MILLISECOND HALF-LIFE ISOMERS PRODUCED IN REACTIONS INVOLVING 14-Mev NEUTRONS

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The short-lived γ-radiation produced by pulsed irradiation of 43 elements with 14.5-Mev neutrons was investigated. Nine isomer activities with half-lives ranging from 10^{-3} to 10^{-1} sec were detected in Mg, Al, Ge, As, Y, In, Pb and Bi. The half-lives and γ-ray energies were measured and in some cases the isomer production cross sections were estimated. Besides the Pb^{207m} and Bi^{208m} activities all other isomer activities were produced in the neutron reactions for the first time. As a result it has been possible to identify a number of the isomers and to discuss the possible decay schemes.

1. INTRODUCTION

THE present paper is concerned with a search for and preliminary investigation of nuclear isomers with half-lives of 10^{-3} to 10^{-1} sec produced in reactions with 14-Mev neutrons. Part of the experiments described below was designed to establish or make more accurate measurements on the types of reactions which could explain the γ radiation with millisecond half-lives observed earlier.[1-5]

We carried out experiments on the lighter elements, for although the existence of isomer states is theoretically possible in several of these only a few have actually been found. The heavy and medium elements are of interest because the reaction (n, 2n) at 14-Mev neutron energies has a large cross section and therefore the mechanism whereby this reaction takes place should provide a large yield of isomers.[1]

We investigated the following 43 elements (Li, C, Na, Mg, Al, S, Ca, Sc, Ti, V, Mn, Co, Ni, Zn, Ga, Ge, As, Se, Br, Rb, Cu, Fe, Sr, Y, Zr, Nb, Mo, Pd, Cd, In, Sn, Te, La, Ce, Ta, W, Au, Hg, Tl, Pb, Bi, Th, U) and the effect was found for eight (Mg, Al, Ge, As, Y, In, Pb and Bi). The energies and the half-lives of the activities were measured and an estimate was made of their production cross-sections. The negative results obtained with 35 elements cannot be considered final and the measurements should be continued under improved experimental conditions and better measurement methods.

2. APPARATUS AND METHODS OF MEASUREMENT

1. Neutron monitor, determination of γ-radiation energy and half-lives of the isomer activities. The experiments concerned the γ-radiation spectra and the half-lives of the isomers produced in reactions with neutrons, and an estimate was made of the cross sections of several reactions that produce neutrons. The γ-radiation was recorded during the intervals between neutron pulses.

Neutrons were obtained from the reaction $T(d, n)He^4$ using 500-kv accelerating system previously described.[6] The unsorted ion beam was incident upon a thick tritium-zirconium target. The neutron pulse was produced by applying a square wave pulse of anode voltage to the ion source. The square wave was obtained by discharging a capacitor through a shaping circuit consisting of four resonant networks. The capacitor discharge circuit was closed by a photoelectric relay operated by a light signal from the low voltage end of the accelerator. The pulse repetition frequency was about 1 pulse per second. The target received a rectangular pulse of ion current with a duration of 1.3 milliseconds and amplitude up to 2 ma; under these conditions 2×10^7 neutrons were emitted per current pulse.

The neutron monitor consisted of a type FEU-19M photomultiplier tube with scintillation screen sensitive to neutrons (ZnS on Plexiglas). Pulses obtained from the photomultiplier were applied to the input of the PS-10,000 ("Floks") apparatus. The average pulse count rate, controlled by the neutrons, was of the order of 10 per second (10 pulses for 1 pulse of ion current). Pulses due to possible discharges in the accelerator could interfere with the measurements, so that for this reason the "Floks" scaler was shut off by a special circuit[7] and was switched on for 8 millisec by means of a photo relay operating from the same light signal as the photo relay of the ion source. It was during this time interval that the ion current pulse took place. The "Floks" sensitivity was set so as to discriminate against pulses

caused by Co^{60} γ radiation. This made it possible to control the sensitivity of the equipment. With such a choice of sensitivity, discrimination was had also against pulses associated with the long period activities produced in the scintillation material when it was radiated with neutrons during the period of continuous operation of the accelerator. The ratio of yield for the reactions studied and for the reaction $Cu^{63}(n, 2n)Cu^{62}$ to the monitor count was reproducible within limits of $\pm 10\%$. The absolute calibration of the neutron beam, required for an evaluation of the reaction cross section, was carried out with copper indicators using the yield from the reaction $Cu^{63}(n, 2n)Cu^{62}$, the cross section for which is known.[8] The copper cross section was taken equal to 500 millibarns.

Measurements of the γ radiation from the isomers were carried out by means of a NaI(Tl) crystal (diameter, 29 mm, h = 13 mm in a standard duraluminum container) with a type FEU-S photomultiplier. Pulses from the multiplier were applied to an analyzer with a grey wedge.[9] This device made it possible to obtain a photograph of the amplitude distribution of the pulses in a relatively short time interval. The resolving time of the device was 3×10^{-6} sec, the linear portion of the oscilloscope screen being 40 mm long. At the maximum sensitivity, input pulses with amplitude of 1 v produced a deflection of about 40 mm on the screen.

In addition, the pulses from the FEU-S were applied to a single channel amplitude analyzer,[10] which made it possible to count the pulses in a chosen portion of the amplitude spectrum. The resolving time of the analyzer was 0.8×10^{-6} sec. The amplifier, which was linear up to 120 v, had a rise time of 5×10^{-8} sec. The bandwidth could be changed in several steps from 0.5 to 3 v. By means of this analyzer we obtained the spectra of the isomer radiation produced after pulsed irradiation of the samples by neutrons. The results of these measurements were utilized to estimate the isomer yield cross section.

To determine the half-life of an isomer, the analyzer was set to the photo peak of the investigated line, so as to reduce the contribution of the background to the total count. The shaped pulses arriving from the amplitude analyzer were fed to a 16-channel time analyzer.[11] The channel bandwidth was variable from 0.1 to 4×10^{-5} sec and the resolving time of the channel was 0.8×10^{-6} sec. The time analyzer was switched in by the leading edge of the ion current pulse of the accelerator, and the count was started in the first channel with the particular time delay with respect to this leading edge chosen for each experiment. The photomultiplier, which was normally cut off by a negative voltage on its first focusing electrode, was switched in during the measurements. As a result, the photographs obtained with the grey wedge show a spectrum of the pulses, whose time distribution was studied, with a reduced contribution from the pulse background.

The equipment was carried out by means of γ lines of known energy: Zn^{65} — 1.118 kev, Cs^{134} — 800 and 600 kev, Cr^{51} — 323 kev, Hg^{203} — 279 kev, and Ce^{141} — 144 kev. With the crystal and photomultiplier used in this work, resolution of the Zn^{65} line was 7%. The position of the light peak was found not to vary with the intensity of radiation, right up to counting speeds of 3×10^4 pulses per second (integrated count). The intensity did not exceed this value in our experiments.

With pulsed operation, when the FEU-S was shut off and then turned on for definite periods of time after intensive pulsed neutron bombardment of the crystal and specimen, we observed a change both in sensitivity and resolution of the photomultiplier. When the photomultiplier was exposed for 300 μsec, the resolution became somewhat worse but for a period of exposure equal to about a millisecond and more the resolution did not change.

When determining the energy of the radiation studied, the source calibration lines were obtained either under the same conditions of photomultiplier operation as for irradiation of the samples, or simultaneously with the photomultiplier operation, so as to be able to account for possible changes of sensitivity in the operation of the FEU under pulsed conditions. The sensitivity of type FEU-S photomultiplier, when operated continuously after being turned on, was increased approximately 10% by the light from the crystal irradiated by the γ-source, and after 20 or 30 minutes reached a value that remained constant to within 1 or 2% during its subsequent operation. After cessation of the radiation, the sensitivity of the photomultiplier did not change significantly over a period of an hour.

A block diagram of the equipment is given in Fig. 1. The entire apparatus enabled us to measure the half-lives of isomers with a duration from 2 milliseconds up to 1 second and energies from 100 kev to 1.5 Mev.

The arrangement of the target, sample, and crystal is shown in Fig. 2. The tritium target was placed on the bottom of a steel cup (thick-

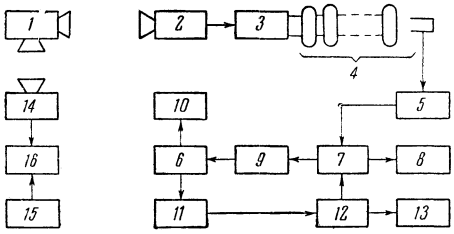

FIG. 1. Block diagram of the equipment: 1–pulsed radiator, 2–photorelay, 3– pulsed ion source, 4–linear accelerator, 5–delay network, 6–photomultiplier FEU-S with cathode follower[NaI(Te) crystal], 7–sixteen-channel time analyzer, 8–sixteen scalars, 9–circuit for shutting off FEU-S, 10–analyzer with gray wedge, 11–amplifier, 12–single channel differential discriminator, 13–scalar type PS-10,000, 14–photorelay and circuit for turning the "Floks" on, 15–photomultiplier FEU-19M with cathode follower (scintillation-screen – ZnS on Plexiglass), 16–scalar PS-10,000, "Floks."

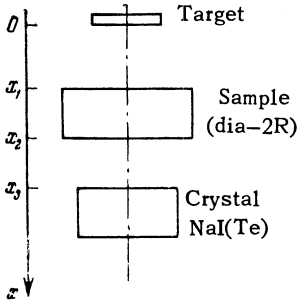

FIG. 2. Experiment geometry.

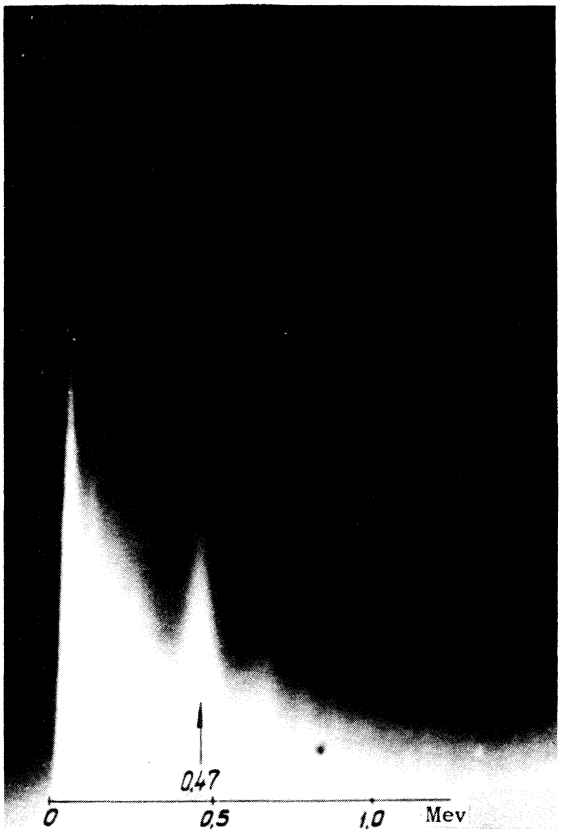

FIG. 3. Background spectrum in absence of sample, obtained by starting the exposure 4 millisec after start of neutron pulse. Monitor count, 11,600.

ness of walls and bottom 1 mm) and the samples were placed between the target and the crystal used to detect the γ radiation. The distance from crystal to sample $(x_2 - x_3)$ was 3.0 cm, the distance x_3 from the target to the crystal was varied from 5.5 to 9 cm, depending on the intensity of the radiation being studied. In the vicinity of the target the amount of scattering materials was reduced to the least amount possible. In the first experiments, we observed intense γ radiation with E = 470 kev, $T_{1/2}$ = 20 millisec, due, as further experiment showed, to aluminum and producing a background which interfered with the study of other materials. For this reason, aluminum parts of the equipment were replaced by steel and Plexiglas wherever possible. A typical background spectrum is shown in Fig. 3. During operation a shutter could be set over the tritium target to cut off the current reaching the target. In this case the current pulse started the recording equipment but no neutrons were present. Experimental conditions were chosen such that the equipment recorded only the pulses associated with neutrons (x-rays, background due to stray electrical pickup, etc.).

Experiments were performed in the following order. The background γ-radiation was measured with the gray-wedge analyzer with no specimen between target and crystal. The sample was then set in place and the γ-radiation spectrum was again obtained under the same conditions as the background spectrum. If new lines (other than those of the background) appeared, their energy was measured. After this, by means of the single channel amplitude analyzer, we selected a section of the spectrum containing the new line and, using the time analyzer, measured the time distribution of pulses both with the sample and without it. To obtain satisfactory statistics, several hundred neutron pulses were used. By analysis of the time distribution of γ-radiation pulses we obtained the half-lives for the isomer activities.

As has been pointed out above, γ-radiation spectra were obtained for a number of elements with the aid of the single-channel amplitude analyzer. In these experiments the exposure times of the FEU-S were chosen in accordance with the half-life to permit the measured activity to decay completely during the measurement time interval. The amplitude analyzer channel was switched over automatically after the monitor had counted a definite number of pulses. Recording was accom-

plished by means of 16 scalers which were simultaneously switched in when an analyzer channel was switched over.

2. Estimates of the Isomer Production Cross Sections. We carried out additional experiments on some elements to enable us to evaluate isomer production cross sections. In view of the fact that the mean neutron yield was not large ($\sim 10^7$ neutrons per sec over a solid angle of 4π), we used samples of rather large dimensions and placed them near the tritium-zirconium target. In this case, the dimensions of target, samples, and crystal were comparable with the distances between them. Cylindrical specimens were used in these measurements (2R = 4.5 cm and 2R = 10 cm). The formula for the cross section was derived by relating the number of neutrons passing through a circular section of specimen of thickness dx at a distance x from the target, with the number of pulses at the photopeak due to the γ quanta emitted by this layer. The first of these quantities was measured by means of a copper indicator (copper foil 33.6 mg/cm^2, diameter 2R, located at a distance x from the target during irradiation by neutrons); the second was determined by model experiments in which the irradiation of the layer dx was represented by the γ radiation of a thin γ emitter of known power located in the same position between sheets of the material under study. Here we measured the effectiveness of the spectrometer $\epsilon(x, E)$ at the photopeak, with allowance for specimen absorption. By integration of the effects produced by each layer dx we obtained the full count n of peaks in the spectra of the isomer radiation, a count connected with the cross section σ for isomer production through the following formula:

$$\sigma = \sigma_{Cu}\, nMB(x_2 - x_1) \Big/ \nu P \int_{x_1}^{x_2} \xi(x)\, \varepsilon(x, E)\, dx. \qquad (1)$$

Here σ_{Cu} is the cross section for the $Cu^{63}(n, 2n)Cu^{62}$ reaction, M is the molecular weight of the specimen, P the weight of the specimen taking into account the isotopic composition, ν the monitor count when the sample is irradiated, B a factor that accounts for the decay in isomer activity, x_1 and x_2 are shown in Fig. 2, and $\xi(x)$ is a function that accounts for the number of neutrons that have passed through the layer dx:

$$\xi(x) = n_{Cu} M_{Cu} B_{Cu} / \nu_{Cu} P_{Cu} \eta \mu, \qquad (2)$$

where n_{Cu} is the reading of counter AC-2, around which a copper foil was wrapped to count the positrons of the Cu^{62} decay after pulsed irradiation by neutrons, η is a factor that accounts for the absorption in the foil and the absorption in the counter walls (44.5 mg/cm^2 aluminum), μ is a geometrical factor (we assumed the solid angle of the counter to be equal to 2π, therefore $\mu = 0.5$), the rest of the quantities being those of Eq. (1) but refering to experiments with the copper indicator. $\xi(x)$ was measured for several distances x for two values of 2R. A graph of these results is given in Fig. 4.

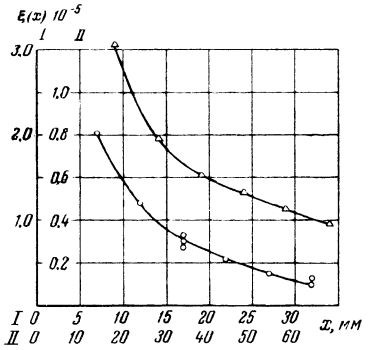

FIG. 4. The function $\xi(x)$. The abscissa gives the distance from the tritium target to the copper indicator. △ – sample diameter 10 cm, ⊙ – sample diameter 4.5 cm.

For the measurement of $\epsilon(x, E)$, thin γ-ray sources of diameter 2R were required. By means of a counter with a known dependence of sensitivity on γ-radiation energy,[12] supplied to us by V. N. Sakharov, we measured the power of Ce^{141}, Hg^{203}, Cr^{51}, Au^{198}, Zn^{65} compounds, which could be considered as point sources in the measurements. After this, the activities of the sources were uniformly distributed in thin layers around circles of diameter 2R. The completed compounds were placed between sheets of Mg, Al, In, and Pb at various distances from the crystal in a manner such as to retain the geometry of Fig. 2. The value of $\epsilon(x, E)$ was determined as the ratio of total count at the peaks to the number of γ quanta emitted by the source. Figure 5 shows the spectrometer effectiveness for E = 0.411 Mev (Au^{198}) for an aluminum sample. Values of $\epsilon(x, E)$, interpolated by energy, were substituted in the integral of formula (1). For the heavy elements we used here the results of measurements of $\epsilon(x, E)$ on In and Pb, while for the light elements we used the measurements on Al and Mg.

In evaluating the cross-section we did not take into account the dependence of σ_{Cu} on neutron energy. Work was carried out on an unsorted

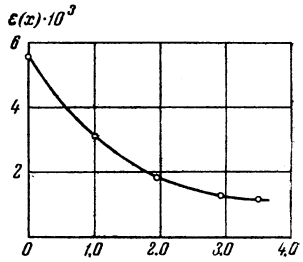

FIG. 5. Spectrometer effectiveness at the Au^{198} line (E_γ = 9.411 Mev), taking into account the absorption in $(x_2 - x)$ cm of aluminum. Point 0 corresponds to a distance of 3 cm to the crystal. Abscissa is $(x_2 - x)$, cm Al.

Specimen	Energy of γ rays, Mev	Half-life, millisec	Cross-section,	Suggested reaction
Mg	0.47±0.01	20±1	0.08	$Mg^{24}(n, p)\ Na^{24m}$
Al	0.47±0.01	20±1	0.04	$Al^{27}(n, \alpha)\ Na^{24m}$
Ge	0.17±0.01	16±1	0.3	—
As	0.28±0.01	17±1	0.13	$As^{75}(n, n')\ As^{75m}$
Y	0.24±0.01	14±1	—	$Y^{89}(n, n')\ Y^{89m}$ or $Y^{89}(n, 2n)\ Y^{88m}$
In	0.32±0.01	42±2	0.8	$In^{115}(n, 2n)\ In^{114m}$
Pb	0.48±0.01; 0.94±0.02	5±0.5	—	$Pb^{206}(n, 2n)\ Pb^{205m}$
	0.58±0.01; 1.04±0.03	$8\cdot10^2$±$1.5\cdot10^2$	1.5	$Pb^{208}(n, 2n)\ Pb^{207m}$ $Pb^{207}(n, n')\ Pb^{207m}$
Bi	0.48±0.01; 0.86±0.02	2.7±0.3	0.6	$Bi^{209}(n, 2n)\ Bi^{208m}$

deuteron beam of unknown composition. The errors in the quantities entering into the cross-section formula were: $\xi(x)$ — around 10%, $\epsilon(x, E)$ — around 10% for $E_\gamma \sim 1$ Mev and around 15% for $E_\gamma \sim 100$ kev; the ratio of the photopeak areas to the monitor count, with allowance for some arbitrariness in separating the peaks of the pulse spectrum, could be repeated with an accuracy up to 10 to 15%. The factor B in formula (1), for $T_{1/2}$ on the order of several milliseconds, was known to an accuracy of 10%, while for the long half-lives the accuracy was 1 to 2%. The probable maximum error in the cross section was 40 to 50%. It is for this reason that we consider our measurements of cross-section as estimates.

3. RESULTS OF MEASUREMENTS

The results of our measurements are given in the table.

Bismuth. To check the accuracy of our equipment, we investigated the isomer activity known to us from previous work in our laboratory, which involved the bombardment of bismuth by 14 Mev neutrons.[1] In reference 1 the measurements of γ-radiation energy were quite rough, and we therefore first made a more accurate measurement of this quantity. The radiation spectrum of a sample of bismuth (weight 962 g, diameter 100 mm, distance to the tritium target 24 mm) was obtained by an analyzer with a gray wedge. The photomultiplier was exposed for 24 millisec, 4 millisec after the start of the neutron pulse. One of the spectrum photographs obtained is shown in Fig. 6. Two γ lines are clearly visible. The energies of these lines, determined from several photographs, are 0.48 ± 0.01 and 0.86 ± 0.02 Mev. The results presented here and below are averaged over several experiments, while the errors are the mean deviations from these results.

The half-life was determined by means of the time analyzer, with the single channel discriminator set to each of the two γ lines of the spectrum. Measurements on both lines gave $T_{1/2}$ = 2.7 ± 0.3 millisec. To ascertain whether the 0.48-Mev line belongs to the bismuth spectrum and is not the sum of a background 0.47-Mev line and a Compton-effect 0.86-Mev line, we performed the following experiment. The channel of the pulse analyzer was first set to that point in the pulse distribution at which there is a Compton peak with energy 0.86 Mev, and then to the 0.48-Mev line. A count was taken for equal monitor indications. At these same conditions, we measured the background radiation. It turned out that the

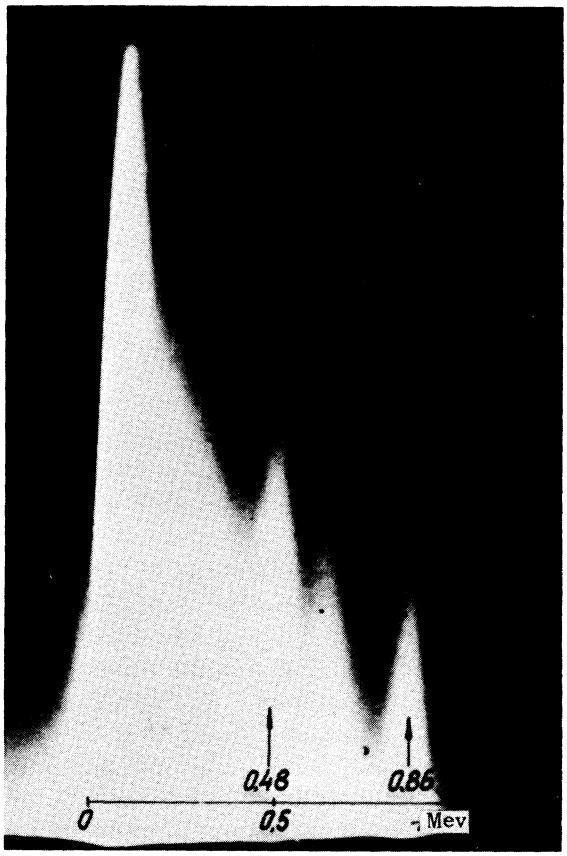

FIG. 6. Spectrum of Bi specimen. Two lines are seen, corresponding to energies of 0.48 and 0.86 Mev. The photomultiplier was exposed for 24 millisec, 4 millisec after start of neutron pulse.

difference in count caused by the radiation of Bi was twice as great at the 0.48-Mev line as at the Compton peak, which proves the actual existence of two γ lines.

The results obtained agree with the data in previously published papers. In the bombardment of bismuth by fast neutrons,[1] radiation with $T_{1/2}$ = 2.4 millisec was found and ascribed to Bi^{208}. In the irradiation of bismuth by γ quanta in the 24-Mev betatron,[4] an isomer activity was found with $E_\gamma = 500 \pm 20$ and (930 ± 30) kev and $T_{1/2} = (2.7 \pm 0.3)$ millisec. On bombarding bismuth with 20-Mev protons[2] an activity was found with $T_{1/2} = (3.0 \pm 1)$ millisec. In the same work, upon bombardment of lead by protons, radiation was observed with $E_\gamma = 0.7$ Mev and with approximately the same $T_{1/2} = (2.0 \pm 0.5)$ millisec. According to our measurements, carried out on the 0.86-Mev line, the cross section for the bismuth isomer production was estimated to be 0.6×10^{-24} cm^2. This comprises ~ 0.3 of the cross section for the reaction $Bi^{209}(n, 2n)Bi^{208}$, for which statistical theory gives 2.2×10^{-24} cm^2. An estimate of the multipole nature of the transitions based on the Montalbetti[13] nomogram, for the measured energies and periods, does not determine which of these transitions is the first in the cascade. Thus, for a transition energy of 0.48 Mev, an M3 transition is possible (the nomogram yields for this energy $T_{1/2} \sim 45 \times 10^{-3}$ sec, which in view of the low accuracy of the nomogram, is close to the measured period). For an energy of 0.86 Mev, the same M3 transition is possible ($T_{1/2} \sim 10^{-3}$ sec). In view of the fact that M3 transitions are the most common for odd-odd nuclei, it is possible to suggest that in this case the first transition to take place in the cascade is M3. Here, regardless of which transition takes place in the ground state, the difference in moments of the ground and first excited state cannot be greater than 3. To explain the large probability of isomer production in the reaction $Bi(n, 2n)Bi^m$ and the small yield of this isomer in the reaction $Pb(p, n)Bi^m$ observed in reference 2, we can assign, for example, a spin of 9 to the (480 + 860) kev level.

The possibility of the Bi^{209m} isomer production was not analyzed in detail, but existing results make it possible to assign a lower probability to this possibility.

Magnesium and aluminum. For a number of light alloys with $A < 30$, in which filling of the $p_{3/2}$ and $d_{3/2}$ shells occurs, two odd nucleons give rise to a configuration with a large value of spin in the ground state [for example $Bi^{10}(3^+)$, $Na^{22}(3^+)$, $Na^{24}(4^+)$, $Al^{26}(5^+)$, $Al^{28}(3^+)$]. If low lying excited levels with moments 0 and 1 exist for these configurations, these states will be isomeric. Indeed, a long-lived isomer of Al^{26m} has recently been found.[14] Existence of a millisecond Na^{22m} isomer is also theoretically possible. However, many experimental attempts to find the isomer Na^{22} have so far led to negative results.[4]

In view of the great interest presented by the possibility of the existence of isomers in so many light nuclei, we investigated Na^{24m}, which can be obtained either by the radiative capture of slow neutrons by Na^{23}, or in the reactions $Al^{27}(n, \alpha)Na^{24}$ and $Mg^{24}(n, p)Na^{24}$.

A sample of metallic aluminum (weight 159 g, diameter 44 mm, distance from target 58 mm) was irradiated in the direct neutron beam. In the γ-radiation spectrum we found a line of (0.47 ± 0.01)-Mev line with a measured half-life of (20 ± 1) millisec. The cross-section for the production of a 0.47-Mev level was estimated to be 0.04×10^{-24} cm^2.

The found γ line was ascribed to an isomer state Na^{24m}. In view of the fact that the cross scction for the reaction $Al^{27}(n, \alpha)Na^{24}$ is 0.12×10^{-24} cm^2,[8] the ratio of the cross section for production of an isomer state to the reaction cross section is ~ 0.3.

To check the correctness of the isomer identification we irradiated metallic magnesium (weight 100 g, diameter 44 mm) under the same conditions. The measured half-lives were the same as in the case of aluminum. The cross-section for Mg is 0.08×10^{-24} cm^2.

In reference 15, Na^{24m} was identified through study of the decay of Ne^{24} ($E_\gamma = (472 \pm 5)$ kev, $5 \leq T_{1/2} \leq 50$ millisec).

These results, as well as the circumstance that a 0.47-Mev line is observed in the irradiation of Na^{23} by thermal neutrons,[16] confirm our assumption that the observed γ radiation is associated with the production of the Na^{24m} isomer in the (n, α) and (n, p) reactions with Al and Mg.

Germanium. Pulsed irradiation of a specimen of metallic germanium (weight 17 g, thickness 3 mm, distance to tritium target 27 mm) was accompanied by γ radiation with $E_\gamma = (0.17 \pm 0.01)$ Mev and a $T_{1/2} = (16 \pm 1)$ millisec. In spite of the intense background, the line that appears during the irradiation of germanium in the spectrum obtained by means of an analyzer with a gray wedge, is distinctly visible. The cross section for production of a 0.17-Mev metastable level is estimated to be 0.3×10^{-24} cm^2.

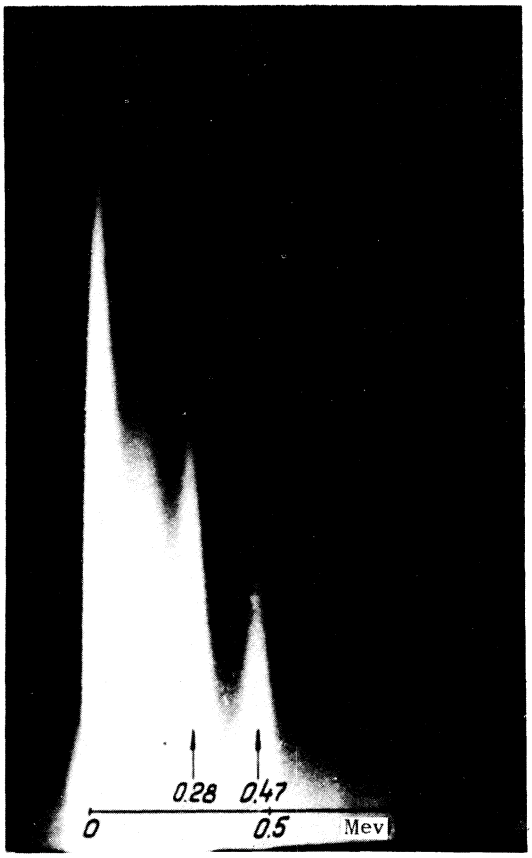

FIG. 7. Spectrum of As. The 0.28 Mev line, not found in the background spectrum, is quite pronounced. The photomultiplier was exposed for 134 millisec, 4 millisec after start of neutron pulse. Monitor count – 21,400.

We assume that the radiation found, as well as the radiation observed previously in the irradiation of Ga by protons,[3] belong to one of the isomers of Ge or Ga.

Arsenic. Among the elements with atomic numbers from 60 to 80, a considerable number of isomers is known. For this reason, an investigation of millisecond isomers, for a number of such nuclei, is of particular interest.

Upon irradiation of a sample of metallic arsenic (weight of sample, 43 g, distance to tritium target, 40 mm), we observed a short-lived γ activity with an energy of 0.28 ± 0.01 Mev. This spectrum is shown in Fig. 7. Along with the new line 0.28-Mev line, a background line is also seen at 0.47 Mev. Half-life measurements for the 0.28-Mev line gave $T_{1/2} = (17 \pm 1)$ millisec. The graph for the determination of the period is given in Fig. 8.

An estimate of the cross section for the production of isomers in this reaction gave a value of 0.13×10^{-24} cm^2. The spectrum obtained with the one-channel differential discriminator used to estimate the cross section is shown in Fig. 9. The found γ activity apparently belongs to As, which is formed by the reaction $As^{75}(n, n')As^{75m}$, in good agreement with the results obtained by other authors. As a matter of fact, it has been shown in reference 18 that the γ radiation with $E_\gamma = 0.28$ Mev, which accompanies K capture by Se^{75}, is a delayed radiation with $T_{1/2} = (18 \pm).5)$ millisec and may be ascribed to the isomer As^{75m}.

In the irradiation of As in a 24 Mev betatron,[4] an activity was obtained with $E_\gamma = (305 \pm 15)$ kev and $T_{1/2} = (12 \pm 3)$ millisec. The γ-radiation found[3] upon irradiation of Ge by 20-Mev protons with $T_{1/2} = (17.5 \pm 2)$ millisec and $E_\gamma = 0.31$ Mev evidently also belongs to As^{75m}, which is produced in the $Ge^{76}(p, 2n)As^{75m}$ reaction.

Yttrium. A sample of yttrium oxide Y_2O_3 pressed into the shape of a disc with diameter 44 mm (weight 20 g, distance to tritium target, ~ 20 mm) was irradiated. At first an attempt was made to find the well known isomer Y^{88m},[19,4] with $T_{1/2} = 0.37$ millisec and $E_\gamma = 393$ kev However, we did not succeed in finding it since the minimum delay after the start of neutron pulse could not be made less than 2 millisec (the neu-

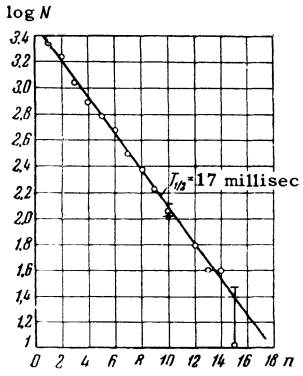

FIG. 8.

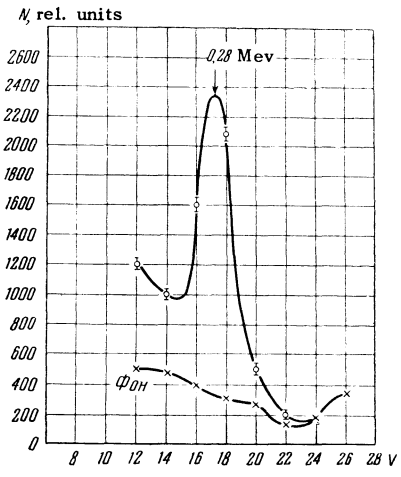

FIG. 9.

FIG. 8. Decay of As ($E_\gamma = 0.28$ Mev). Bandwidth of channel = 7.95 millisec. Abscissa – channel number. Ordinate – logarithm of difference between counts with and without specimen.

FIG. 9. Spectrum of As obtained with the single channel discriminator. Bandwidth of channel – one volt. Abscissa – discrimination voltage. Ordinate – channel count referred to 2000 monitor pulses. This spectrum is used to estimate the cross section.

tron pulse did not have a sufficiently steep trailing edge), and our equipment did not allow us to measure activities with so short a period.

For photomultiplier exposure times of ~100 millisec it was possible to find activities with $E_\gamma = (0.24 \pm 0.01)$ Mev and $T_{1/2} = (14 \pm 1)$ millisec. This same isomer activity ($E_\gamma = 0.2$ Mev and $T_{1/2} = 13$ millisec) was evidently observed earlier, when yttrium was irradiated by fast protons.[3] From an analysis of the cross reactions it follows that this is either the isomer Y^{89m} obtained in inelastic scattering of neutrons and protons, or the isomer Y^{88m} obtained by us in the reaction $Y^{89}(n, 2n)Y^{88m}$ and by Leĭpunskiĭ et al.[3] in the reaction $Y^{89}(p, pn)Y^{88m}$. From Montalbetti's nomogram it follows that the E3 transition corresponds to this isomer.

The assumption that the observed γ radiation belongs to Y^{88m} and that the 240-kev level in the scheme of reference 17, shown in Fig. 10, has a moment (1^+), evidently is in disagreement with reference 19, since it is difficult to explain the absence of β decay of Zr^{88} at this level. Moreover, another unexplained fact is the absence of this activity in the irradiation of strontium by fast protons $[Sr^{88}(p,n)Y^{88}]$[3] and of yttrium by γ quanta $[Y^{89}(\gamma n)Y^{88}]$.[4] If, on the other hand, we assign to the 240-kev level of Y^{88m} a moment (7^+), then these difficulties disappear: the β decay of Zr^{88} is strictly forbidden at this level, while the probability of exciting the (7^+) level in the reactions $Sr^{88}(p,n)Y^{88}$ and $Y^{89}(\gamma,n)Y^{88}$ is small because the Sr^{88} spin is 0^+, while the Y^{89} spin is $\frac{1}{2}^-$. In this case we can also explain the relatively large yield of isomers in the (n, 2n) and (p, pn) reactions: the average moment of the residual nucleus may be ≥ 4, which will lead to a large probability of transitions to the 7^+ level. For this reason, it seems to us that the assumption about Y^{88m} deserves serious attention and should be very thoroughly studied.

Indium. Upon irradiating a sample of indium (weight 54 g, diameter 40 mm, distance to target 24 mm) we observed a γ-activity with energy

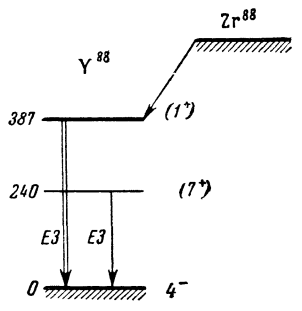

FIG. 10. Level scheme for Y^{88}.

(0.32 ± 0.01) Mev and a half-life (42 ± 2) millisec. The cross section estimated from the measurements with the single-channel analyzer comes to 0.8×10^{-24} cm.

The following circumstance is of interst. A known regularity is noted when we study the tabulated data on the decay of the odd-odd isotopes of indium. In In^{110} and In^{112} we observe an M3 isomer transition, while in In^{114} and In^{166} the transition of the E4 type. If we plot $\log(\tau A^2)$ as a function of E_γ for this type of transition, the experimental points will in general lie on a straight line. If we pass such a straight line through the points for In^{110} and In^{112}, we find that there may be an M3 type transition in In^{114} with energy 0.3 Mev and a half-life of some tens of millisec. Bearing this in mind we can assume that we have observed the radiation of In^{114} which is obtained from the reaction $In^{115}(n, 2n)In^{114}$. The experimental point fits rather well the straight line drawn through the known points for In^{110} and In^{112}. To explain the large isomer-production cross section one should assume that the γ transitions from the highly excited states which have a large moment after emission of two neutrons take place, basically, at the 8^+ isomer level which is 320 kev away from the known 5^+ level.[17]

The assumption that the observed radiation belongs to In^{114} is confirmed also by the results of other workers. When Cd was irradiated by 20 Mev protons, a γ-activity was observed[3] with $E_\gamma = 0.28$ Mev and $T_{1/2} = (47 \pm 10)$ millisec. An analysis of thresholds shows that the most probable reaction is $Cd^{114}(p,n)In^{114}$.

As a result of a photonuclear reaction, an activity was produced[5] with $E_\gamma = (0.312 \pm 0.01)$ Mev and $T_{1/2} = (45 \pm 10)$ millisec. Evidently the reaction that took place was $In^{115}(\gamma, n)In^{114}$.

In conclusion, let us note that the magnitude of half life estimated from the Montalbetti nomogram for In^{114} and the M3 transition, is equal to 25×10^{-3} sec and is sufficiently close to the one observed by us.

Lead. During irradiation of a metallic lead specimen (weight 1448 g, diameter 100 mm, distance to target 24 mm) we observed a short-lived activity with a complicated spectrum. To determine the nature of this activity we obtained the γ-radiation spectrum of lead for various delays after the start of the neutron pulse. If the photomultiplier is exposed for 60 millisec and a 4-millisec delay is used, we can distinguish in the spectrum of Fig. 11 four γ lines: $E_{\gamma_1} = (0.48 \pm 0.01)$ Mev; $E_{\gamma_2} = (0.58 \pm 0.01)$ Mev; $E_{\gamma_3} = (0.94 \pm 0.02)$ Mev and $E_{\gamma_4} = (1.04 \pm 0.03)$ Mev. How-

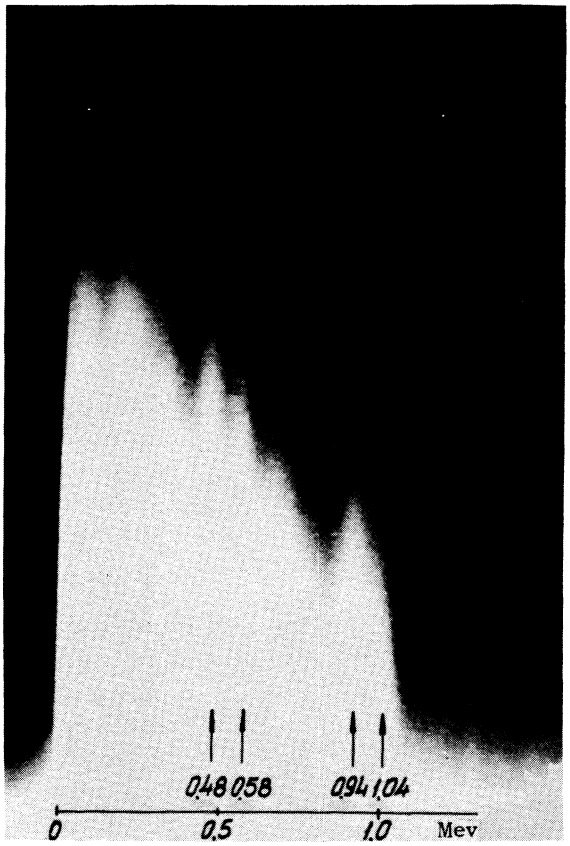

FIG. 11. Spectrum of Pb. Photomultiplier exposed for 60 millisec with 4 millisec delay after start of neutron pulse.

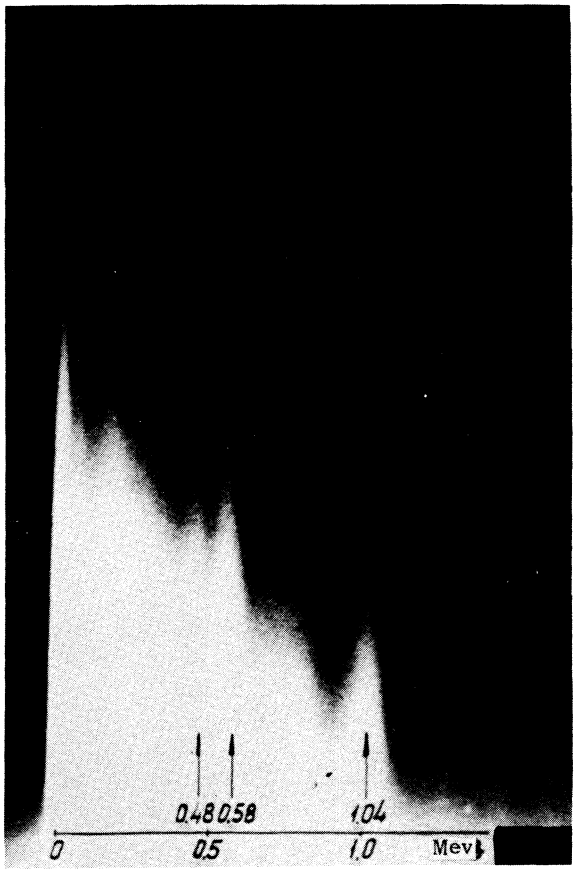

FIG. 12. Spectrum of Pb. Photomultiplier exposed for 60 millisec with 35 millisec delay from start of neutron pulse.

ever, if we expose the photomultiplier for the same period of time but use a delay of 35 millisec (Fig. 12), we can see clearly only two lines, γ_2 and γ_4, which belong to the known lead isomer Pb^{207} ($T_{1/2}$ = 0.8 sec). The intensity of the γ_1 and γ_3 lines is greatly reduced in this case and therefore they have considerably shorter half-lives than γ_2 and γ_4.

Measurements of the half-lives showed that the lines with E_γ = 0.48 and 0.94 Mev have $T_{1/2}$ = (5 ± 0.5) millisec, while the lines with E_γ = 0.58 and 1.04 Mev have a half-life of (0.8 ± 15) sec. The latter result is in good agreement with the data in the literature pertaining to the study of the Pb^{207m} isomer (for example, in reference 20, E_γ = 0.50 and 1.0 Mev and $T_{1/2}$ = 0.9 sec). To decide whether the 0.48-Mev line belongs to lead and whether it occurs in the cascade with the 0.94-Mev line, we performed an experiment similar to the one described above for bismuth. The measurements showed that both lines, with an activity of 5 millisec, have approximately equal intensities.

Let us note that this activity has not been observed previously in lead bombarded by neutrons. In reference 2 a γ radiation with energy ~ 0.9 Mev and a similar period ($T_{1/2}$ = 6.5 millisec) was noted upon irradiation of Tl by protons. Comparing these data, we ascribed the isomer activity to Pb^{205}, obtained in our work from the reaction $Pb^{206}(n, 2n)Pb^{205m}$ and obtained in reference 3 by the reaction $Tl^{205}(p, n)Pb^{205m}$.

The existence of the Pb^{205m} isomer was predicted by Pryce[21] as the result of a theoretical computation of the Pb^{205} levels, based on the shell model. The energy predicted for the transition, 0.4 ± 0.2 Mev, and the half-life of several milliseconds do not contradict our data, but according to Pryce's calculation this transition must take place at a level of 703.3 kev with a moment of $^7/_2^-$ and, therefore, is accompanied by γ radiation of this energy or less.

From our estimates, the cross section for the production of isomers with 0.8 sec activity, at the 1.04 Mev line, is 1.5×10^{-24} cm^2.

In conclusion we consider it our pleasant duty to express our gratitude to O. I. Leĭpunskiĭ for his significant aid to the work, to O. B. Likin, N. M. Meleshin, N. K. Parshenkov, V. A. Shabashov for the development and the adjustment of the equipment, and also to Yu. Ya. Lapitskiĭ, A. V.

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