410-keV γ quanta (curve a). The end-point energy obtained was 1050 ± 60 keV, in good agreement with the data obtained by resolving the β^+ spectrum of Co^{55}.

Curve b of Fig. 7 corresponds to the Fermi plot for the β^+ spectrum of Co^{55}, which correlates with the 940-keV γ quanta. In this case the

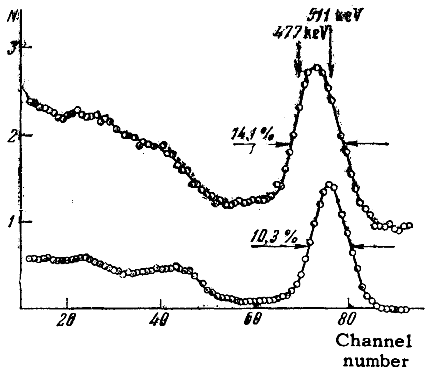

FIG. 6. γ spectrum of Co^{55} (upper curve) and γ spectrum of annihilation radiation of Cu^{64} (lower curve), measured with conical lead collimator.

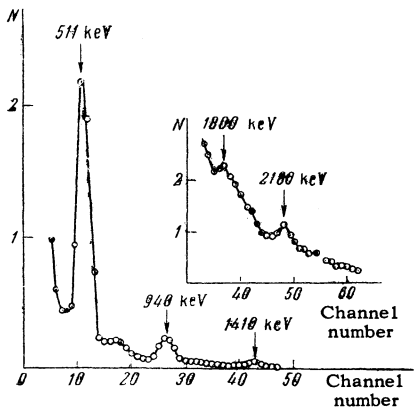

FIG. 5. γ spectrum of Co^{55} measured with scintillation γ spectrometer. The hard portion of the γ spectrum, measured with a 25-mm lead filter, is shown in the upper right corner.

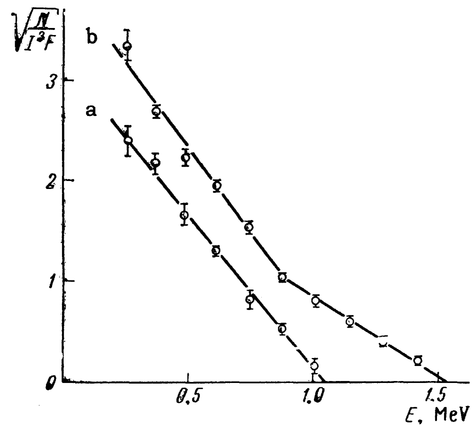

FIG. 7. Fermi plot of coincidences between β^+ particles and 1410-keV γ quanta (curve a) or 940-keV γ quanta (curve b) for Co^{55}.

hard component has an end-point energy 1540 ± 60 keV. This indicates that the β^+ transition with end-point energy 1.5 MeV is to an excited level, with subsequent emission of 940-keV γ radiation. The bend in the Fermi plot is essentially due to "additional" coincidences of the β^+ transition with end-point energy 1040 keV with the 940-keV γ transition.

The results obtained are in good agreement with those of Caird and Mitchell.[7] The results of A. Mukerji et al [8] which imply the absence of the 1800- and 2180-keV γ transitions and of the β^+ transition with end-point energy 550 keV, are apparently doubtful.

Figure 8 shows the decay scheme of Co^{55}, taken from [7], where the double lines indicate the measured $\beta\gamma$ coincidences. The quantum characteristics of the levels were borrowed from the papers by Lee and Mooring[10] and Bauer and Deutsch.[11]

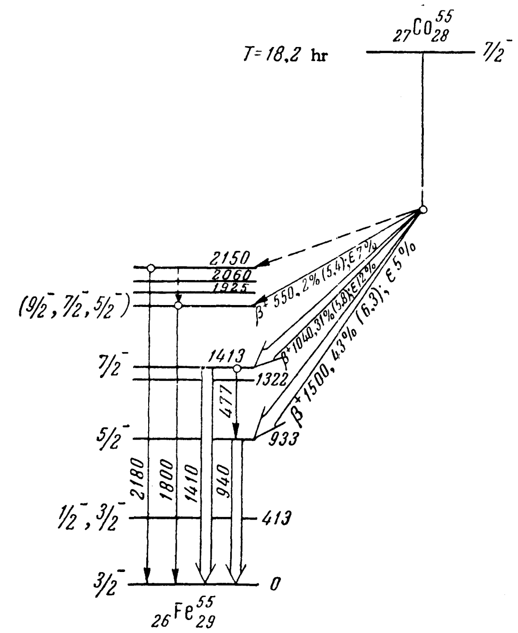

FIG. 8. Decay scheme of Co^{55}, from[7].

Mn^{51} (T = 44 min)

The radioactive Mn^{51} was obtained from the reaction $Cr^{50}(d, n)Mn^{51}$. The target used was Cr enriched to 87.7% Cr^{50} (the natural mixture contains 4.31% of Cr^{50}).

The Fermi plot of the resultant β^+ spectrum of Mn^{51} is shown in Fig. 9. The Fermi plot is straight down to β^+-particle energies on the order of 600 keV. The end-point is 2170 ± 60 keV. This is in good agreement with the data obtained by a method with absorption in aluminum filters.[12] The small deviation of the Fermi plot from line-

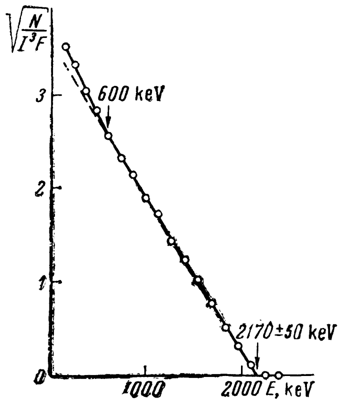

FIG. 9. Fermi plot for β^+ spectrum of Mn^{51}.

arity in the region $E_\gamma \leq 600$ keV is due to the presence of a partial β^+ spectrum. This also follows from the measured γ spectrum of Mn^{51}.

The initial measurement of the γ spectrum with the scintillation γ spectrometer has disclosed only annihilation radiation. For a detailed investigation of the low-intensity γ radiation in the hard region, a lead filter 25 mm thick was placed in front of the γ counter. Figure 10 shows the γ spectrum of Mn^{51}, measured with the lead filter. The γ spectrum shows clearly the previously known 1560- and 2030-keV γ lines (the intensities of these γ lines decreased with a half-life 50 ± 10 min).

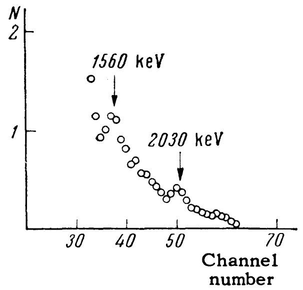

FIG. 10. γ spectrum of Mn^{51}, measured with a lead filter 25 mm thick.

The ratio of the intensities of these γ transitions to those of the annihilation radiation were found to be 1% (1560 keV) and 0.5% (2030 keV) per β^+ particle. By balancing the energies and the intensities of the β (600 keV) and the γ (1560 keV) transitions we can conclude that the 1560-keV γ transition follows the 600-keV β^+ decay. The γ transitions corresponding to the excited levels at 1569 and 2030 keV are confirmed by the nuclear reaction $V^{51}(p, n)Cr^{51}$.[13]

Figure 11 shows the decay scheme of Mn^{51}, plotted on the basis of our data and the work of Nozawa et al,[14] in which low-intensity γ lines

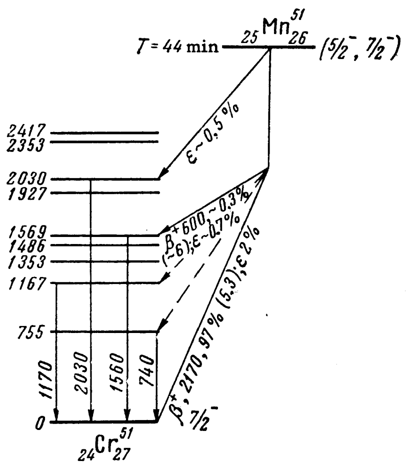

FIG. 11. Decay scheme of Mn^{51}.

with energies 0.74 (0.004) and 1.17 (0.002) MeV were observed (the parentheses contain the intensities per β^+ particle). All the excited levels of Cr^{51} were taken from the paper by Ferguson and Paul.[13]

V^{47} (T = 33 min)

The radioactive V^{47} was obtained from the (p, n) reaction in titanium enriched to 76.1% Ti^{47}. The half-life was determined from the decrease in the intensity of the annihilation peak and from the decrease in the count of the β^+ particles released in a fixed energy interval, using a magnetic β spectrometer. The half-life was 33 ± 1 min in both cases, in good agreement with the literature data (see, for example, [15]).

Measurement of the β^+ spectrum has shown that the β^+ spectrum of V^{47} is simple with an end-point energy 1890 ± 30 keV. This value is in good agreement with the end-point energy indicated in the paper by Daniel.[16]

The investigation of the γ spectrum of V^{47} has disclosed γ lines with energies 1800 and 2160 keV. The resultant γ spectrum is shown in Fig. 12. The

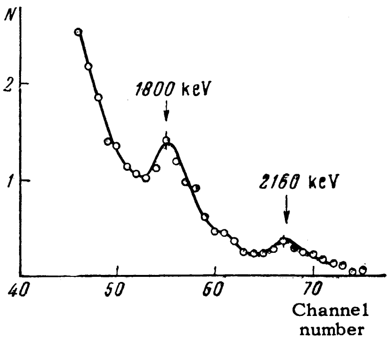

FIG. 12. γ spectrum of V^{47}, measured with a lead filter 25 mm thick.

identification of these γ lines was based on the decrease in the intensity of the photoelectron line. The half-life was found to be 35 ± 5 min. The intensities of the 1800- and 2160-keV γ transitions were (0.8 ± 0.3) and (0.2 ± 0.1)% per β^+ particle.

The excited levels of the Ti^{47} daughter nucleus were carefully investigated by Rietjens et al,[17] who used the nuclear reaction $Ti^{46}(d, p)Ti^{47}$. Since their paper mentions the presence of an 1800-keV excited level, the 1800-keV γ transition can be connected with this excited level. The 2160-keV excited level has not been observed to date in nuclear reactions. As follows from [17], a slight rise above the background is observed in this energy region on the descending portion of a strong peak; this rise is related by the authors of [17] to the 1380-keV level of Ti^{49}. Naturally, the authors could not note the peak connected with the 2160-keV level of Ti^{47} against so large a background.

The 160-keV γ transition corresponding to the first excited state was observed neither by us nor by Ramaswamy et al.[18]

Figure 13 shows the proposed decay scheme of V^{47}. The data on the excited levels of Ti^{47} were borrowed from [17].

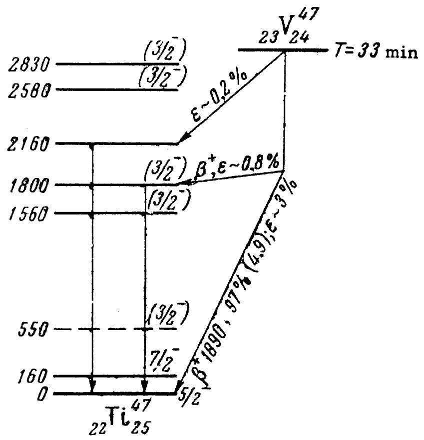

FIG. 13. Decay scheme of V^{47}.

Se^{83} (T = 25 min)

The radioactive Se^{83} was obtained by irradiating selenium enriched to 74.6% Se^{82} with 9-MeV deuterons, using the reaction $Se^{82}(d, p)Se^{83}$. This reaction was simultaneously accompanied by the reaction $Se^{82}(d, n)Br^{83}$ (T = 2.3 hours), and to account for the contribution made by the Br^{83} to the activity, the β^- spectrum was repeatedly measured using the same source. This enabled us to account for the contribution due to Br^{83} and obtain the β^- spectrum of Se^{83} by subtracting the β^-

spectrum of Br^{83} from the overall β^- spectrum.

The Fermi plot for the β^- spectrum of Se^{83} disclosed three groups with end-point energies 1.0, 1.8, and 3.3 MeV (Fig. 14). The intensities of these partial β^- transitions were 58, 40, and ~ 2%, respectively. These data are fundamentally in agreement with the results of Cochran and Pratt,[19] where the β^- spectrum of Se^{83} was investigated with a scintillation spectrometer. The low-intensity β^- transition with end-point energy 3.3 MeV was not observed before.

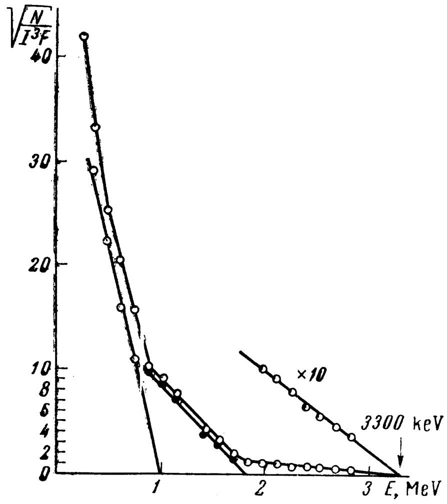

FIG. 14. Fermi plot for β^- spectrum of Se^{83}.

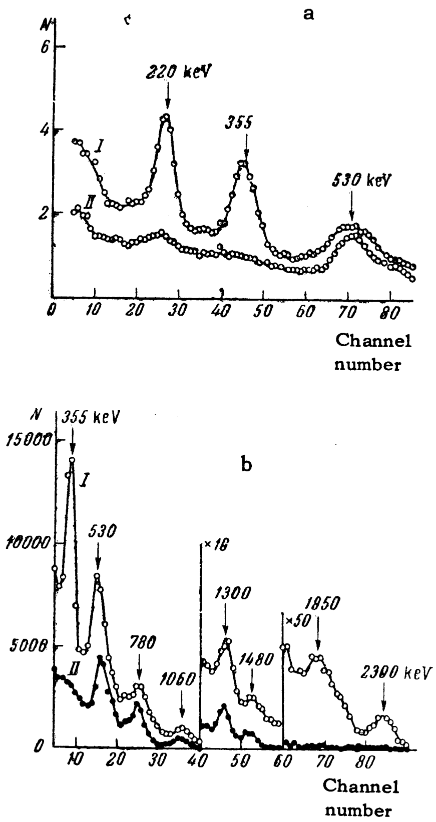

FIG. 15. γ spectrum of Se^{83} + Br^{82}; a – soft part of the spectrum, b – hard part. Lower curves correspond to the γ spectra measured after several hours.

Figure 15 shows the γ spectrum of Se^{83}. As can be seen from this figure, there were nine γ transitions with energies 220, 355, 530, 780, 1060, 1300, 1480, 1850, and 2300 keV. However, measurements have shown that the intensities of only four γ peaks with energies 220, 355, 1850, and 2300 keV decreased with a half life (25 ± 1) min, whereas the remaining photoelectron peaks remain practically unchanged for several hours (lower curves of Fig. 15). These γ peaks can apparently be ascribed to Br^{82} on the basis of their energies, relative intensities, and half-lives.

These results do not agree with the data of Cochran and Pratt[19] or of Ythier and van Lieshout,[20] where the presence of nine γ transitions is indicated. The relative intensities and energies of the Se^{83} γ transitions are listed in the table, together with the results of Cochran and Pratt.[19]

It was deemed interesting to measure the β^- (3.3 MeV)—γ coincidences to ascertain whether a β^- transition with 3.3-MeV end-point energy occurs between the ground states of the daughter and parent nuclei. However, in view of the extremely low intensity of this partial β^- transition (~ 2%), we could not use the magnetic β spectrometer for this purpose. A new setup was therefore assembled. The β^- particles were now registered by an end-window counter, and the γ quanta by a scintillation spectrometer with a 100-channel pulse-analyzer of the "Raduga" type. The analyzer was controlled by pulses from the β counter in coincidence with the γ-counter pulses. Aluminum filters placed between the β counter and the

Data of [19]		Our data		Data of [19]		Our data	
E_γ, keV	I_γ	E_γ, keV	I_γ	E_γ, keV	I_γ	E_γ, keV	I_γ
225	100	220	100	1058	36	—	—
358	157	355	180	1309	57	—	—
524	136	—	—	1880	36	1850	20
712	57	—	—	2294	22	2300	18
833	93	—	—				

source sorted out β^- particles in fixed energy intervals.

These measurements have shown that the β^- transition (3.3 MeV) produces no coincidences with the γ transitions. One can conclude therefore that this β^- transition is from the ground state of Se^{83} to the ground state of Br^{83}.

It is difficult to contruct a decay scheme for Se^{83} from the presently available data. A more detailed investigation of the radiation of Se^{83} is needed for this purpose.

A classification of certain excited states of odd nuclei, similar to that of Nussbaum,[1] was made on the basis of the experimental data obtained by others and by ourselves.

Nussbaum combines the odd nuclei containing equal numbers of odd protons or neutrons in one group. A comparison of similar excited states was made for odd nuclei containing an odd number of protons or neutrons, ranging from 17 to 29. The recently accumulated experimental data enable us to supplement and refine the quantum characteristics of the nuclei grouped in accordance with this feature.

In the present work we classified only the odd nuclei containing 27 or 29 protons or neutrons. A comparison of these nuclei is interesting because in one group there is a single nucleon in excess of the filled $1f_{7/2}$ shell and in the other one "hole" in this shell.[21]

Figure 16a shows the scheme of several low-lying excited states of odd nuclei containing 29 protons or neutrons. The figure shows that all these nuclei have in the ground state a total angular momentum $^3/_2$ with negative parity, in full agreement with the shell-model predictions.

The first excited levels are near 600 keV. The quantum characteristics of these levels have not yet been finally established, but the available data do not contradict the value $^1/_2{}^-$. These levels are ascribed a configuration $(2p_{1/2})^1$ by Nussbaum.[1] The second excited level appears at about 1000 keV and has a total angular momentum $^5/_2$ with negative parity. It is interesting to note that levels with total angular momentum $^7/_2$ and negative parity are observed near 1400 keV. Owing to the lack of experimental data, there is no clearcut indication of the existence of such a level in [1]. This level can apparently be assigned a configuration $(1f_{7/2})^{-1}(2p_{3/2})^2$.

An exception is Ca^{49}, for which the first excited level $^1/_2{}^-$ is at 2020 keV. Nussbaum[1] attempts to connect this deviation with the fact that the "core" of Ca^{49}, which contains 20 protons and 28 neutrons, has a more compact structure.

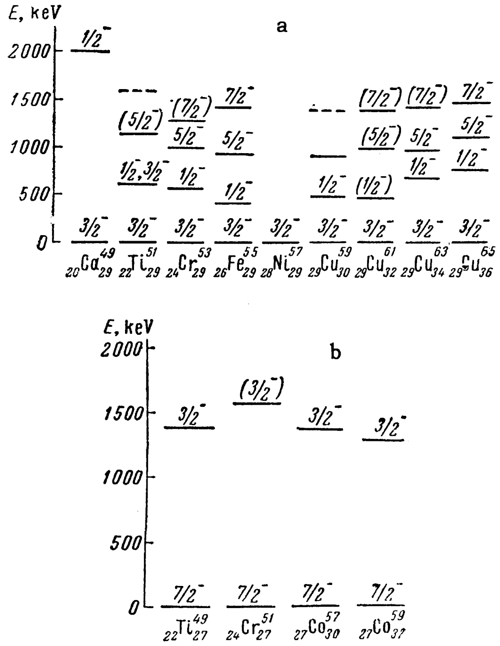

FIG. 16. Scheme of low-lying excited states of odd nuclei: a – for odd nuclei containing 29 protons or neutrons; b – for odd nuclei containing 27 protons or neutrons. The dashed lines denote excited states not established reliably.

Figure 16b shows the scheme of excited levels in the energy region close to 1400 keV for odd nuclei with 27 protons or neutrons. The total angular momentum in the ground state is $^7/_2$, with negative parity. The excited levels close to 1400 keV have a total angular momentum $^3/_2$ with negative parity. The configuration of these excited levels is apparently $(1f_{7/2})^{-2}(2p_{3/2})^1$.

A certain deviation is observed for Cr^{51}, whose excited level has a somewhat greater energy (1560 keV) compared with other analogous nuclei. The value of log τf determined for the Mn^{51} β^+ transition with end-point energy 600 keV to this level is found to be approximately 6. This indicates that this β^+ transition can apparently be regarded as allowed. The quantum characteristics of Mn^{51} in the ground state, given in the book by Dzhelepov and Peker,[22] are $^5/_2{}^-$. The 1560-keV excited level of Cr^{51} can therefore apparently be also ascribed the configuration $(1f_{7/2})^{-2}(2p_{3/2})^1$.

The foregoing classification leads to the following conclusion.

1. Three similar excited levels at energies ~600, 1000, and 1400 keV are observed for nuclei containing 29 protons or neutrons. Such levels are observed for nuclei with 27 protons or neutrons only at excitation energies on the order of 1400 keV.

2. The excitation energy of similar levels has a smooth variation for nuclei containing 29 protons

or neutrons. As can be seen from Fig. 16a, the excitation energy decreases with increasing number of even protons and increases with increasing number of even neutrons.

3. The excited levels of the indicated groups of nuclei, with energy close to 1400 keV, can be ascribed the following configurations:

$$(1f_{7/2})^{-1}(2p_{3/2})^2 \text{ for } Z(\text{or } N)=29,$$
$$(1f_{7/2})^{-2}(2p_{3/2})^1 \text{ for } Z(\text{ or } N)=27.$$

Since the excitation energy of these levels is approximately the same, the pairing energy of the levels $1f_{7/2}$ and $2p_{3/2}$ apparently does not come appreciably into play in this case.

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