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# GAMMA RAYS FOLLOWING THE BETA DECAY OF RARE-EARTH ALPHA EMITTERS *

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## ABSTRACT

The beta-decay properties of the rare-earth alpha emitters, $Dy^{150}$, $Dy^{151}$, $Dy^{152}$, and $Tb^{149}$, are discussed. By bombardment of stable praseodymium with $N^{14}$ ions at different energies in the Berkeley heavy-ion linear accelerator the three dysprosium isotopes have been produced. Gamma spectra have been obtained and the following gamma rays have been assigned to the decay of the three nuclides, 390 kev ($Dy^{150}$), 145 kev ($Dy^{151}$), and 255 kev ($Dy^{152}$). Annihilation peaks have been observed to decay with the half-lives of the three isotopes, indicating that the nuclides must emit positrons. In addition, the mass assignments of $Dy^{150}$ and $Dy^{151}$, the 8-min and 19-min dysprosium alpha emitters respectively, have been determined with certainty. $Tb^{149}$ has been produced by bombarding stable praseodymium with $C^{12}$ ions. The energies of the gamma rays following the decay of $Tb^{149}$ are 170, 230, 360, and 640 kev.

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## INTRODUCTION

In a recent publication we discussed the alpha-emitting properties of a number of rare earth isotopes.[1] The nuclides discussed included, in addition to previously known activities $Dy^{150}$, $Dy^{151}$, $Dy^{152}$, $Tb^{149}$, and $Tb^{151}$, two new alpha emitters $Dy^{153}$ and $Dy^{154}$.

From the estimated alpha half lives it is evident that these isotopes not only decay by the emission of alpha particles but also should be beta-unstable. With the exception of $Tb^{151}$ the beta-decay properties of these isotopes had never been studied. Consequently, an attempt was made to determine the alpha-branching ratios of $Dy^{152}$ and $Dy^{153}$ and to identify some gamma rays following their beta decays. The two nuclides were produced by bombarding enriched $Gd^{152}$ with 48-Mev helium ions in the Berkeley 60-inch cyclotron. The dysprosium fraction was isolated by a separation method described previously.[1] The presence of $Dy^{152}$ and $Dy^{153}$ in the dysprosium fraction was established by studying the alpha particles emitted in the decay of the two isotopes. The gamma spectrum of the sample was also obtained. The decay curve of the K x-ray peak yielded no 2.5-hr ($Dy^{152}$) or 5-hr ($Dy^{153}$) components. The shortest half life seen was about 9 hours, believed to be a composite of an 8.2-hr ($Dy^{157}$) half life and a new 10-hr ($Dy^{155}$) activity. None of the photon peaks exhibited a 2.5-hr or 5-hr half life. Our inability to see either of the two activities was very probably due to the fact that they were both obscured by the large quantities of $Dy^{155}$ and $Dy^{157}$ present in the sample. The latter two isotopes are the chief products in alpha-particle

bombardments on gadolinium enriched in $Gd^{152}$ because of the large amounts of $Gd^{154}$, $Gd^{155}$, $Gd^{156}$, and $Gd^{157}$ present in the target material. Even the use of higher-energy helium ions does not prevent the formation of $Dy^{155}$ and $Dy^{157}$ from the numerous stable isotopes of gadolinium.

To study the beta-decay properties of the dysprosium alpha emitters (with mass numbers between and including 150 and 154) these extremely neutron-deficient isotopes have to be produced free of the interfering $Dy^{155}$ and $Dy^{157}$. The use of heavy bombarding particles — specifically nitrogen ions—solves the problem. Nitrogen ions impinging on natural monoisotopic praseodymium (mass number 141) form the compound nucleus, $Dy^{155}$. This unstable intermediate then possesses sufficient energy to boil off at least several neutrons, thus forming the dysprosium alpha emitters with no $Dy^{155}$ or $Dy^{157}$. By the use of $C^{12}$ ions on praseodymium $Tb^{149}$ has been produced and its beta-decay properties have been studied, free of the less neutron-deficient terbium isotopes.

Recently the heavy-ion linear accelerator has come into operation at the University of California Radiation Laboratory, facilitating the studies herein described.

## EXPERIMENTAL METHOD

The accelerator imparts an energy of 10 Mev for each nucleon making up the accelerated particle. Thus $N^{14}$ ions are accelerated to 140 Mev. The target assembly used necessitated the interposition of two aluminum foils between the beam and the target material. The thicknesses of the foils were varied and three $N^{14}$ bombarding energies were employed. The energies were approximately 110, 80, and 35 Mev, according to Rosemary J. Barrett's range-energy curves of $N^{14}$ ions in aluminum.[2] At the lowest bombarding energy, the heaviest product seen was $Dy^{152}$, while at the highest bombarding energy evidence of the (N, 7n) reaction was observed. $Tb^{149}$ was produced in a 65-Mev $C^{12}$ bombardment.

In most of the experiments no chemical separations were attempted. Rather, the targets (praseodymium oxide powder) were counted directly so that the short-lived products such as the 7-min $Dy^{150}$ and the 19-min $Dy^{151}$

could be seen. The chemical separations were not especially necessary since the dysprosium isotopes could be identified by following their decay by means of alpha-particle counters. Once the isotopes present in the samples had been determined, the same half lives could be looked for among the peaks observed in the gamma spectra that were being obtained at the same time as the alpha counting was proceeding. A 100-channel gamma pulse-height analyzer was employed to obtain the gamma-ray spectra. The analyzer is used with a scintillation counter with a 3 by 3-inch NaI(Tl) crystal.

## The Gamma Rays of $Dy^{150}$, $Dy^{151}$, $Dy^{152}$

In order that the presentation of our results may be somewhat clearer the previously determined half lives of the isotopes entering into the discussion are listed:

| | | |
|---|---|---|
| (a) | $Dy^{150}$ | 8 min |
| (b) | $Dy^{151}$ | 19 min |
| (c) | $Dy^{152}$ | 2.5 hr |
| (d) | $Tb^{149}$ | 4 hr |

In the two bombardments using 35- and 80-Mev nitrogen ions the following experimental procedure was employed. In each case the target material was divided into two samples. Within 10 minutes of the termination of the bombardment both the samples, in each experiment, were counted. One sample was counted in an alpha counter while simultaneously the second sample was gamma-analyzed by use of the 100-channel pulse-height analyzer. The alpha-counter decay curve was then resolved into its components and the half lives present in the sample were determined in this manner. The half lives seen in the two alpha-decay curves were

35 Mev: 19 min, 2.5 hr, and some longer-lived activity;

80 Mev: 8 min, 4 hr, and possibly some 19-min activity, which may have caused the nonlinearity of the later decay points in the 8-min component after the 4-hr one had been subtracted out.

From the above decay curves it was thus learned that (a) $Dy^{151}$ and $Dy^{152}$ were present in the 35-Mev bombardment and that (b) $Dy^{150}$, $Tb^{149}$, and possibly some $Dy^{151}$ were present in the 80-Mev bombardment.

The gamma spectrum obtained in the 35-Mev experiment approximately 10 min after bombardment time is shown in Fig. 1. The spectrum taken with the same sample 5 hr later is shown in Fig. 2. In the first spectrum the most prominent peak, excluding the K x-ray and annihilation peaks, is at 145 kev. At the later time this particular gamma ray has disappeared. A 255-kev gamma ray, which in the first diagram appears only as a small peak, is now the most intense one (again excluding the K x-ray and annihilation peaks). The half life of the 145-kev gamma ray was found to be about 25 min. The 255-kev gamma ray diminished in intensity with a 2.5-hr half life. The two gamma rays, 145 and 255 kev, evidently follow the decay of $Dy^{151}$ and $Dy^{152}$ respectively.

Figures 3 and 4 show the gamma spectra obtained in the 80-Mev bombardment, where the first one was taken approximately 10 min after bombardment time and the second about 40 min after the first. An intense gamma ray is seen at the earlier time at 390 kev. Forty minutes later the gamma ray has essentially disappeared. The half life of the 390-kev peak was determined and found to be about 8 min. The gamma ray thus seems to follow the decay of the 8-min dysprosium alpha emitter.

The gamma ray following the decay of $Dy^{151}$ has an energy of 145 kev and represents a transition in $Tb^{151}$. It is interesting to note that a nucleus with the same number of neutrons (86) as $Tb^{151}$, $Eu^{149}$, has a level at 150 kev.[3] This level depopulates to the ground state of $Eu^{149}$ by the emission of a gamma ray of the same energy. The gamma ray is the most prominent one seen in the decay of $Gd^{149}$ to $Eu^{149}$. It seems quite possible that the 145-kev gamma ray seen in the decay of $Dy^{151}$ may also represent a transition from the first excited state to the ground level of $Tb^{151}$.

The decay curves obtained from the annihilation peaks in the two bombardments indicated the presence of components with the half lives of the three dysprosium alpha emitters discussed in this section. Thus all three of them, $Dy^{150}$, $Dy^{151}$, and $Dy^{152}$, must emit positrons. The alpha-branching ratios of the three isotopes were not determined because the samples were thick, as a result of which their true alpha disintegration rates were not determinable.

## The Assignment of Mass Numbers to $Dy^{150}$ and $Dy^{151}$

In the publication on rare-earth alpha emitters[1] it was stated that the 8-min and 19-min dysprosium alpha emitters were almost certainly $Dy^{150}$ and $Dy^{151}$ respectively, for the following reasons:

(a) The 2.5-hr dysprosium alpha emitter had been assigned a mass number of 152.

(b) A new isotope had been found which was probably $Dy^{149}$.

(c) From the first two facts it followed that the 8-min and 19-min activities must have mass numbers between 150 and 152.

(d) Because a higher decay energy usually belongs to a lighter nucleus (for the same atomic number) the 8-min activity with an alpha-decay energy of 4.2 Mev was logically $Dy^{150}$, and the 19-min activity with an alpha-decay energy of 4.06 Mev was $Dy^{151}$.

Up to now in our discussion we have assumed the mass assignments to be correct. The evidence in this work is sufficiently clear to make the mass assignments a certainty.

The 8-min activity, as identified by the alpha particles it emits, was observed in greatest relative abundance in the 80-Mev bombardments when compared with the abundance of the alpha particles from the 4-hr $Tb^{149}$. A gamma ray with the same half life was also observed in the same experiment. The alpha activity due to this isotope was seen in much less abundance in the 110-Mev bombardment, again when compared with the alpha activity due to $Tb^{149}$. The gamma ray was also identified at this energy (see Fig. 5) but again in much less abundance. The half life was not identified in the 35-Mev bombardment either by its alpha particles or by the gamma ray. Alpha activity with a 19-min half life was seen clearly at the 35-Mev bombardment. A gamma ray was also observed that decayed with the same half life. At 80 Mev there was a possibility that the 19-min activity may have been seen in the alpha-decay curve. However, the gamma ray assigned to the isotope was absent in the gamma spectrum. The evidence clearly demonstrates that the 8-min activity has a lower mass number than does the 19-min nuclide.

That the 8-min activity appeared in less abundance (relative to the 4-hr $Tb^{149}$) at 110 Mev than at 80 Mev indicates that the mass number of the 8-min

activity has to be greater than 149. Summing the available information and representing the mass number of the isotopes by "A", we have

(a) "A" of the 19-min isotope > "A" of the 8-min isotope > 149,

(b) from the previous work, "A" of the 19-min isotope is less than 152.

Therefore, the 8-min activity must be $Dy^{150}$, and the 19-min activity must be $Dy^{151}$.

## Results of the 110-Mev Bombardment

The experiment at this energy was performed three times. The results in all three cases were in essential agreement. Because the only alpha emitter seen in this case was $Tb^{149}$, it was difficult to make assignments as unambiguously as was done in the previous section. However, some conclusions can be drawn and these are presented below.

From the alpha-counter decay curve we were able to determine approximately with what half life $Tb^{149}$ grew in from $Dy^{149}$. The half life found in this case was closer to 20 min than to the 8-min half life reported for $Dy^{149}$ by us previously.[1] One thing is certain, $Dy^{149}$ has been seen and its half life is on the order of 10 or 20 minutes.

Figure 5 is the gamma spectrum taken approximately 10 min after the termination of the 110-Mev bombardment. The differences between Figs. 3 and 5 are apparent. First, the 390-kev gamma ray of $Dy^{150}$ decay is in much less abundance at the higher energy (Fig. 5). Second, the 780-kev gamma, assigned to $Tb^{148}$ decay in some recent work,[4] has increased in intensity in Fig. 5. Third, a gamma ray at 300 kev has appeared in Fig. 5 which was absent in Fig. 3. The half life of the 300-kev peak was found to be between 18 and 25 min. The gamma rays at 165 and 635 kev have been found to belong to $Tb^{149}$ decay. The two appear in approximately the same intensities in both the spectra, indicating that $Tb^{149}$ (initially $Dy^{149}$) must be produced in about equal amounts at the two bombarding energies. In addition to the 4-hr component in the decay curve of the 165-kev peak, there was a shorter component with a half life of about 16 min. The decay curve of the 510-kev peak yielded an activity of about 20 min plus the 1-hr activity of $Tb^{148}$.

It is difficult to determine whether the 165-kev gamma ray really does have a shorter-lived component or whether the short half life is due only to the Compton background underneath. If the component is real, it would be logical to assign it to $Dy^{149}$, because the relative intensity of the 165-kev peak seems not to change appreciably at the two bombarding energies (80 and 110 Mev), rather than to an isotope with a greater or smaller mass number. This is done because the same is true of the 635-kev gamma ray which is known to belong definitely to $Tb^{149}$. The latter gamma ray has only the 4-hr component. Using the opposite argument, the 300-kev gamma ray should be assigned to some isotope with a mass number smaller than 149 since it appears only in the 110-Mev bombardment. What dysprosium or terbium isotope it belongs to is difficult to say. Also, it is impossible to say to what isotope the short-lived component of the 510-kev peak belongs.

## The Gamma Rays of $Tb^{149}$

The target material obtained from the 65-Mev $C^{12}$ bombardment was chemically purified by means of an ion-exchange method described previously.[1] The terbium fraction was then studied. By the use of an alpha counter the 4-hr $Tb^{149}$ was shown to be present in the terbium fraction. The gamma-ray spectrum was obtained; it is shown in Fig. 6. The spectrum was taken after all of the $Tb^{148}$ mentioned previously[4] had decayed. The half life of $Tb^{148}$ has been found to be approximately 70 min, so that it was necessary only to wait long enough to be certain that the 70-min activity was no longer present. The spectrum was taken soon enough after chemical separation, however, so that only a small amount, if any, of the 9-day $Gd^{149}$ was present. The half lives of the peaks shown in Fig. 6 were found to be 4 hrs. The energies of the gamma rays assigned to the decay of $Tb^{149}$ are 170, 230, 360, and 640 kev. There is also a peak at approximately 500 kev, which may be either the annihilation peak due to positrons or a gamma ray of that energy. According to previous workers,[5] $Tb^{149}$ does not emit positrons, but the observation was not sufficiently quantitative to enable us to decide about the existence of a 500-kev nuclear gamma.

The alpha-branching ratio of $Tb^{149}$ has been determined recently by Winsberg[6] using a $4\pi$ gamma scintillation detector. He quotes a figure of

10 ± 2% for the ratio $\alpha/(EC + \alpha)$. The decay scheme of $Tb^{149}$ has not been determined. A large number of gamma rays do seem to follow the decay of $Tb^{149}$ indicating that the disintegration scheme of $Tb^{149}$ must be rather complex.

## ACKNOWLEDGMENT

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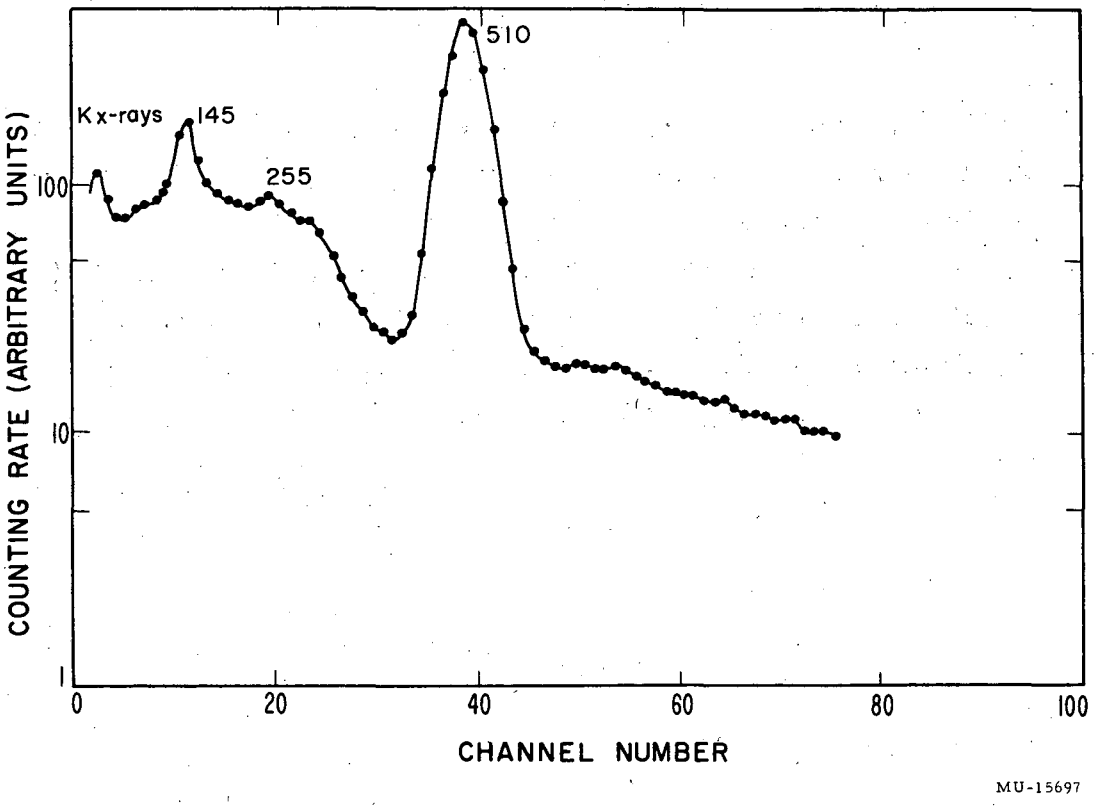


Fig. 1. Gamma spectrum taken 10 min after termination of the 35-Mev $N^{14}$ bombardment on $Pr^{141}$. Energies of peaks are indicated in kev.

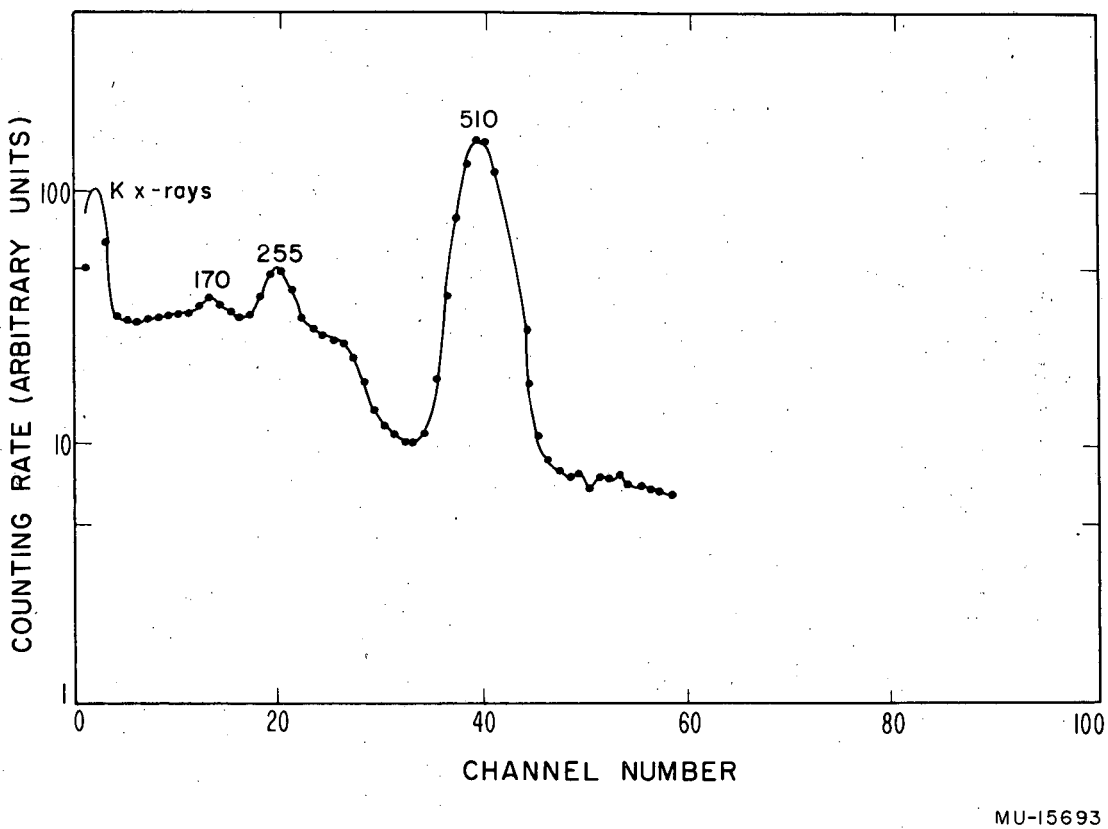


Fig. 2. Gamma spectrum taken 5 hr after completion of the 35-Mev $N^{14}$ bombardment on $Pr^{141}$. Energies of peaks are indicated in kev.

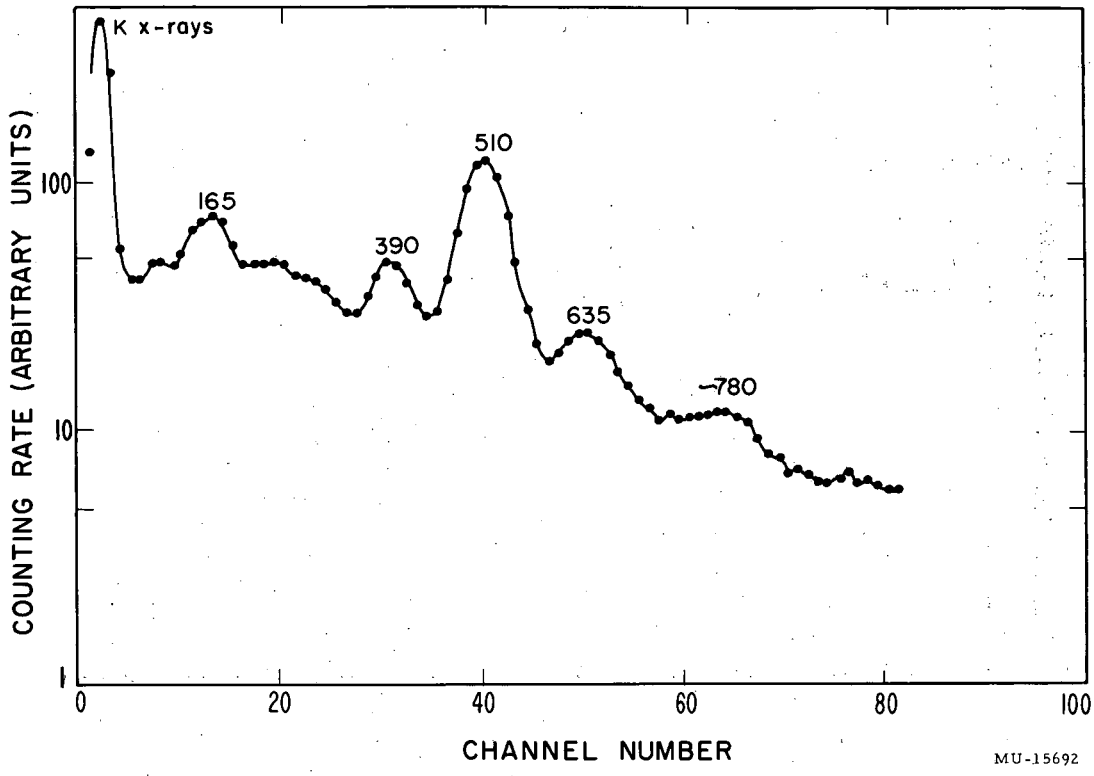


Fig. 3. Gamma spectrum taken 10 min after completion of the 80-Mev $N^{14}$ bombardment on $Pr^{141}$. Energies of peaks are indicated in kev.

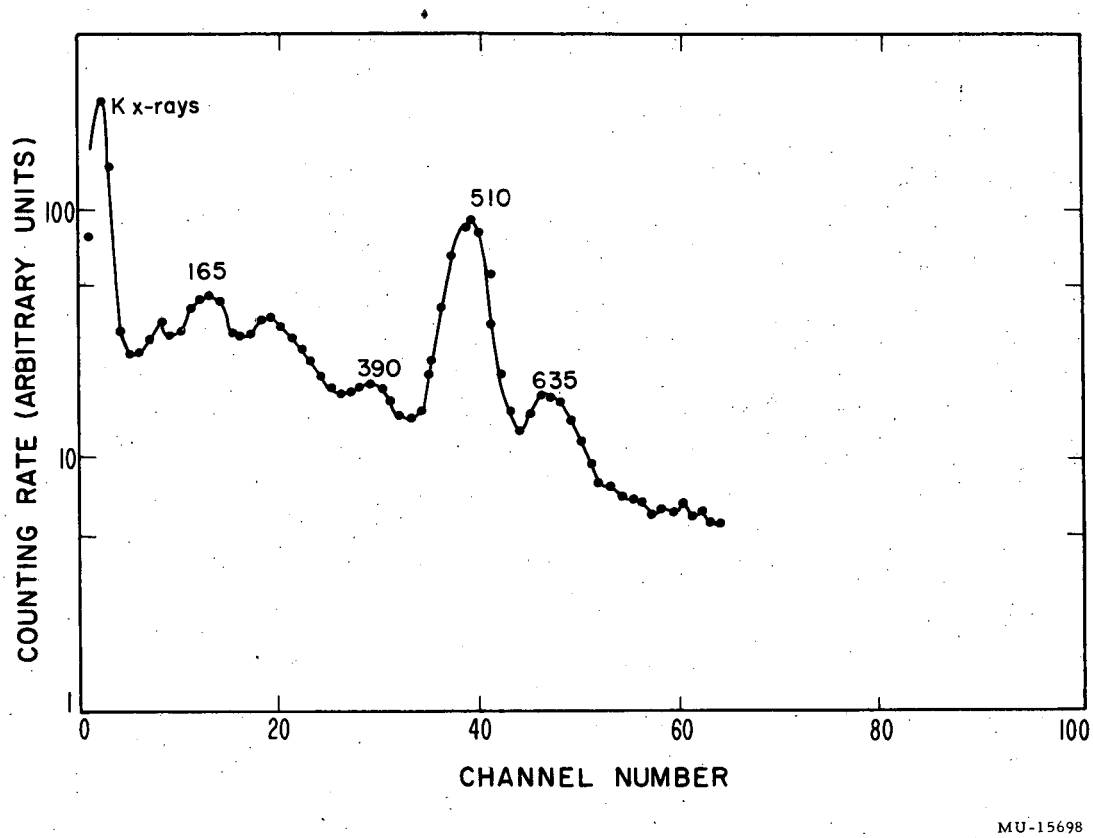


Fig. 4. Gamma spectrum taken 50 min after termination of the 80-Mev $N^{14}$ bombardment on $Pr^{141}$. Energies of peaks are indicated in kev.

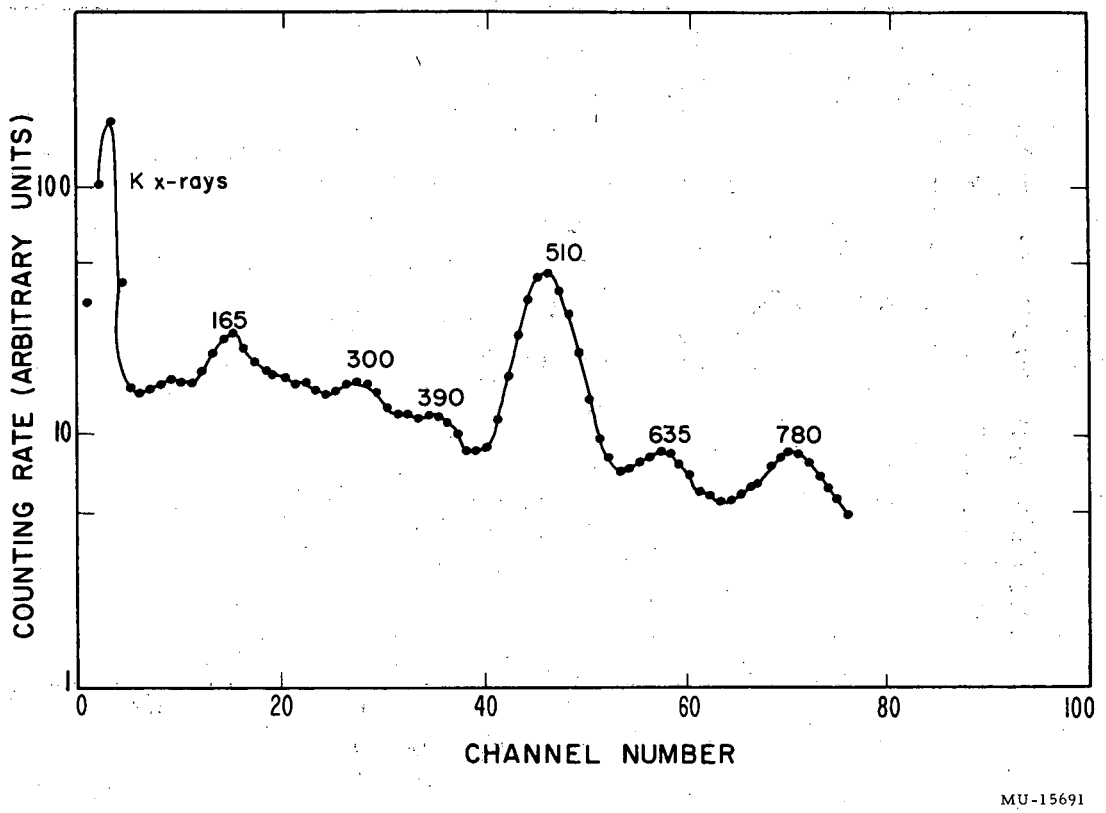


Fig. 5. Gamma spectrum taken 10 min after completion of the 110-Mev $N^{14}$ bombardment on $Pr^{141}$. Energies of peaks are indicated in kev.

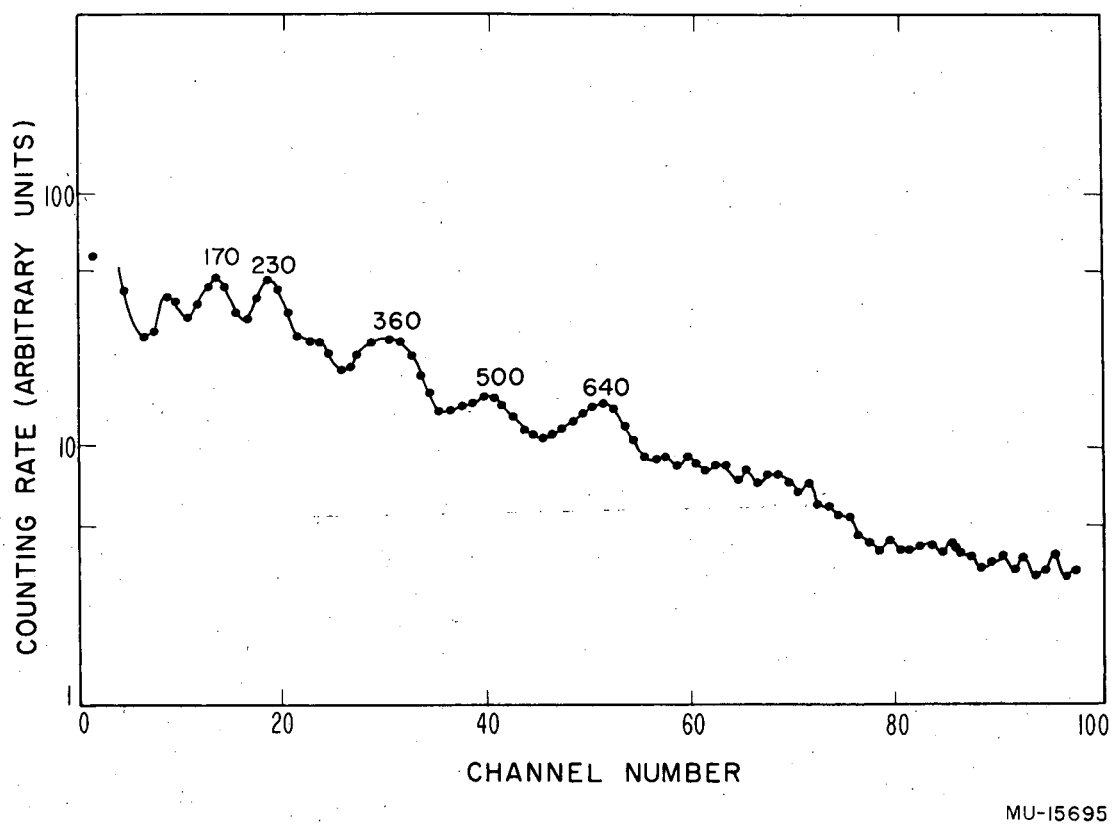


Fig. 6. The gamma ray of the spectrum of $Tb^{149}$, an activity produced in a 65-Mev $C^{12}$ bombardment on $Pr^{141}$. Energies of peaks are indicated in kev.

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