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N^{17} Energy Levels and Gamma Rays*

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The nuclear reaction Li^7+B^{11} was studied with the use of a three-parameter analysis technique. The three parameters recorded were particle type, particle energy, and energy of gamma rays in time coincidence with the charged particles. Both ungated particle spectra and particle–gamma-ray coincidence data were taken simultaneously. Particles were detected by a $E\text{-}dE/dX$ system made up of solid-state detectors. The gamma rays were detected in a large NaI (Tl) crystal. The data gathering and analyzing system consisted of three pulse-height analyzers (256 channels for E_γ and ΔE, and 1024 channels for E_{particle}), and a small general-purpose computer with magnetic tape units and an oscilliscope display. The energies of protons from the reaction $B^{11}(Li^7,p)N^{17}$ were measured. Groups corresponding to previously observed states in N^{17} were seen as well as 14 new states. Spectra of gamma rays from the bound levels of N^{17} were analyzed to give the decay schemes and some branching ratios. Calibrations were obtained from gamma rays of known energy produced in the reaction and from the known energies of some of the proton, deuteron, and triton groups.

INTRODUCTION

Relatively little is known concerning the energy levels of N^{17}, and no information is available concerning their decay, with the exception of the ground-state beta decay.[1–4] The energy levels were first measured by Littlejohn[5] using the $B^{11}(Li^7,p)N^{17}$ reaction, and significant refinements were made by Jarmie and Silbert[6] who observed the alpha particles from the $O^{18}(t,\alpha)N^{17}$ reaction with a magnetic spectrometer. From these measurements energy levels up to 4.22 MeV were observed.

To further investigate the energy levels in N^{17} and to determine their decay modes, a three-parameter analysis of the Li^7+B^{11} reactions was made. The three parameters recorded were:

(1) energy lost by charged particles in a thin detector;

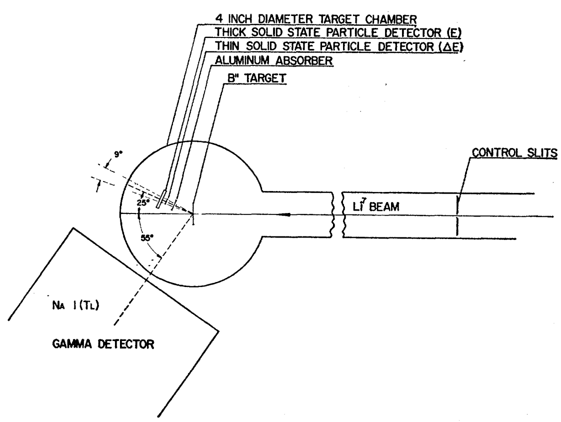

Fig. 1. Schematic diagram of experimental geometry.

(2) total energy of charged particles;

(3) energy of gamma rays in coincidence with charged particles.

The positive Q reactions which can result from the bombardment of B^{11} by Li^7 are:

$$
\begin{aligned}
Li^7+B^{11} &\rightarrow O^{18}+24.36\text{ MeV}\\
&\rightarrow O^{17}+n+16.31\text{ MeV}\\
&\rightarrow O^{16}+2n+12.17\text{ Mev}\\
&\rightarrow p+N^{17}+8.42\text{ MeV}\\
&\rightarrow p+N^{16}+n+2.54\text{ MeV}\\
&\rightarrow d+N^{16}+4.77\text{ MeV}\\
&\rightarrow d+N^{15}+n+2.27\text{ MeV}\\
&\rightarrow t+N^{15}+8.52\text{ MeV}\\
&\rightarrow \alpha+C^{14}+18.13\text{ MeV}\\
&\rightarrow \alpha+C^{13}+n+9.95\text{ MeV}\\
&\rightarrow \alpha+C^{12}+2n+5.01\text{ MeV}\\
&\rightarrow 2\alpha+Be^{10}+6.12\text{ MeV}\\
&\rightarrow He^6+C^{12}+5.97\text{ MeV}\\
&\rightarrow Be^8+Be^{10}+6.02\\
&\rightarrow Be^9+Be^9+0.874\text{ MeV}.
\end{aligned}
$$

Only those reactions which result in charged particles energetic enough to pass through the ΔE detector could be observed. This eliminates the first three and last five of the above reactions.

APPARATUS AND PROCEDURE

3.3-MeV Li^7 ions from a Van de Graaff accelerator bombarded a thin B^{11} target. The target was prepared by evaporating B^{11} onto a thin (1.67 mg/cm^2) aluminum foil using an electron bombardment apparatus similar to that described by Muggleton and Howe.[7] The target chamber, detectors, and experimental geometry were as shown in Fig. 1. The chamber has been previously

* Supported in part by National Science Foundation.
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[1] N. Knable, E. O. Lawrence, C. E. Leith, B. J. Mayer, and R. L. Thorton, Phys. Rev. **74**, 1217 (1948).
[2] Luis W. Alvarez, Phys. Rev. **75**, 1127 (1949).
[3] Evans Hayward, Phys. Rev. **75**, 917 (1949).
[4] M. G. Silbert and J. C. Hopkins, Phys. Rev. **134**, B16 (1964).
[5] C. S. Littlejohn, Phys. Rev. **114**, 250 (1959).
[6] N. Jarmie and M. G. Silbert, Phys. Rev. **120**, 914 (1960).
[7] A. H. F. Muggleton and F. A. Howe, Nucl. Instr. Methods **13**, 211 (1961).

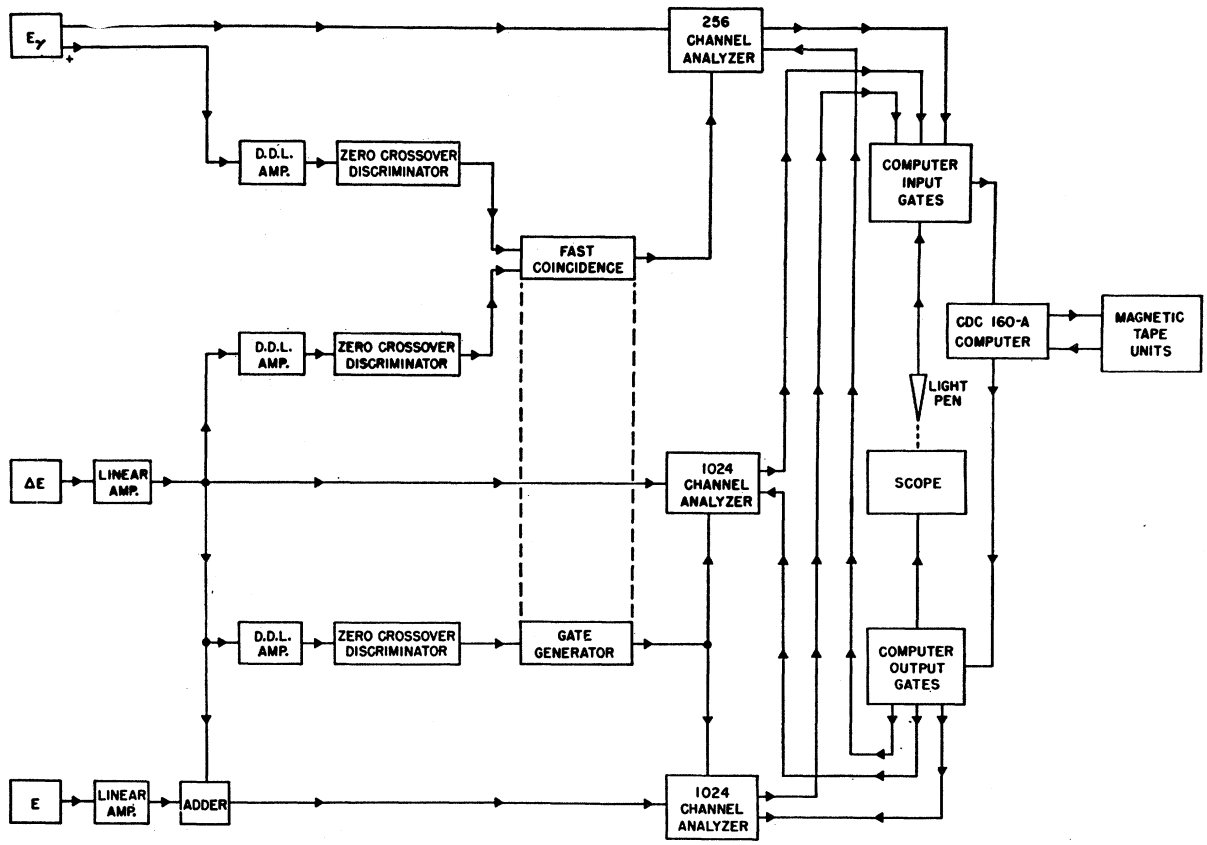

FIG. 2. Block diagram of electronics used to collect and analyze three parameter data.

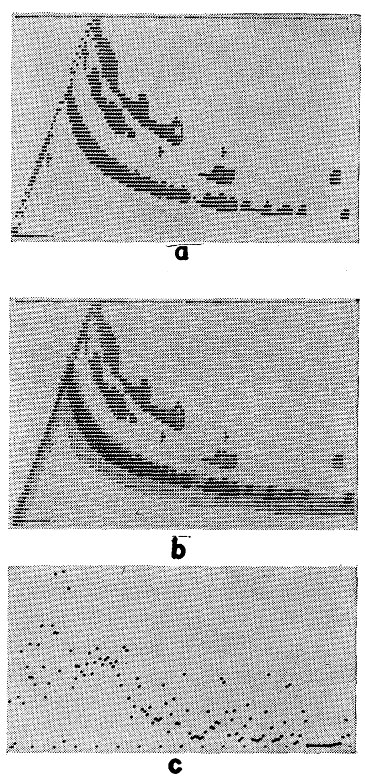

FIG. 3. Polaroid pictures of oscilliscope screen displaying 2 of 3 parameters. (a) ΔE versus E for all charged particles from Li^7+B^{11} reactions. Each spot represents a channel which contains at least 40 counts. (b) ΔE versus E with protons marked. (c) Proton energy spectrum obtained by summing counts in each column between limits shown in (b).

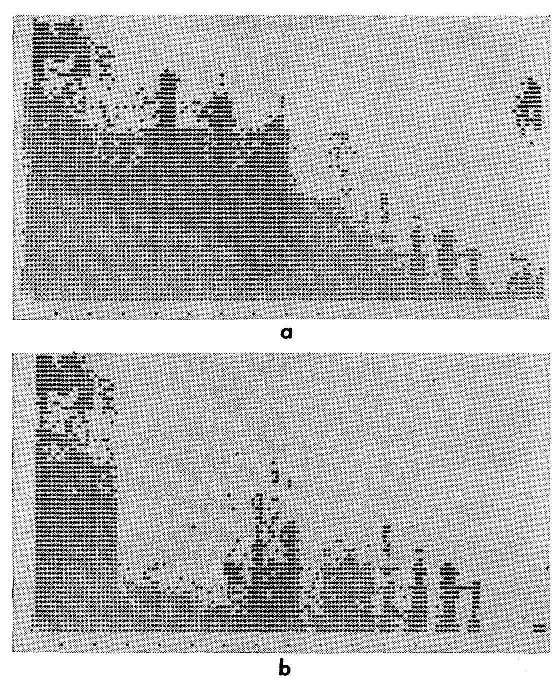

FIG. 4. Polaroid pictures of oscilliscope screen displaying gamma-ray energy vertically and coincident particle energy horizontally. All charged particle–gamma-ray coincidences are displayed in (a). Only proton–gamma-ray coincidences are shown in (b).

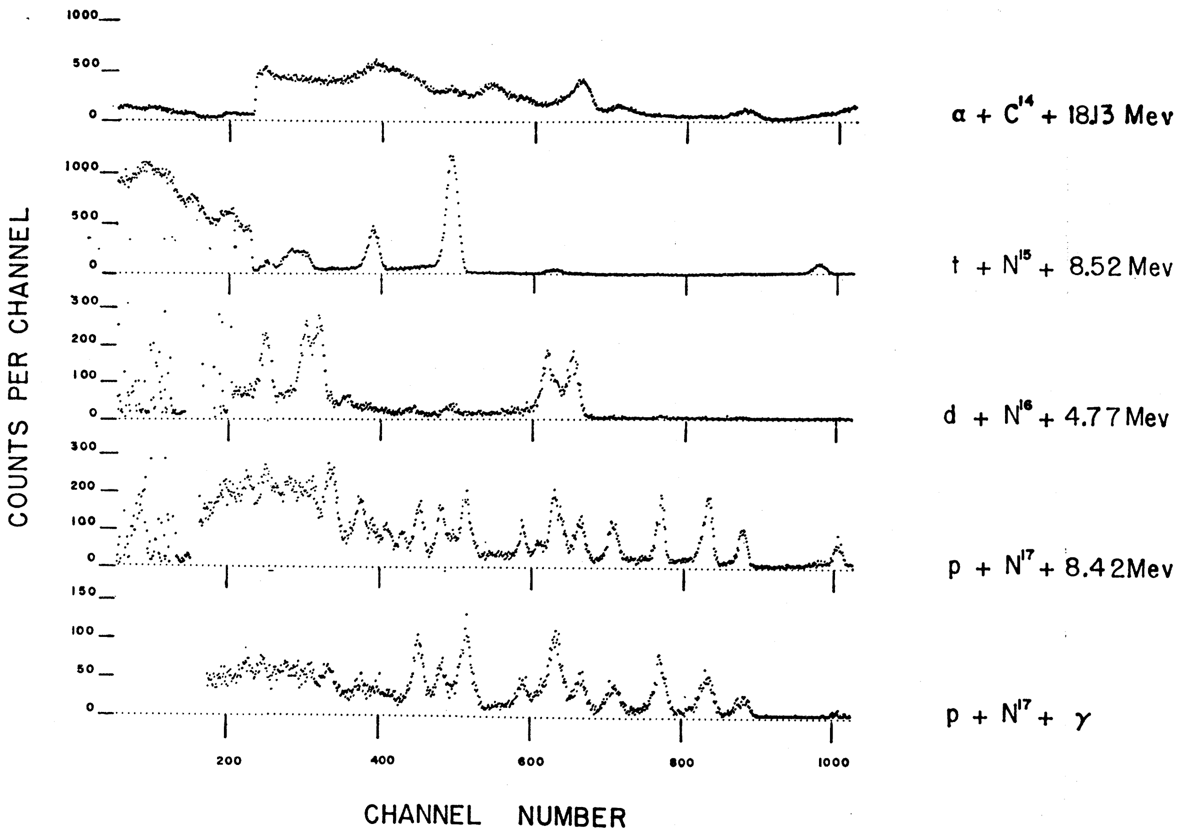

FIG. 5. Energy spectra of alphas, tritons, deuterons, and protons resulting from bombardment of B^{11} by Li^7. The bottom spectrum shows the energy spectrum of protons which were in coincidence with gamma rays.

described[8] except for a minor modification in the detector holder which allows it to hold the $E-dE/dX$ telescope.

Figure 2 shows a block diagram of the electronics used for taking and analyzing three-parameter data. Most of this equipment has been described in previous papers reporting two-parameter experiments.[8,9] With this system, particle–gamma-ray coincidence data can be taken simultaneously with noncoincident, ungated particle spectrum data. The 256-channel gamma-ray analyzer is gated by coincident E_γ and ΔE signals (50-nsec resolving time). The ΔE and $E+\Delta E$ analyzers are gated by each ΔE signal. The computer is programmed to read the analyzers, to store the condensed data in memory for a live display and to record the data on magnetic tape in full detail for future analysis. The magnetic tapes can be scanned and any two of the three parameters displayed on the oscilliscope. Two such displays are shown in Figs. 3(a) and 4(a). These figures show a 60 by 128 channel display of ΔE and E_γ plotted in the vertical direction and particle energy plotted in the horizontal direction. Using the light pen[9] and suitable computer programs the data can be marked[9] and summed to produce particle spectra such as are shown in Figs. 3(b) and 3(c). With the mark of Fig. 3(b) stored in the computer, the tape is scanned again to give the proton-gamma ray coincidences shown in Fig. 4(b). The gamma-ray spectrum corresponding to a particular particle group, i.e., to a particular state in the residual nucleus, is obtained by summing the counts in each row between specified columns of Fig. 4(b). Although Figs. 3 and 4 show the data in condensed form only, the detailed particle and gamma ray spectra can be obtained. These spectra are shown in Figs. 5 and 6.

PARTICLE SPECTRA

Alpha Spectrum

Alpha particles corresponding to the ground and first few excited states of C^{14} are off scale in Fig. 5. The broad peak centered at channel 875 is due to the 8.32-MeV state in C^{14}. All of the other peaks in the alpha spectrum can be accounted for by known states in C^{14}. Gamma rays seen in coincidence with alpha particles were from C^{14}(7.3-MeV gamma rays and

[8] R. R. Carlson and E. Norbeck, Phys. Rev. **131**, 1204 (1963).
[9] R. A. Mendelson, Jr., E. Norbeck, and R. R. Carlson, Phys. Rev. **135**, B1319 (1964).

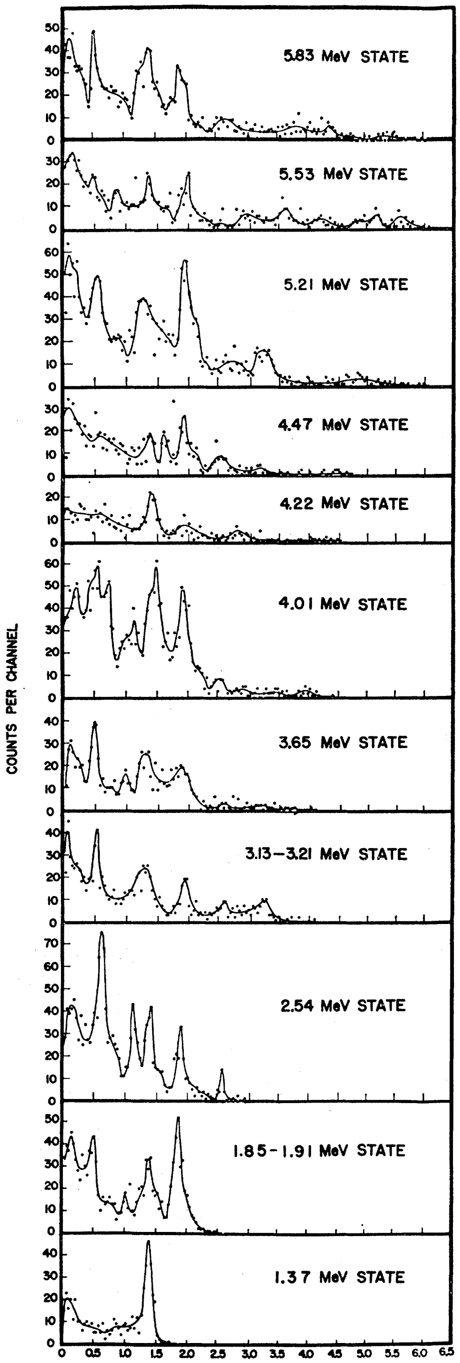

FIG. 6. Spectra of gamma rays from the bound states of N^{17}.

lower); C^{13}(3.09- and 3.7-MeV gamma rays from $C^{14*} \rightarrow C^{13*}+n$); and a trace of gamma rays from N^{15} due to the contaminant reaction $C^{12}(Li^7,\alpha)N^{15}$.

Triton Spectrum

Peaks in the triton spectrum correspond to states in N^{15}. All of the states up to the 7.57-MeV state are seen. The small peak centered in channel 627 is due to including some deuterons in the marked region of tritons and possibly from the $C^{12}(Li^7,t)O^{16}$ reaction.

Deuteron Spectrum

All of the states seen in the deuteron spectrum have been previously reported. A small peak at channel 494 is undoubtedly due to the inclusion of tritons in the deuteron mark. The small peaks at channel 446 and 355 are attributed to the contaminant reaction $C^{12}(Li,d)O^{17}$.

No gamma rays were observed from the unbound states of N^{16}. Gamma rays in coincidence with deuterons can all be explained as either coming from the bound states of N^{16}, from trace amounts of O^{17} formed in the contaminant reaction, or from N^{15}. These latter gamma rays are present because some tritons were included in the marked deuteron region.

Proton Spectrum

The proton groups correspond to previously observed states in N^{17} and to some new states. All of the states seen by Jarmie and Silbert[6] have been confirmed including the 4.22-MeV state which they reported as being doubtful. The 1.85–1.91- and 3.13–3.21-MeV doublets were not resolved in the particle spectrum. A level at 2.82 MeV reported by Littlejohn[5] was not seen.

The energies of the new states in N^{17} were calculated from a calibration based on known energies of the protons, deuterons, and tritons discussed above. Table I lists the energies of these new states in N^{17} with their probable error.

The errors shown in the table are due to the uncertainty in the channel numbers of the peaks. Data from two independent runs were available for fixing the levels in N^{17}. The geometry for both experiments was the same, but different targets, absorbing foils, and bombarding energies were used. Also, in one experiment only 512 channels were used to record particle energies and no coincident gamma-ray data were taken. Comparing level assignments from these two runs, one finds that the maximum difference is 0.061 MeV and the average is 0.036 MeV. The standard deviations resulting from the two sets of data are never greater than the errors shown in the table.

TABLE I. Energy in MeV of previously unobserved states in N^{17}. These states were observed by measuring the energy of protons from the $B^{11}(Li^7,p)N^{17}$ reaction.

4.47 ± 0.01	$6.60\ \pm0.03$
5.21 ± 0.02	$6.99\ \pm0.03$
5.53 ± 0.02	$(7.26)\pm0.05$
5.83 ± 0.02	$(7.51)\pm0.07$
6.07 ± 0.05	$7.79\ \pm0.02$
6.25 ± 0.03	$8.00\ \pm0.03$
6.45 ± 0.04	$(8.25)\pm0.03$

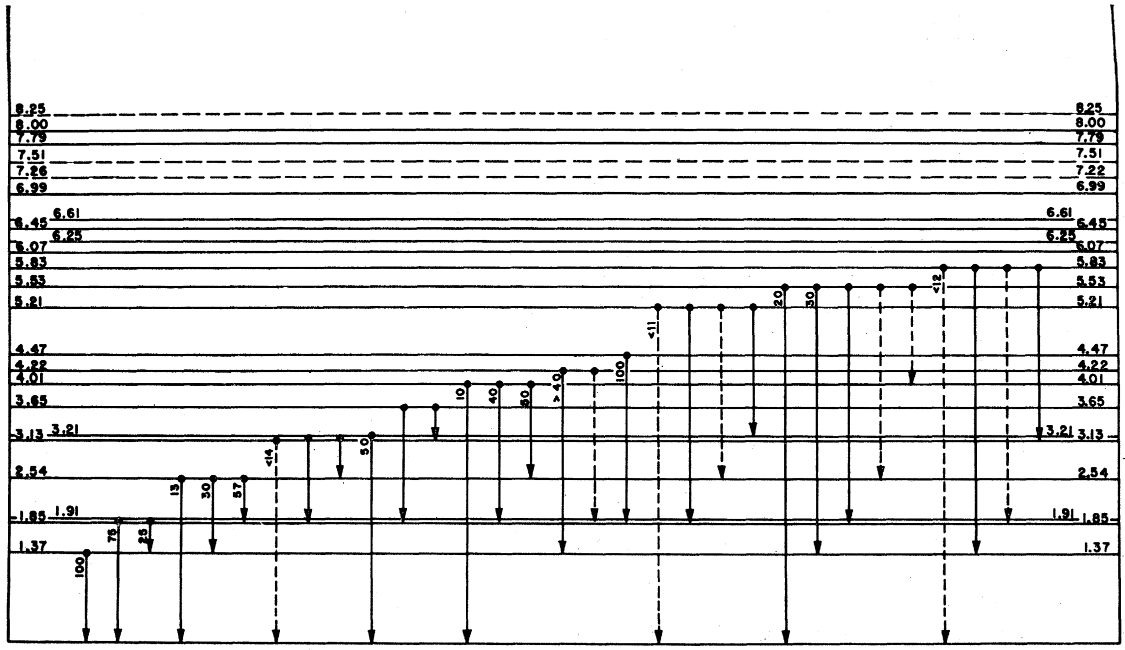

FIG. 7. Energy levels and decay scheme of N^{17}.

GAMMA-RAY SPECTRA

Figure 6 shows the gamma ray spectra from a number of states in N^{17}. A smooth curve was drawn through the points as a visual aid and to illustrate the interpretation of each spectrum. Because of the large statistical errors, some of the decay schemes are uncertain. Figure 7 shows the gamma-ray transitions deduced from these spectra with uncertain ones indicated by a dashed arrow. Only two of the peaks could not be explained on the basis of the known energy levels of N^{17}. These are the peaks at 1.6 MeV in the spectrum corresponding to the 4.47-MeV state and the peak at 0.9 MeV in the 5.53-MeV state spectrum.

Special attention is called to the two doublet states in N^{17}. Although neither of these could be resolved in the particle spectra, we were able to resolve the 3.13–3.21-MeV doublet using the coincident gamma-ray data. The spectra of gamma rays in coincidence with protons in the high- and low-energy side of the unresolved 3.13–3.21-MeV proton peak were obtained. The high-energy side spectrum contains a peak at 3.2 MeV indicating a ground-state transition. There were very few counts in this region of the low-energy side spectrum. Therefore, we conclude that the 3.21-MeV state has a ground state transition while little, if any, of the 3.13-MeV state decays to the ground state.

The 1.85–1.91-MeV doublet could not be resolved in this way. If both of these states are formed in approximately the same intensity in this reaction, then they must have nearly the same decay modes. Figure 8 shows the gamma-ray spectra from the high- and low-energy sides of each doublet.

The small number of counts in the gamma-ray spectra makes assignment of branching ratios difficult. For the lower energy levels of N^{17} these ratios can be obtained; at higher levels, only limits can be placed on some transitions.

A qualitative estimate of the branching ratios is obtained by comparing peak sizes in the noncoincident and coincident proton spectra of Fig. 5. For example, in the noncoincident spectrum, the three large peaks between channels 400 and 600 are of nearly equal intensity. In the coincident spectrum the middle peak is noticeably smaller than either of the others indicating that this state decays by higher energy gamma rays than do either of the others.

In general, branching ratios were calculated by esti-

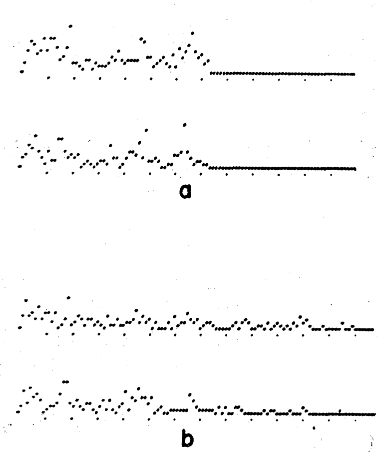

FIG. 8. Spectra of gamma rays from unresolved doublets. (a) Shows the spectrum of gamma rays in coincidence with protons in the high (top) and low (bottom) energy sides of the 1.81–1.91-MeV doublet. (b) Shows the spectrum of gamma rays in coincidence with protons in the high (top) and low (bottom) energy sides of the 3.13–3.21-MeV doublet.

mating the number of counts in the photopeaks and correcting these with the photofraction and interaction ratio (ratio of number of gamma rays which interact with the crystal at least once to the total number which pass into the crystal). These numbers were obtained from calculations similar to those reported by Miller and Snow.[10] In cases where only one photopeak could be used, the number of primary photons responsible for the remaining counts were obtained by estimating the average number of photons produced per primary cascade and using an efficiency appropriate for an average gamma ray in the remaining spectrum. To illustrate these procedures, detailed attention is given to several states.

1.85–1.91-MeV Doublet State

This doublet was considered as a single state decaying to the ground and 1.37-MeV states. The 1.87-MeV photopeak contains 319 counts. Correcting with the photofraction yields 696 counts in the 1.87-MeV spectrum. The complete spectrum of the 1.85–1.91-MeV state contains a total of 1276 counts. Subtracting the 696 counts leaves 580 counts for the transition to the 1.37-MeV state and its subsequent decay. These 580 counts must be divided between 1.37- and 0.50 MeV spectra in a ratio equal to the ratio of the interaction ratios. A simple calculation yields 335 as the number of counts in the 0.5 MeV spectrum. From these considerations and using the interaction ratios for 0.5- and 1.87-MeV gamma rays we calculate the branching ratios to be 27% to the 1.37-MeV state and 73% to the ground state.

2.54-MeV State

Branching ratios for this state were determined by reducing the spectrum to one containing counts from the 2.54 MeV ($2.54\rightarrow 0$), 1.17 MeV ($2.54\rightarrow 1.37$) and 0.67 MeV (2.54 ($2.54\rightarrow 1.87$) gamma rays only. Spectra of gamma rays from the 1.37- and 1.85–1.91-MeV states were subtracted from the spectrum of gamma rays from the 2.54-MeV state to obtain this reduction. A program was written for the computer to subtract the entire 1.87- and 1.37-MeV spectra, containing specified numbers of counts from the 2.54-MeV spectrum. From the reduced spectrum one determines the number of counts in each photopeak, applies the photofraction and interaction ratio corrections, and calculates the branching ratios given in Fig. 7.

3.21-3.13-MeV States

For these states two methods were used. First, the doublet was treated as a single state and the procedure used with the 2.54-MeV state applied. This results in a 39% branch from the doublet to the ground state. Second, use is made of the 3.21-MeV spectrum in Fig. 8(b). This spectrum contains 194 counts with 20 of these being in the 3.21-MeV photopeak. After correcting for photofraction, we find that 55 counts are due to 3.21-MeV gamma rays and the remaining 139 to cascades. By inspection of the 3.21–3.13 MeV state spectrum in Fig. 6, we estimate that the average gamma ray, excluding the 3.21 MeV gamma ray, has an energy of 1.5 MeV. The corresponding interaction ratio is 0.65. Consequently, there are approximately 215 counts due to photons from cascades to the 2.54- and 1.85–1.91-MeV states and their subsequent decay.

If the cascade goes to the 1.87-MeV state, there are about 2.2 photons for each cascade. If the cascade is to the 2.54-MeV state there are about 2.9 photons per cascade. Over-all we consider 2.5 to be the average number of photons per cascade. From these considerations, we conclude that 85 photons originate from the 3.21-MeV state and result in cascades. There are 14 photons from the ground-state transition. Therefore, the branching ratios from the 3.21-MeV state to the ground state is 52%. A similar calculation, but again treating the doublet as a single state, yields 33% for the branching ratio to the ground state.

Since the 3.21-MeV state decays to the ground state about 50% of the time and since the doublet, taken as a single state, decays to the ground state about 35% of the time, we can conclude that the ratio of the population of the two states (3.13 to 3.21) is about 3 to 7 in this reaction.

States above 4 MeV

Branching ratios for these states were computed using both methods discussed above as well as combinations of the two. The best values obtained by these methods are the ones which appear in the decay schemes in Fig. 7. The errors in these numbers range from about $\pm 10\%$ for the lower energy levels to about $\pm 25\%$ for the higher states.

CONCLUSION

The new properties of the N^{17} nucleus which have been observed are shown in Fig. 7. These are the energy levels above 4.22 MeV, the gamma-ray decay schemes of the bound states, and some of their branching ratios. N^{17} becomes unbound for breakup to $N^{16}+n$ at 5.87 MeV. No evidence was seen for gamma-ray transitions from levels in N^{17} about this threshold, with the possible exception of the 6.25-MeV state. The few gamma rays which are seen in coincidence with these particles can be explained as a transition to the 1.87-MeV doublet state. Although this possibility cannot be ruled out, it is more likely that these gamma rays came from a small amount of O^{18} formed. O^{18} is formed in the reaction $C^{12}(Li^7,p)O^{18}$ ($Q=8.40$ MeV), and since other Li^7+C^{12} reactions were observed, we must assume that this one also occurs. In this experiment protons from the 6.19-

[10] W. F. Miller and William J. Show, Rev. Sci. Instr. **13**, 39 (1960).

MeV state in O^{18} cannot be distinguished from those from a 6.25-MeV level in N^{17}. The gamma-ray transitions in O^{18} are known for only a few states, but not the states between 4.45 and 6.86 MeV. A transition from the 6.19-MeV state to the 1.98-MeV state could account for those gamma rays observed with the protons associated with the 6.45-MeV state in N^{17}.

Little new information was learned from the B^{11}-$(Li^7,d)N^{16}$, $B^{11}(Li^7,t)N^{15}$, or $B^{11}(Li^7,\alpha)C^{14}$ reactions which were also studied.

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Lifetimes of the First Excited States in Ru^{99} and Xe^{129}†

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Lifetimes of the first excited states in Ru^{99} (90 keV) and Xe^{129} (40 keV) were measured using the delayed coincidence technique. The half-lives obtained are $(20\pm1)\times10^{-9}$ sec for Ru^{99} and $(0.96\pm0.05)\times10^{-9}$ sec for Xe^{129}. These are in agreement with the lower limits previously determined by Mössbauer experiments. The $E2$ part of the 90-keV transition of Ru^{99} is enhanced by a factor of $\sim$50 relative to the Weisskopf estimate, while the $M1$ part is retarded by a factor between 2400 and 7400. The 40-keV $M1$ transition in Xe^{129} is retarded by at least a factor of 31 relative to Weisskopf estimates.

INTRODUCTION

RECENTLY the Mössbauer effect has been observed with the 90- and 40-keV transitions in Ru^{99} and Xe^{129}, respectively. The widths of the resonance lines correspond to half-lives of about 8 nsec [1] for the 90-keV first excited level in Ru^{99} and 0.8 nsec [1,2] for the 40-keV first excited level in Xe^{129}. However, measured widths of resonance lines are often appreciably larger than the natural width, and provide only lower limits for the state lifetimes. Since a knowledge of the natural widths of these levels would facilitate the interpretation of the Mössbauer spectra, we performed an accurate determination of their lifetimes using the delayed-coincidence technique. The Ru^{99} transition has been observed in Coulomb excitation by Temmer and Heydenburg[3] and we compare our results with their $\epsilon B(E2)$ value.

EXPERIMENTAL PROCEDURE AND RESULTS

I. The 90-keV Transition in Ru^{99}

A source of Rh^{99} was prepared by bombardment of ruthenium metal powder, enriched in Ru^{99}, with 10-MeV protons from the Brookhaven cyclotron. The measurements were performed several days after bombardment to allow for decay of the 4.5-h Rh^{88m} activity. No chemical separation was necessary. The partial decay scheme of Rh^{99m} is shown in Fig. 1 where only those levels and transitions pertinent to our measurements are shown. The source of Rh^{99m} was viewed by a gamma-ray counter and an electron counter which were both Naton 136 plastic scintillators having dimension 2.5 cm thick$\times$2 cm diam and 1 mm thick$\times$7 mm diam, respectively. The scintillators were mounted on 56 AVP photomultiplier tubes, the multiplier used for

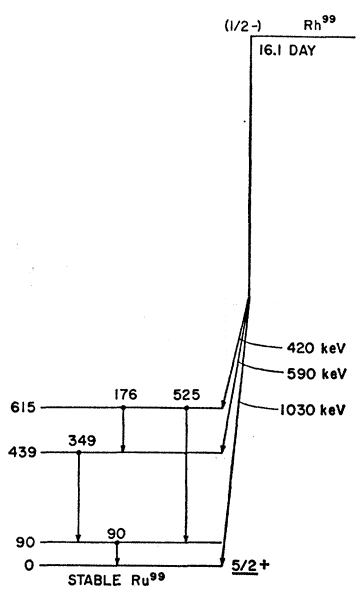

FIG. 1. Partial decay scheme of Rh^{99}. Gamma-ray energies are given in keV.

† Under the auspices of the U. S. Atomic Energy Commission.
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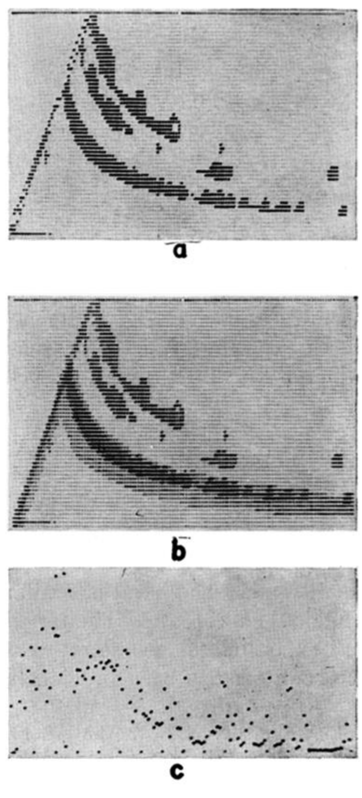
[1] O. C. Kistner, S. Monaro, and R. Segnan, (Ru^{99}) Phys. Letters 5, 299 (1963); Xe^{129} (to be published).

[2] During the course of this work, another measurement of the lifetime of the 40-keV state in Xe^{129} performed by Mössbauer effect was reported by C. L. Chernick, C. E. Johnson, J. G. Malm, G. J. Perlow, and M. R. Perlow, Phys. Letters 5, 103 (1963). Their result was $\tau_{1/2}=(0.58\pm0.07)$ nsec.

[3] *Nuclear Data Sheets*, compiled by K. Way, *et al.* (Printing and Publishing Office, National Academy of Sciences—National Research Council, Washington 25, D. C.), NRC 61-1-49, 50, and 59; G. M. Temmer and N. P. Heydenburg, Phys. Rev. 104, 967 (1956).



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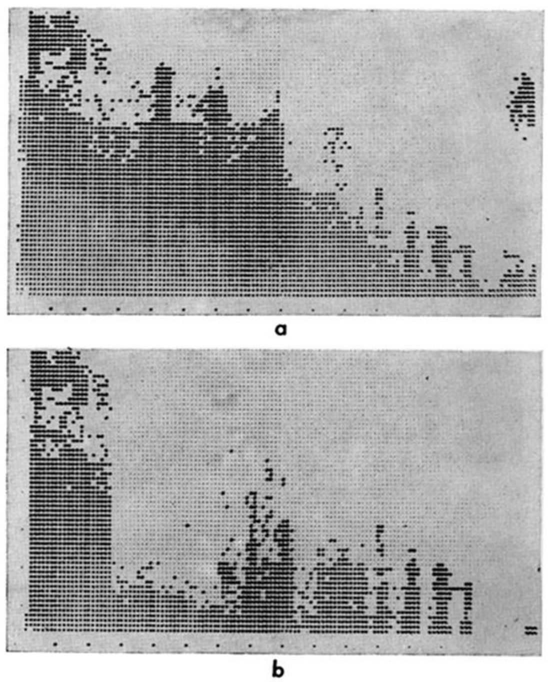

FIG. 4. Polaroid pictures of oscilliscope screen displaying gamma-ray energy vertically and coincident particle energy horizontally. All charged particle–gamma-ray coincidences are displayed in (a). Only proton–gamma-ray coincidences are shown in (b).