EXCITED STATES OF Cs^{134}

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Cascade γ transitions induced in cesium nuclei by thermal neutron capture were studied. The scheme of low energy Cs^{134} levels of excitation energies up to 320 kev is discussed.

INTRODUCTION

A large number of odd-odd nuclei are known; however, the excited states of most of them have been little studied. Also, theoretical ideas on the structure of the energy levels of such nuclei have not been developed, which is evidently connected both with the difficulty of the problem and with the lack of experimental material. At the same time, the character of the energy states of odd-odd nuclei can give additional information on the interaction of the odd proton with an odd neutron,[1] and also of these nucleons with the even-even core of the nucleus. In the present work, the low-lying excited states of the odd-odd nucleus Cs^{134} (55 protons, 79 neutrons) are studied.

Almost all odd-odd nuclei are radioactive. The energy states of similar nuclei can be studied in nuclear reactions and also by investigating the γ radiation emitted by nuclei in neutron capture.[2] The soft γ radiation emitted by nuclei in the radiative capture of thermal neutrons has been studied by us previously.[3,4] Here the position of the energy levels and their quantum characteristics were determined non-uniquely. More complete data can be obtained by measurement of cascade γ quanta, as has been shown by a number of authors.[2,5,6] In the present work, cascade γ radiation of radiative neutron capture has also been investigated.

For measurement of cascade γ quanta, use is made of a luminescence coincidence spectrometer. The method of the work and the subsequent results are described below; these results make it possible to establish the system of the low excited levels of Cs^{134}.

APPARATUS AND METHOD OF MEASUREMENTS

The block diagram of the luminescence coincidence spectrometer developed by one of the authors[7] is shown in Fig. 1. The spectrometer consists of the control and main channels. In the control channel, the pulses entering from the luminescence counter [FEU-11 with NaI(Tl) crystal], are fed after amplitude selection to the coincidence circuit which controls the bandpass filter. Pulses in the main channel [FEU-13 with NaI(Tl) crystal] are directed by the bandpass filter to the multi-channel amplitude analyzer. The spectrometer makes it possible to measure the spectrum of pulses that are coincident in time with the chosen energy interval (the resolving time of the coincidence selector was 8×10^{-8} sec). For measurement of the spectrum of random coincidences, a delay was introduced for the pulses in the main channel.

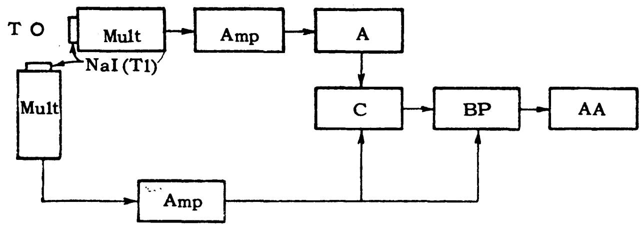

FIG. 1. Block diagram of the luminescence coincidence spectrometer: M – target, Amp – amplifier, A – amplitude analyzer, C – coincidence circuit, BP – bandpass filter, AA – 20-channel amplitude analyzer.

The target of CsF (a disk of diameter 20 mm and mass 0.25 g) was placed in the beam of neutrons emerging from the shield of the heavy-water reactor of the U.S.S.R. Academy of Sciences. The luminescence counters in the shield of lead and B_4C were located in a plane perpendicular to the beam of neutrons. In the absence of the target, the number of coincidences was negligibly small in comparison with the number of coincidences in the presence of the target. With the CsF target, the total number of coincidences amounted to 20 – 60 pulses/sec for an intensity of light in the channels of $2 - 5 \times 10^4$ pulses/sec. Approximately half the total number of coincidences were random. The spectrum of the random coincidences was

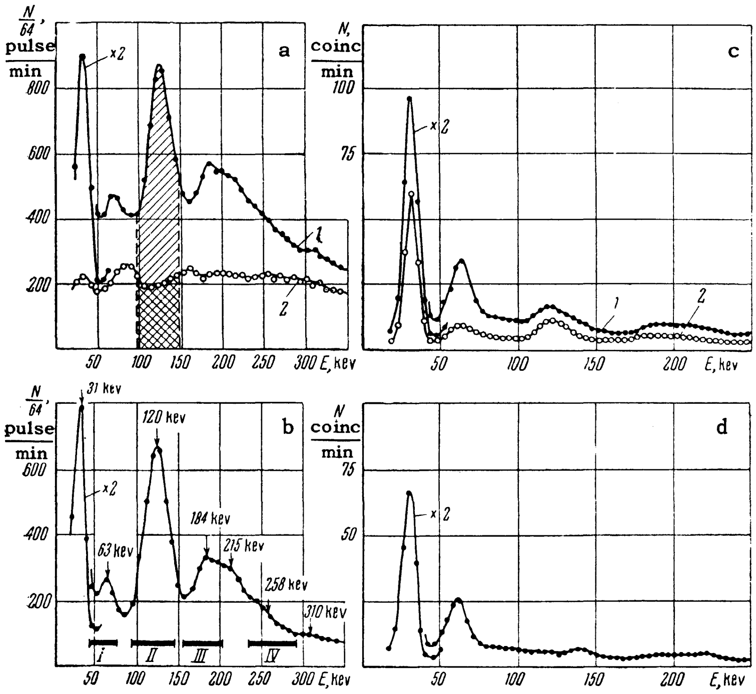

FIG. 2. Pulse spectra in the control channel for the following radiations: a – unfiltered and passed through 2 mm lead (curves 1 and 2, respectively), b – absorbed in 2 mm lead; the spectra of the coincidence pulses with the region 120 kev for control of the pulses; c – unfiltered and passed through 2 mm lead, curves 1 and 2 respectively, and d – absorbed in 2 mm lead. I, II, III, IV correspond to separate series of measurements. The exposure for measurement of the spectrum in c amounted to 40 minutes.

similar to the spectrum of the pulses in the channels. Each measurement of the spectrum of the total number of coincidences was accompanied by measurement of the spectrum of the random coincidences. The desired spectrum of true coincidences was obtained by finding the difference of these two successively measured spectra. In what follows only the spectra of the pure coincidences will be discussed.

Gamma radiation which takes place in the beam along with the neutrons can in the scattering produce noise readings in the counter. In experiments with a single crystal luminescence spectrometer[3] for consideration of this effect, the beam of neutrons at the exit of the neutron collimator was intercepted by a thin layer of B_4C. In the measurement of coincidences, this layer lowers the number of coincidences up to several per cent of the number of coincidences with an uninterrupted beam. In the experiments described, this correction was neglected.

The method of measurement is illustrated by the curves of Fig. 2. Curve 1 in Fig. 2a demonstrates the characteristic spectrum of pulses in a control channel produced by γ radiation of a CsF target. The peaks of the soft γ lines appear on a sizable "base" of Compton distribution of the harder γ lines. As was shown earlier[3] [by means of measurement with lead filters in the collimator of the γ rays (curve 2 in Fig. 2a)], one can separate the spectrum of the soft γ radiation. The curve of Fig. 2b shows the γ-ray spectrum absorbed in a lead filter of thickness 2 mm. The corresponding spectra of coincidences, obtained in one of the experiments, are shown by the curves of Fig. 2c and 2d. In these measurements, coincidences with light peaks of γ rays of energies 120 kev were neglected (the gap in the control channel is shown by the shaded region in Fig. 2a). Curve 1 of Fig. 2c was obtained in measurements without the filter. Curve 2 of the same drawing, which takes into account coincidences with the "base," was measured with a lead filter in the γ-ray collimator of the control channel. The difference of curves 1 and 2 in Fig. 2c, obtained in successive measurements, gives the coincidence spectrum (Fig. 2d) with soft γ radiation absorbed in a lead filter of 2 mm (see Fig. 2b).

The resulting coincidence spectra of the type shown in Fig. 2d will be discussed in the paper. In certain cases, control experiments were carried out with a lead filter in the γ-ray collimator, placed in front of a luminescence counter of the base channel; this served to make more accurate measurements of the low-intensity γ lines. These controls of measurement made it possible to reduce the noise in the coincidence spectra of the given type.

ISOMERIC TRANSITION OF Cs^{134m}

A peak appears in coincidence spectra, along with the peaks from the γ lines whose energy (31 ± 2) kev is equal to the energy of the x radiation of the Cs atom. This radiation is explained principally by internal conversion of γ quanta in the K shell of the atom, and in part by the photoeffect of γ quanta in self-absorption in the target.

For a thin target of CsF employed in the work, the effect of self-absorption was taken into account; it was not large. By comparison of the area of the peak from the x radiation with the area of the light peak, the coefficient of internal conversion of γ rays α_K in the K shell of the atom was determined. In this case, corrections[3,4] were introduced for the effectiveness of the luminescence counter for γ rays (ϵ), absorption of radiation on the path to the crystal of NaI(Tl), (k), and inside the target (κ). The experimentally measured values of α_K were compared with the theoretical[8] for determination of the multipolarity of the corresponding radiative transition.

With a view toward testing the accuracy of the determination of α_K in the introduction of the listed corrections, a control experiment was carried out with Cs^{134m} ($T_{1/2}$ = 3.1 hours), the radiation of which was studied in researches of other authors.[9] In the experiments under consideration, the isomer was obtained in a sufficiently long exposure of the working target of CsF by a neutron beam. The spectrum from the induced activity was measured after turning off the beam with the same target and with the same geometry as for the measurement of the γ-ray (n, γ) reaction. The coincidence spectrometer was used in these experiments as a single crystal luminescence spectrometer. A γ-ray peak with energy 127 kev and a peak with energy 31 kev (x radiation of Cs) were observed in the spectrum. Comparison of the areas of these two peaks made it possible to determine the value of the coefficient of internal conversion of the γ rays of an isomeric transition in the K shell of the atom, $\alpha_K = 2.8 \pm 0.3$, which is in excellent agreement with the value obtained in the research of Sunyar, Mihelich and Goldhaber,[9] and with the theoretical value $\alpha_{theor} = 2.82$ for the E3 transition.[8]

γ RADIATION OF RADIATIVE NEUTRON CAPTURE IN Cs

In the investigation of cascade γ transitions that arise in the radiative capture of neutrons in Cs, four series of experiments were carried out (I, II, III, and IV in Fig. 2b) which differ in energy intervals isolated in the control channel. These experiments were supplemented by measurements with a single crystal spectrometer. As a result, the previous data[4] on energies and intensities of the γ quanta of the reaction $Cs^{133}(n, \gamma)Cs^{134}$ were made more precise, a number of new γ lines were revealed, and the coincidences between them were tested. A summary of the data is given in Table I.

TABLE I

Number of γ lines	Energy, kev	Number of γ quanta per neutron trapped, per cent	Appeared in coincidences
X	31±2	50±8	I, II, III, V
γ_1	63±2	9±2	II, V
γ_2	75±5	~1.5	III, does not contradict I and II
γ_3	120±3	18±3	I, V
γ_4	138±4	2±1	III, V, does not contradict II
γ_5	184±4	9±2	V
γ_6	195—260	3±2	I
γ_7	215±4	7±2	V
γ_8	258±4	5±1	V
γ_9	310±5	4±1	V

In the supplementary experiment, a crystal of NaI(Tl) 4 cm thick was inserted in the luminescence counter of the control channel. Pulses corresponding to γ quanta with energies close to the binding energy of the last neutron in the Cs^{134} nucleus, equal to E_n = 6.8 Mev (width of the gap 2 Mev) were selected. The γ lines observed in these experiments are listed in the last column of Table I by the symbol V. All the radiative transitions appearing in the measurement of coincidences have a lifetime of less than 4×10^{-8} sec, which is demonstrated by an estimate of the lifetime according to the method of lagging coincidences. Thus, the γ transitions under consideration are of the E1, M1, and E2 type. The M2 transitions or those of higher multipolarity would have a much longer lifetime.

In the series of experiments IV, the coincidence spectrum with light peaks from 258-kev γ quanta was measured. No coincidences of these γ lines with any other soft γ quanta were observed.

In series III, coincidences in the region of the peak from γ quanta with energy 184 kev were selected (see Feg. 2b). After introducing corrections in the spectrum of coincidences, peaks from two low intensity lines with energies of 75 and 138 kev and x radiation, whose intensity n_X was approximately three times the intensity of the γ quanta with energy 138 kev, were observed. As has already been noted, introduction of transitions of higher multipolarity contradicts the estimates of the lifetimes. For an explanation of the observed intensity n_X, it is necessary to take into account the conversion of the two previously mentioned γ lines in the K shell of the atom. In this case, the intensity of γ quanta with energies 75 kev is shown to be ~ 1.5 per cent for a single trapped neutron, which does not contradict the estimates of the intensity obtained in other researches. The transition with energy 75 kev can be E2 or a mixture M1 + E2. In the chosen scheme of transitions, preference is given to the latter.

In the series of experiments II, the spectrum was measured of coincidences with γ quanta of energies 120 kev. The results of one of these experiments are shown in Fig. 2d. Sharp peaks were discovered of x radiation, and a peak of γ quanta with energy 63 kev. Peaks from low intensity γ lines with energies 75 and 138 kev were also observed. Moreover, in the energy region 195 — 260 kev, unresolved γ lines appeared with a total intensity (3 ± 2) per cent per single trapped neutron. The intensity of the x radiation n_X relative to the number of 63-kev γ quanta, n_{63}, was found to be equal to $n_X/n_{63} = 4.9 \pm 0.6$. The coefficient of internal conversion of the 63-kev γ quanta was obtained with allowance for the possible conversion of the low-intensity γ lines appearing in the measurements. The corrected value of α_K is shown in Table II, as is also the experimental value. Comparison with theoretical values of α_K leads to the conclusion that the 63-kev, transition is electric quadrupole.

In series I, the spectrum of coincidences with the 63-kev γ line was measured. The result of one of these measurements is shown in Fig. 3.

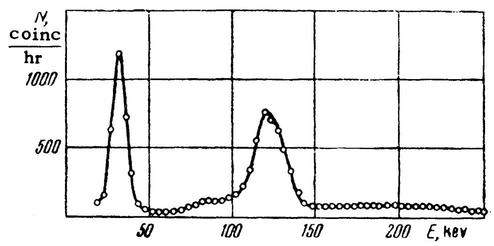

FIG. 3. Spectrum of coincidence pulses with 63-kev γ line.

Peaks from 120-kev γ quanta and a peak of x radiation are seen. The relative intensity of x radiation is $n_X/n_{120} = 0.81 \pm 0.20$. The coefficient of internal conversion of the 120-kev γ quanta in the K shell of the atom can be obtained here by introducing corrections for the possible conversion of the 75- and 138-kev γ quanta. This correction reduces the accuracy of the determination of α_K (120 kev). As is seen from Table II, an unambiguous choice between the transitions of type M1 and E2 cannot be made. In the most probable scheme of transitions, the 120-kev γ quanta are regarded as dipole.

DISCUSSION OF THE LEVEL SCHEME

A proposed scheme of excited levels of the Cs^{134} nucleus and the transition between them is shown in Fig. 4. In the construction of the scheme, consideration has been given to the coincidences which appeared in the research and to the anticoincidences of the separate γ transitions (see

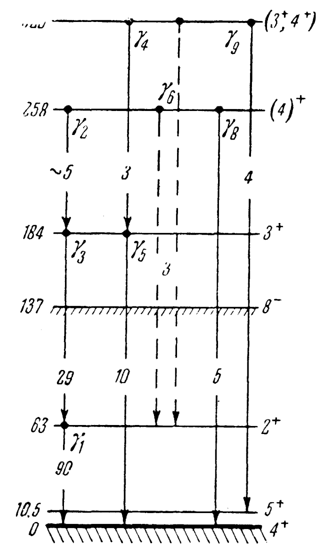

FIG. 4. Scheme of nuclear levels of Cs^{134}.

Table I). The values of the energy and the intensity of the transitions, lifetimes, spin, and parity of the levels (both those known previously and those assumed on the basis of the experimental data of the present research) are also taken into account. In addition to the levels whose existence has been established in this research, the levels 10.5 and 137 kev, known from the decay of the isomeric state Cs^{134m}, were also included in the scheme. The numbers of the γ transitions in Fig. 4 correspond to the numbers of the γ lines of Table I. The total probabilities of radiative transitions, including the intensity of the γ transition and the internal conversion in the K and L shells of the atom, are shown at the breaks of the arrows in the scheme. The accuracy of these data is defined by the accuracy of measurement of the intensities of the γ lines (Table I).

The most intense cascade, 63 — 120 kev, is fundamental in the construction of the scheme. It follows from intensity considerations that the 120-kev transition dominates the 63-kev transition. The large value of the absolute intensity of the latter suggests that it is located close to the ground state. The hypothesis that it terminates on the 10.5-kev level leads to worse agreement between the energies of cascade and direct transitions. In this case difficulties also arise in the choice of possible spin of the level from which the 63-kev transitions takes place.

The 63 — 120 kev cascade is not divided into intermediate levels, since there is a direct 184-kev transition, found in anticoincidences with the cascade in question. On the basis of coincidence measurements, levels are introduced in the scheme the energies of which, 258 or 320 kev, are equal, respectively, to the sums of the energies of 184- and 75-kev, or 184- and 138-kev γ lines.

In regard to direct transitions with energies of 258 and 310 kev, there is not sufficient convincing evidence that they terminate on the ground and first excited states, respectively. Furthermore, the doublet of these γ lines (transitions from corresponding levels can also lead to the ground and to the first excited levels) does not contradict the experimental result.

TABLE II

Energy of the transition, kev		63	120
Theory	$M1$	2.82	0.46
	$E2$	4.47	0.685
Experiment		4.3±0.6	0.6±0.25

In the proposed scheme, the characteristics of the 63-kev level are determined by the multipolarity of the transition found experimentally (Table II) with account of the characteristics of the isomeric and ground states. The characteristics of the 184-kev 3^+ level make it possible to explain the comparable intensities of transitions from it, if it is assumed that these transitions are magnetic dipole in nature.

The moment of the level with excitation energy 258 kev is selected from the same considerations, although less uniquely. The positive parity of this level follows from the fact that the 75-kev transition does not change the parity. The presence of concurrent transitions from the 320-kev level and consideration of their intensities makes it possible to assume the most appropriate characteristics of this level (3^+ or 4^+).

Measurements of the hard γ quanta of the reaction $Cs^{133}(n, \gamma)Cs^{134}$, carried out in a recently-published work,[10] confirm the existence in Cs^{134} of levels with energies 184 and 320 kev. In addition, transitions from the initial state to the level with energy 63 kev were not found. Therefore, the state which is realized in the capture of a thermal neutron probably has the characteristics of 4^+, not 3^+.

As is seen from the scheme of transitions, ${}_{55}Cs^{134}_{79}$ has many excited levels around the ground state; this is characteristic for odd-odd nuclei. We shall attempt to explain these levels by comparison with the levels of neighboring even-odd and odd-even nuclei. The configuration $(g_{7/2}, d_{3/2})$ corresponds to the ground state of Cs^{134}, where the shells of the last proton and neutron are indicated. The angular momentum and parity of the ground state 4^+ do not contradict the weak rule of Nordheim[1] for the addition of total momenta of the odd neutron and proton. The configuration $(g_{7/2}, d_{3/2})$ assumes states with characteristics 5^+, 4^+, 3^+, and 2^+. The level with excitation energy 10.5 kev was previously assigned to this configuration.[9] The level with excitation energy 63 kev also probably refers to it. Here we meet up with the multiplet structure of nuclear levels.[11] However, the probability of transition of type E2 from the 63-kev level is more than 200 times greater than the probability of a single particle transition.

Like the isomeric levels of the neighboring odd-even nuclei, the isomeric level of Cs^{134m} (137 kev) is interpreted as the first excited level of the neutron. The isomeric level is ascribed to the configuration $(d_{7/2}, h_{11/2})$. However, the energy of this level differs markedly from the energy of the isomeric transitions in the neighboring even-odd nuclei with the number of neutrons $N = 79$ the same as in the Cs^{134} nucleus (232 kev — ${}_{54}Xe^{133}$, 268 kev — ${}_{56}B^{135}$). Probably the interaction is that of odd nuclei.

The energy of the first excited level of the odd proton in the state $d_{5/2}$ in odd-even isotopes of Cs is equal to 82 kev (Cs^{133}) and 250 kev (Cs^{135}). In this region of excitation energies, one can expect the appearance of a multiplet structure corresponding to the configuration $(d_{5/2}, d_{3/2})$ with characteristics 4^+, 3^+, 2^+, and 1^+. It is possible that the levels of Cs^{134} with excitation energies 184 and 258 kev refer to this configuration. Unfortunately, there are no theoretical values with which one could compare the splitting of the levels of the nuclear multiplet.

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