Gamma Radiation from the Reaction $C^{13}(p, \gamma)N^{14}$†

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(Received August 28, 1953)

The capture radiation from $C^{13}(p,\gamma)N^{14}$ has been investigated and found to show cascade transitions which involve bound levels in N^{14} at 2.31, 3.95, 5.09, 5.81, 6.26, and 6.44 Mev in addition to the resonance levels at 8.06, 8.62, 8.70, 8.90, 8.98, 9.17, and 9.49 Mev.

INTRODUCTION

THE thin-target excitation curve for the reaction $C^{13}(p,\gamma)N^{14}$ has previously been investigated in this laboratory for proton bombarding energies up to 2.7 Mev.[1] Five definite resonances were found, corresponding to excited states of N^{14} at 8.06, 8.62, 8.70, 9.17, and 9.49 Mev. It was observed that the gamma-ray spectrum changed considerably from one resonance to another and involved cascades through intermediate levels of N^{14}. In addition, recent work in this laboratory on the elastic scattering of protons on C^{13} has clearly demonstrated the existence of two other resonances corresponding to excited states at 8.90 Mev and 8.98 Mev[2] which were tentatively reported in reference 1.

In order to obtain more information on the energy levels of N^{14} below 9.5 Mev, we have investigated the gamma-ray spectrum in detail at each of the 7 resonances by using a sodium iodide scintillation counter as a gamma-ray spectrometer.

EXPERIMENTAL PROCEDURE

The NaI(Tl) crystals used most frequently in our work were $1\frac{1}{2}$ inches in diameter by $1\frac{1}{2}$ inches long. Originally the crystals were enclosed in mineral oil in a Lucite container which was placed on the photocathode of a selected 5819 photomultiplier tube. Mineral oil was used to provide optical contact between the Lucite and the phototube, while a magnesium oxide reflector was placed around the sides and top of the Lucite container. Later, a more permanent arrangement was employed in which the crystal was cemented to a quartz disk which in turn was cemented to a magnesium oxide coated aluminum can enclosing the crystal. A thin Lucite light pipe and viscous silicone oil were used to provide optical contact between the photomultiplier and the quartz disk. A smaller ($\frac{1}{2}$-inch cube) NaI(Tl) crystal, which was placed directly on the photomultiplier with a small aluminized cup used as a reflector, was occasionally used to give supplementary information on the pulse-height spectra. These three crystal arrangements appeared to have about the same light-gathering efficiency. The resolution obtained with Cs^{137} (0.661 Mev) and the type-5819 photomultiplier tube ranged from 9 to 12 percent depending on the phototube used. In the most recent work, a DuMont type 6292 photomultiplier tube was used with which the instrument has a resolution of 7.5 percent for the Cs^{137} radiation.

The spectrum obtained with the small crystal for gamma rays of about 3.5 to 7 Mev consists primarily of a "pair peak" at an energy 1.02 Mev less than the gamma-ray energy. On the other hand, the larger crystal also gives peaks at E_γ and $E_\gamma - 0.51$ Mev, which are produced by the absorption of the scattered photon as well as the primary Compton electron or by the absorption of one or both annihilation quanta in addition to an electron-positron pair. At higher energies, even with the larger crystal, the resolution of the scintillation counter was not sufficient to permit these three peaks to be well separated and the resulting spectrum showed only an asymmetric peak with two bumps on the high-energy side.

After amplification the pulse-height spectrum was obtained either by a photographic method or by means of a single channel pulse-height analyzer designed by M. Sands. Later, a ten-channel analyzer of Los Alamos design[3] was employed. For the oscilloscope presentation, the pulses were shaped by a 1.5-microsecond delay-line clipper and were applied to the vertical deflection plates of a Tectronix 511D oscilloscope with the horizontal sweep being triggered by the pulse. The face of the oscilloscope was masked except for a vertical strip 2 cm wide, and a sweep speed of 10 cm per microsecond was used. Peaks in the pulse-height distribution then appeared as horizontal lines and a permanent record was obtained by making a time exposure with a Land camera. The range of intensities obtainable with a single exposure was increased by means of a colored cellophane filter placed over 1 cm of the 2-cm wide strip. To correct for non-linearities in the system, which were mainly in the oscilloscope tube and in the optical system of the camera, a series of pulses whose height could be varied in equal voltage increments was fed into the input of the preamplifier and photographed on the oscilloscope. Since five exposures could be made on

† This work was assisted by the joint program of the U. S. Office of Naval Research and the U. S. Atomic Energy Commission.
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[1] J. D. Seagrave, Phys. Rev. 85, 197 (1952).
[2] E. A. Milne, Ph.D. thesis, California Institute of Technology, 1953 (unpublished) and private communication.
[3] C. W. Johnstone, Nucleonics 11, No. 1, 36 (1953).

each film the general practice was to include this linearity calibration with each pulse-height spectrum of interest, in addition to the spectrum of gamma-rays of known energy which were used to establish the energy calibration. For this latter purpose, Na^{22} (0.511 Mev and 1.277 Mev) and ThC″ (2.615 Mev) were most frequently used. This technique proved to be very rapid and convenient, not only for qualitative "surveying" but also for energy measurements accurate to about 2 percent.

The oscilloscope arrangement was also used in obtaining pulse-height spectra in gamma-gamma coincidence measurements. A second counter with a NaI(Tl) crystal $1\frac{1}{2}$ inches in diameter by $1\frac{1}{2}$ inches long was placed on the opposite side of the target from the first (both counters were at 90° to the beam). Their outputs went to a coincidence circuit with a resolving time of 0.1 microsecond which was used to trigger the sweep of the oscilloscope. The output of one of the counters was applied to the vertical deflection plates of the oscilloscope, while a sufficiently high bias on the coincidence input fed by the other prevented false coincidences from back-scattered Compton gamma rays or from annihilation radiation. The counting rates were low enough that accidental coincidences could easily be taken into account.

In using the pulse-height analyzer, the procedure was to alternate the measurement of pulse-height spectra from $C^{13}(p,\gamma)$ with those from artificial radioactive sources (such as Na^{22} or ThC″), which were used to provide the energy calibration. After each spectrum had been obtained, the pulse height corresponding to peaks in the spectrum was measured with a precision pulser which was accurate to a few tenths of a percent. These pulses were fed into the preamplifier in parallel with those from the photomultiplier. It was thus possible to eliminate the effects of any non-linearities in the amplifier or analyzer. Since the alternation of the gamma rays from $C^{13}(p,\gamma)$ with known pulse-height spectra gave one a check on drifts in the photomultiplier gain, one could feel confident that the gamma-ray energy measurements were not being affected by instrumental difficulties.

Since the energies of the transitions to the ground state of N^{14} could be calculated from the Q value of the reaction and the proton bombarding energy, it was possible to check the pulse-height linearity of the scintillation counter up to 9 Mev. It was found that as long as the voltage on the type 5819 photomultiplier was kept less than about 750 volts this linearity was good within the experimental accuracy (1 percent). For lower-energy gamma rays it was possible to raise the photomultiplier voltage above 750 volts before non-linear effects were encountered. The type 6292 photomultiplier showed considerably more nonlinearity and it was not used where much extrapolation was involved.

The gamma rays were produced by bombarding C^{13} targets with protons from the 3-Mev electrostatic generator. The protons were analyzed by either an electrostatic or a magnetic analyzer set to give an energy resolution of 0.1 to 0.2 percent. At each resonance, before observing the pulse-height spectrum, an excitation curve was run in order to obtain the maximum intensity and also to be sure that the observed radiation was characteristic of the resonance. The two targets used were 7 and 16 kev thick at 1.7 Mev and were composed of carbon, enriched to 60 percent C^{13}, deposited on a tantalum backing. The preparation of these targets is described in detail in reference 1. The background radiation produced by reactions in the C^{12} content of the target or the tantalum backing was investigated independently and found to be much less intense than the radiation from the reaction $C^{13}(p,\gamma)$. It could also be distinguished from the latter by its excitation function, since the resonances in $C^{13}(p,\gamma)$ are well known.[1] In most cases the pulse-height spectra were measured with the scintillation counter placed at 90° to the beam about $\frac{3}{4}$ inch from the target. Several resonances were also investigated at 0° to the beam and these results will be discussed in a later section.

EXPERIMENTAL RESULTS OBSERVED AT 90° TO THE BEAM

Typical pulse-height distributions, which show the various features encountered at three of the resonances in $C^{13}(p,\gamma)$, are illustrated in Figs. 1–3. In Fig. 1 are shown the results obtained at a resonance bombarding energy of 0.55 Mev corresponding to an excited state in N^{14} at 8.06 Mev. In what follows such a state will be referred to as the 8.06(0.55)-Mev resonance level.[4] The peaks at 1.3 and 2.3 Mev in Fig. 1 have the proper shape and separation to be the pair and photopeaks of a 2.3-Mev gamma ray, while the rise just below 2 Mev is the Compton edge for this gamma ray. The peak at 1.6 Mev is the photopeak of a 1.6-Mev gamma ray whose Compton edge is obscured by the 1.3-Mev pair peak. The rise below 1.3 Mev is the tail of the annihilation radiation from the positron decay of N^{13} which is formed in the reaction $C^{12}(p,\gamma)N^{13}$. A similar pulse-height spectrum also occurred at the 8.62(1.16)-Mev resonance, which suggests that the 1.6- and 2.3-Mev gamma rays are part of a cascade through the lower levels of N^{14}. In the region of pulse heights from 3 to 4 Mev in Fig. 1, there occur three peaks characteristic of a 4-Mev gamma ray. The peak at 7 Mev in this figure is produced by an 8-Mev gamma ray. Its structure is caused by contributions from the high-energy end of the Compton distribution in addition to the secondary effects mentioned previously.

In attempting to detect a weak gamma ray in the presence of other radiation, one is limited by statistical fluctuations in the counting rates of the pulse-height

[4] The Q of this reaction is 7.54 Mev as given by C. W. Li *et al.*, Phys. Rev. **83**, 512 (1951). Thus, the excitation energy of N^{14} in Mev is given by $E_X = 7.54 + (13/14)E_p$, where E_p is the proton bombarding energy in Mev.

analyzer channels and also by variations in channel width. The photographic method of pulse-height analysis eliminated the second difficulty, and by stopping down the camera one could record enough pulses for good statistical accuracy without overexposing the film. By this means, a search was made at the 8.06(0.55)-Mev resonance for a gamma ray at 5.8 Mev corresponding to a transition from the resonance level to the known level at 2.31 Mev. However, no radiation was found in the region from 5 to 7 Mev with an intensity greater than 2 percent of the ground state transition.

The radiation from the 8.06(0.55)-Mev resonance level was intense enough to permit a gamma-gamma coincidence experiment to be performed using the photographic technique to record the pulse-height distribution. This experiment showed that the 4-Mev gamma ray plus the 2.3- and 1.6-Mev gamma rays were related in some sort of cascade transition.

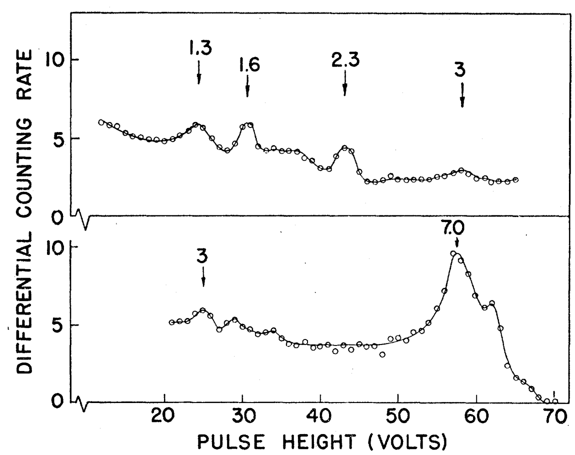

FIG. 1. Differential pulse-height spectrum of the gamma rays from the 8.06(0.55)-Mev resonance level of $C^{13}(p,\gamma)N^{14}$.

The gamma-ray results obtained at this resonance do not agree with previously published results. Fowler and Lauritsen[5] report a 5.8-Mev gamma ray, while Barnes *et al.*[6] found a possible line at 5.81 Mev. It seems likely, as suggested by Barnes *et al.*, that this line is actually due to fluorine contamination. Recently, Hicks *et al.*[7] have published a brief account of their measurements with a scintillation pair spectrometer. They find several gamma rays which we do not detect at this resonance, although the radiation they ascribe to a 5.0-Mev level does show up in our work at the 9.49(2.10)-Mev resonance. Since the details of their work are lacking, it is difficult to account for this discrepancy. Clegg and Wilkinson[8] have also investigated the radiation at the

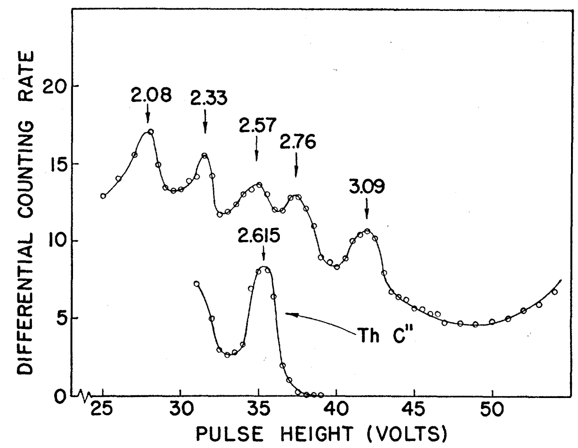

FIG. 2. Differential pulse-height spectrum of the gamma rays from the 8.90(1.47)-Mev resonance level of $C^{13}(p,\gamma)N^{14}$.

8.06(0.55)-Mev resonance and have obtained results in substantial agreement with ours. In particular, they have been able to put an upper limit of 0.7 percent on the intensity of a possible 5.8-Mev line.

At the 8.62(1.16)-Mev resonance, in addition to the 1.6- and 2.3-Mev gamma rays, there appeared in the pulse-height distribution a complicated structure in the 4-Mev region which was resolved into two gamma rays at 3.9 and 4.7 Mev. From energy considerations it is obvious that the 3.9- and 4.7-Mev gamma rays form one cascade while the 1.6-, 2.3-, and 4.7-Mev gamma rays form another. The fact that only one 4.0-Mev gamma ray was found at the 8.06(0.55)-Mev resonance can easily be explained if there is a level at approximately 4.0 Mev in N^{14} since the radiation from the 8.06(0.55)-Mev resonance level to such a level could not be separated from the ground state decay of such a level.

Also at the 8.62(1.16)-Mev resonance, there was found ground state radiation and a 6.3-Mev gamma

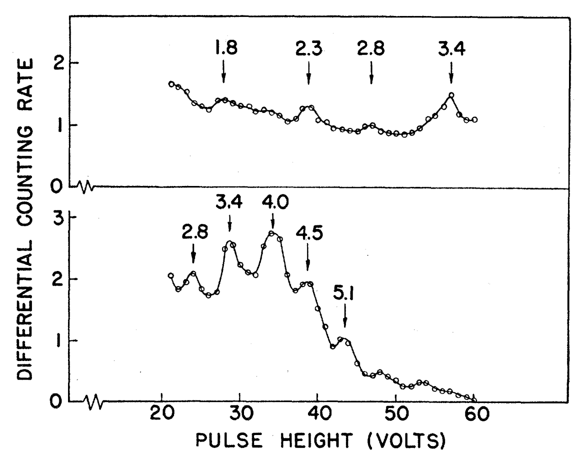

FIG. 3. Differential pulse-height spectrum of the gamma rays from the 9.49(2.10)-Mev resonance level of $C^{13}(p,\gamma)N^{14}$.

[5] W. A. Fowler and C. C. Lauritsen, Phys. Rev. **76**, 314 (1949).
[6] Barnes, Carver, Stafford, and Wilkinson, Phys. Rev. **86**, 359 (1952).
[7] Hicks, Husain, Sanders, and Beghian, Phys. Rev. **90**, 163 (1953).
[8] A. B. Clegg and D. H. Wilkinson (private communication).

ray. At first it was believed that the latter radiation represented a transition to the known 2.31-Mev level, but the interpretation of the elastic scattering of protons by C^{13} indicated that this was improbable since it would require a $0-0$ radiative transition (see discussion). Further work then showed the following: First, the 6.3-Mev radiation exhibited the same excitation curve as the other gamma rays at this resonance. Second, the relative intensities confirmed that the 6.3-Mev radiation was in cascade with a single gamma ray with an energy of approximately 2.3 Mev. Although the photopeak from the stronger 2.31-Mev radiation appeared skew on the high energy side, it could be established quantitatively only that the cascade radiation of interest was less than 2.39 Mev. Thus, the higher energy transition must be greater than 6.23 Mev. Finally, the energy of the 6.3-Mev radiation was measured to be 6.25 ± 0.04 Mev by comparing it with the 6.13-Mev $F^{19}(p, \alpha\gamma)O^{16}$ radiation. This is to be compared with the value of 6.31 Mev for a transition directly to the 2.31-Mev level. These results lead us to believe that this radiation corresponds to a cascade through a level in N^{14} which has an energy greater than 6.23 Mev and less than 6.29 Mev (6.26 ± 0.03 Mev).

The 8.70(1.25)-Mev level decayed primarily by radiation to the ground state. This and the fact that the resonance was very weak prohibited a detailed investigation of the cascading with the ten-channel discriminator. However, the photographic method revealed some cascading (10 percent) that may involve a level in N^{14} at 5.69 Mev. This possibility is briefly discussed below.

To measure the energy of a particular gamma ray, one looks at the pulse-height spectrum in detail on an expanded scale and compares it with the spectrum of a standard source as described above. To eliminate systematic errors due to possible differences in channel widths in using the ten channel analyzer, the bias settings are chosen to give overlapping intervals. An example of this is shown in Fig. 2 where the 2.0-Mev to 3.5-Mev region of the spectrum found at the 8.90(1.47)-Mev resonance is shown. This very complicated spectrum is explained as follows. The 2.08-, 2.57-, and 3.09-Mev peaks are the three characteristic peaks of a 3.09-Mev gamma ray. The 2.33- and 2.76-Mev peaks are the photopeaks for two weaker gamma rays of approximately these energies. There is no question that the 2.33-Mev peak is a photopeak, but since the 2.76-Mev peak coincides with the Compton maximum from the 3.09-Mev gamma ray it may be in doubt. However, the pronounced dip between the 2.76-Mev peak and the 2.57-Mev peak and the general rise in counting rate indicate that there is indeed a gamma ray present of approximately this energy. The rather flattened appearance of the ThC″ line (2.615-Mev photopeak) and the 3.09-Mev peak is due to the fact that the channel width used (1 volt) is comparable to the resolution at this particular setting. Besides these gamma rays, three others at 5.7, 5.1, and 0.73 Mev were also found at this resonance. Since the 3.09-Mev gamma ray was the strongest, it most likely is the first in the cascade. If this is correct, then there must be a level at 5.81 Mev (8.90–3.09) in N^{14}. Energy considerations then indicate that the 5.1- and the 0.73-Mev gamma rays result from the decay of this 5.81 level and the 2.3- and 2.8-Mev gamma rays result from an alternative decay of the 5.1 level. This scheme is further confirmed by the spectrum from the 2.1-Mev resonance and from the relative intensities.

The 8.98(1.55)-Mev resonance level decays primarily to the ground state. Because it was so weak and superimposed on the broad 1.25-Mev resonance, any cascade transitions less than 15 percent as intense as the ground state radiation could not have been detected.

The radiation from the 9.17(1.76)-Mev resonance level leads almost wholly to the ground state of N^{14}. There is, however, a weak cascade consisting of a 6.5-Mev and a 2.73-Mev gamma ray. A coincidence meas-

TABLE I. Gamma radiation from $C^{13}(p, \gamma)N^{14}$ (all energies in Mev).

Resonance	8.06(0.55)	8.62(1.16)	8.70(1.25)	8.90(1.47)	8.98(1.55)	9.17(1.76)	9.49(2.10)	Best values
	8.03±0.10	8.6 ±0.1	8.7±0.1		9.0±0.1	9.17±0.10		
						6.5 ±0.1		6.44 ±0.02
		6.25±0.04						6.26 ±0.03
				5.7 ±0.2				5.81 ±0.02
				5.1 ±0.1			5.09±0.05	5.09 ±0.02
		4.7 ±0.2						4.68 ±0.02
Measured							4.41±0.08	4.36 ±0.02
gamma	4.0 ±0.1	3.94±0.06						3.95 ±0.02
radiation			(3.9)?					
				3.09 ±0.02				
			(3.4)?					
				2.8 ±0.1			2.78±0.04	2.77 ±0.03
			(3.0)?					
						2.73±0.02		
	2.32±0.02	2.33±0.02	2.3	2.32 ±0.04			2.32±0.02	2.310±0.012
	1.63±0.02	1.64±0.02						1.638±0.008
				0.731±0.007			(0.73)?	0.725±0.004

urement showed that these two were indeed in cascade as can be inferred from the fact that their energies add up to the full energy available.

Gamma rays from the 9.49(2.1)-Mev resonance level (Fig. 3) were found at energies of 2.3, 2.8, 4.4, and 5.1 Mev. The radiation above 5.1 Mev did not show resonance and is believed to be from fluorine contamination in the Ta target backing. Energy considerations indicate that there are two cascades, one consisting of the 4.4- and 5.1-Mev gamma rays and the other consisting of the 2.3-, 2.8-, and 4.4-Mev gamma rays. The relative intensities are consistent with this interpretation.

These data are summarized in Table I while the proposed decay schemes are shown in Fig. 4. In Table I, the best values for the energies of these transitions are listed for comparison with our observed values. They were obtained as follows. The three lowest values and the 3.95 value are from the beta-ray spectrometer analysis of the gamma radiation from $C^{13}(d, n\gamma)N^{14}$.[9] The 6.44 and 5.81 values are obtained by subtracting the energy obtained for the softer cascade gamma ray from the calculated Q values of the corresponding resonance involved. The 5.09 value is obtained by subtracting 0.725[9] from 5.81, and the rest are obtained by taking differences between these energies (see the decay schemes in Fig. 4).

The relative intensities listed for the decay schemes in Fig. 4 were obtained by measuring the area under the pulse-height curve which is produced by each gamma ray. This area is proportional to the gamma-ray yield times the detection efficiency of the counter. The efficiency has been calculated for the particular geometrical arrangement used for a number of gamma-ray energies and has been checked with the known gamma-ray fluxes from the reaction $F^{19}(p, \alpha\gamma)O^{16}$ (6.14-Mev gamma ray) and from a calibrated Na^{22} source (1.28- and 0.511-Mev gamma rays). The agreement between the calculated and measured values was better than 10 percent. In determining the area due to each gamma ray for this counter, it has been found that the pulse-height curve below the pair peak can be extrapolated horizontally back to zero pulse height. This fact has greatly simplified the problem of measuring the gamma-ray yield. At several resonances where two or more gamma rays are within one-half to one Mev of each other, no attempt was made to separate the total areas under each. Thus a complete cross check on the decay scheme was not always possible by this method, although a comparison of the relative size of the photo or pair peaks provided an independent check.

Since the 8.06(0.55)-Mev and 8.70(1.25)-Mev resonance levels are formed by s-wave protons,[1,10] any radiation resulting from their decay will be isotropic

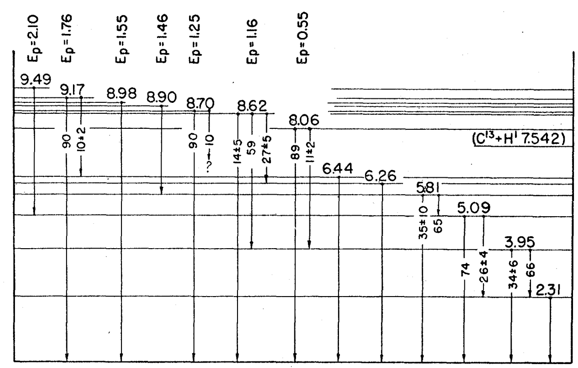

FIG. 4. Gamma-ray decay schemes for seven resonances of $C^{13}(p, \gamma)N^{14}$. The energy levels are designated by the excitation in N^{14} in Mev. The quantities, E_p, represent the proton energies corresponding to the seven resonances investigated. Relative transition probabilities from each level are also given.

and the measured intensity ratios are identical with the ratios obtained by integrating over the whole sphere. Of the other resonance levels, only the relative intensity of the decay of the 9.17(1.76)-Mev resonance level has been corrected for the angular anisotropy of the radiation. However, the expected maximum anisotropy in each of the other cases would not cause more than a 20 percent change in the measured value, and in most cases the difference is probably much less than the experimental error.

RESONANCE CHARACTERISTICS

The resonance characteristics for the seven resonances investigated are listed in Table II. With the exception of the 8.90(1.47)- and 8.98(1.55)-Mev resonance levels and the recalculated reduced widths, the table is essentially Table III in reference 1. The dimensionless reduced width, $\theta^2=\gamma^2(\hbar^2/2Ma)^{-1}$, where γ^2 is the reduced level width of Wigner and Eisenbud,[11] has been calculated employing the Coulomb tables of Bloch *et al.*,[12] with an interaction radius of $1.41(13^{\frac{1}{3}}+1)10^{-13}$ cm. The quantity $1/\theta^2$ may be interpreted as the number of nuclear traversals of the incident particle in the compound system. In these calculations, the variation of level shift with respect to energy[13] has been taken into account. This correction has little effect on values

TABLE II. Resonance characteristics for $C^{13}(p, \gamma)N^{14}$.

E_R (Mev)	Γ_p (kev)	θ^2 s wave	p wave	d wave	f wave	g wave	σ_R ($10^{-3}b$)	$\omega\Gamma_\gamma$ (ev)
8.06(0.55)	32.5 ± 1	0.4	13				1.44	8.6
8.62(1.16)	6 ± 2		0.04	0.3	∞		0.56	1.3
8.70(1.25)	500	0.7	4.5				0.062	13
8.90(1.47)	20		0.05	0.5	∞		0.074	0.72
8.98(1.55)	7		0.016	0.1	4		0.037	0.13
9.17(1.76)	2.1 ± 0.2			0.024	0.4	∞	12.0	15
9.49(2.10)	45 ± 3		0.05	0.3	∞		0.20	6.2

[9] R. G. Thomas and T. Lauritsen, Phys. Rev. **88**, 969 (1952).
[10] S. Devons and M. G. N. Hine, Proc. Roy. Soc. (London) **A199**, 56, 73 (1949). See also the section on Resonance Characteristics below.
[11] E. Wigner and L. Eisenbud, Phys. Rev. **72**, 29 (1947).
[12] I. Bloch *et al.*, Revs. Modern Phys. **23**, 147 (1951).
[13] R. G. Thomas, Phys. Rev. **88**, 1109 (1952) and private communication.

of θ^2 less than one but tends to increase those values greater than one. At all but the 8.06(0.55)-Mev and 8.70(1.25)-Mev resonances, a WKB approximation was used in calculating this level shift correction. This resulted in an over correction and hence the infinities in the table. Wigner's criterion places an upper limit on θ^2 of 6.[14] However, both the initial calculations and the level shift corrections are very inaccurate for values of θ^2 greater than 2 or 3. The general interpretation used, however, was to consider values θ^2 greater than 2 or 3 as highly improbable. In the four cases shown in Table II where infinities appear, the uncorrected values were all greater than 6 and thus the corresponding l values for the incident protons can be most certainly ruled out.

From these calculations, it is seen that the 8.06(0.55)- and 8.70(1.25)-Mev resonances are formed by s-wave protons and that all the rest, with the exception of the 9.17(1.76)-Mev resonance and possibly the 8.98(1.55)-Mev resonance, are formed by partial waves with $l \leq 2$.

Table II also gives the total gamma-ray width Γ_γ times the statistical factor ω for each of the seven resonances. In this reaction $\omega = (2J+1)/4$, where $\hbar J$ is the total angular momentum of the compound state.

ANISOTROPY MEASUREMENTS

In an attempt to determine the spins of some of the levels involved in the cascading, the anisotropy ratio, $a = \text{yield}(0°)/\text{yield}(90°) - 1$, was measured for the first gamma ray in the cascades found at the 8.90(1.47)-, 9.17(1.76)-, and the 9.49(2.10)-Mev resonance levels. Also, the anisotropy ratio of the ground state transition from the 8.62(1.16)-Mev resonance level and the angular distribution of the ground state transition from the 9.17(1.76)-Mev resonance level were measured. The latter measurement was in excellent agreement with previous measurements.[15] The anisotropy ratios for these five cases are listed in Table III.

DISCUSSION

The review article of Ajzenberg and Lauritsen[16] gives a summary of the experiments yielding information on the levels involved in this reaction. Two of these will be discussed in more detail in connection with this work. The first of these is the magnetic lens spectrometer analysis of the gamma-radiation from $C^{13}(d, n\gamma)N^{14}$.[9] Although Thomas and Lauritsen do not report a definite ground-state transition from the 3.95-Mev level, further work under improved conditions has confirmed it,[17] in agreement with what was found in this work. Thomas and Lauritsen also report a 3.38-Mev gamma ray which they assign to N^{14} in cascade with the 2.31-Mev gamma ray. Coincidence measurements with two scintillation counters on the $C^{13}(d, n\gamma)N^{14}$ reaction has confirmed this assignment.[18] This, then, places a level at 5.69 Mev in N^{14} which is shown as 5.7 Mev in reference 16. Thomas and Lauritsen also report a 5.69-Mev gamma ray which they believed to be the ground-state transition of this level. It is believed that the weak, low-energy radiation found at the broad 8.70(1.25)-Mev resonance may involve this level. It is noted that this resonance is the *only* resonance of the seven investigated at which there were indications of a 3.38-Mev gamma ray.

As noted before, Thomas and Lauritsen found a strong 0.725-Mev gamma ray which is believed to correspond to the 0.73-Mev gamma ray found at the 1.47-Mev resonance. In the following discussion, these two gamma rays will be assumed to be the same. Coincidence measurements, again on the $C^{13}(d, n\gamma)N^{14}$ reaction, have shown that this 0.725-Mev radiation is in cascade with radiation above 4.5 Mev and below 5.2 Mev, which disproves the suggestion that the 0.725-Mev radiation was the result of a transition between the 4.8-Mev level and the 3.95-Mev level as shown in reference 16. Thus, the possible levels from which the 0.725-Mev gamma ray can originate are a tentative level reported at 5.5 Mev,[19] the level at 5.69 Mev, and the one indicated by these experiments at 5.81 Mev. The first two levels would presumably decay to the 4.8-Mev level, while the latter goes to the 5.08-Mev level. The energy measurements of the cascading gamma rays associated with the 0.725-Mev gamma ray preclude any such level as low as 5.5 Mev. The 5.69-Mev level cannot be associated with the 0.725-Mev radiation since at the resonance at which the 0.725-Mev gamma ray was found there was no indication of the 3.38-Mev gamma ray (see Fig. 2) which results from the decay of the 5.69-Mev level. Thus the 0.725-Mev gamma ray certainly appears to come from the 5.81-Mev level as postulated. However, one would then expect that Thomas and Lauritsen should have found a 5.81-Mev gamma ray one-third as intense as the 0.725-Mev radiation, which they did not. Dr. Thomas has suggested to the authors that the explanation of this discrepancy lies in the reduced sensitivity of the lens spectrometer at higher energies.

TABLE III. Angular anisotropy of four gamma rays from $C^{13}(p, \gamma)N^{14}$.

E_R (Mev)	Transition in N^{14} (Mev)	Anisotropy ratio a
8.62(1.16)	8.62→gnd state	0.00 ± 0.05
8.90(1.47)	8.90→5.81	$+0.25 \pm 0.10$
9.17(1.76)	9.17→gnd state	-0.48 ± 0.03
9.17(1.76)	9.17→6.44	-0.05 ± 0.10
9.49(2.1)	9.49→5.09	$+0.48 \pm 0.15$

[14] T. Teichmann and E. P. Wigner, Phys. Rev. **87**, 123 (1952).
[15] R. B. Day, Ph.D. thesis, California Institute of Technology, 1951 (unpublished).
[16] F. Ajzenberg and T. Lauritsen, Revs. Modern Phys. **24**, 321 (1952).
[17] R. J. Mackin, Jr. (private communication).
[18] The coincidence measurements were made by J. Thirion for the authors.
[19] R. E. Benenson, Phys. Rev. **90**, 420 (1953).

The second experiment to be noted is the recent work of Benenson[19] on the neutron energy spectrum for the reaction $C^{13}(d, n\gamma)N^{14}$. This work has confirmed the existence of the levels at 6.44 and 6.26 Mev.

From the anisotropy measurements and the reduced widths, few unambiguous conclusions can be drawn. However, limits on the angular momentum of some of the levels can be given. Consider first the 9.49(2.10)-Mev resonance level. Since the radiation from this level is not isotropic (Table III) it cannot be formed by s-wave protons nor can it have an angular momentum of 0. Thus, since the reduced width (Table II) indicates that the level can only be formed by partial waves with $l \leq 2$, the angular momentum and parity of the level must be 1^+, 2^+ (p-wave protons) or 2^-, 3^- (d-wave protons). (Here and below the angular momentum will be given in units of $\hbar$.) *If* the radiation resulting from the transition between this level and the 5.09-Mev level is pure dipole (this radiation has an energy of 4.4 Mev and a width $\omega\Gamma_\gamma$ of 6 ev), then the measured anisotropy ratio precludes the possibility of 3^- for the angular momentum. Also, under this assumption of pure dipole radiation, the anisotropy measurements require that the 5.09-Mev level must have the same angular momentum as the 9.49(2.10)-Mev resonance level (1 or 2).

The 9.17(1.76)-Mev resonance level has been given a tentative angular momentum assignment of 2.[15] If this is the case and *if* the transition to the 6.44-Mev level gives pure dipole radiation (this radiation has an energy of 2.7 Mev and a width $\omega\Gamma_\gamma$ of 1.5 ev), then the anisotropy measurements require that the 6.44-Mev level has an angular momentum of 3.

The elastic scattering of protons by C^{13} and the reduced width indicate that the 8.90(1.47)-Mev resonance level in N^{14} is formed by d-wave protons, which means that the level has an angular momentum and parity of 2^- or 3^-. The interpretation of the elastic scattering favors the second value.[2] The transition between this level and the 5.81-Mev level gives 3.1-Mev radiation which has a width $\omega\Gamma_\gamma$ of 0.7 ev. If this radiation is pure dipole, then the anisotropy ratio agrees best with the 2^- assignment and furthermore it requires that the 5.81-Mev level have an angular momentum of 2. Actually, the agreement is not good. Under the most favorable situation with 100 percent channel spin 1, the calculated anisotropy ratio is 0.42, which is to be compared with the experimental value of 0.25 ± 0.10. If, on the other hand, the radiation is pure quadrupole, then the 3^- assignment is permissible only if the 5.81-Mev level has an angular momentum of 5, which value, however, appears improbable from the decay schemes. In the actual situation, as also in the other cases considered above, there may be involved a mixture of dipole and quadrupole radiation, in which case these arguments are invalidated.

The elastic scattering of protons by C^{13} shows that the 8.62(1.16)-Mev resonance level is formed by p-wave protons and that it has a low angular momentum

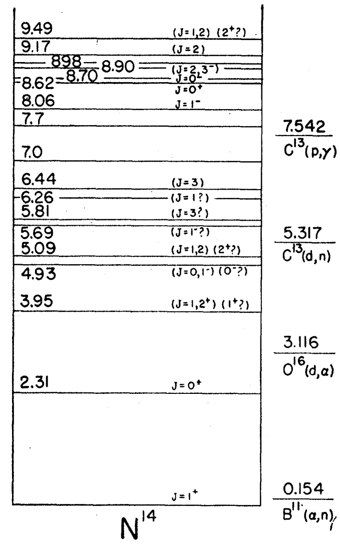

FIG. 5. Energy-level diagram of N^{14} showing established levels below 10 Mev. The energy levels are given in Mev. Values of the total angular momentum (J) and parity which appear to be reasonably well established are indicated on the levels: less certain assignments are enclosed in parentheses while speculative assignment are indicated by question marks.

(0 or 1).[2] The lack of anisotropy at this resonance would appear rather fortuitous if the angular momentum of this level were 1. In particular it would require equal amounts of channel spin 0 and 1, a condition which appears to be definitely ruled out by the elastic scattering experiments.[2] Thus, it seems quite certain that the 8.62(1.16)-Mev resonance level is 0^+. This value of the angular momentum confirms the assignment of the 6.26-Mev radiation to the decay of a 6.26-Mev level. The reason is that a transition directly to the 2.31-Mev level from the 8.62(1.16)-Mev resonance level (the only other alternative) is forbidden since the 2.31-Mev level is known to be a 0^+ level.[16] It has been shown that the 3.95-Mev level has an angular momentum and parity of either 1^+, or 2^+.[19] However, the value of 2^+ seems incompatible with the fact that the transition from the 8.62(1.16)-Mev resonance level to the 3.95-Mev level is favored over the ground state transition of the resonance level. Also, as pointed out by Benenson, the preferential decay of the 3.95-Mev level to the 2.31-Mev level would likewise seem to favor the assignment of 1^+. Similarly, the 6.26-Mev level would certainly seem to require an angular momentum of 1 in order to account for the observed relative intensities.

Besides the 5.69-Mev level, there appears to be only one other well established low lying level in N^{14} that was not involved in the cascading from the seven proton resonances investigated. This is a level with angular momentum and parity of either 0^- or 1^- which has been reported at 4.8 Mev.[19] However, it appears to be responsible for the 4.93-Mev radiation found recently in the reaction $C^{13}(d, n\gamma)N^{14}$[17] and hence we have assumed that this is the best value for its energy.

The foregoing discussion is summarized in an energy-level diagram of N^{14} (Fig. 5) showing the established levels below 10 Mev. Besides the levels discussed above, there are two additional ones at 7.0 Mev and 7.7 Mev reported in reference 19. Since guesses at the probable types of radiation were made in making some of the angular momentum assignments shown in Fig. 5, one cannot uniquely confirm theoretical estimates of transition probabilities for the different types of radiation. However, further work to determine the complete angular distributions of the many gamma rays found at these several proton resonance levels promises to be a fruitful method for uniquely determining the angular momentum of the levels and the types of radiation involved in N^{14}.

Since this work has extended over a period of two years, it is impossible to list individually all those who aided directly or indirectly in the taking of data or in the interpretation of the results. It is a pleasure, however, to acknowledge the contributions and continued interest of Professor C. C. Lauritsen and the staff of the Kellogg Radiation Laboratory.

PHYSICAL REVIEW VOLUME 92, NUMBER 5 DECEMBER 1, 1953

Formation of the Long-Lived Bi^{210} Isomer*

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The thermal activation cross section of Bi^{209} is shown to be definitely less than the absorption cross section, 19 ± 2 mb as compared with 33 ± 2 mb. In order to verify the high absorption value, previously obtained by pile reactivity methods, measurements were made with the long wavelength neutrons available with the Brookhaven slow chopper. The absorption cross section is obtained from the chopper measurements by subtraction of thermal inelastic scattering. The latter scattering is determined from the variation of measured scattering with sample temperature. The difference between the absorption and scattering, or 14 ± 3 mb, is ascribed to the formation of the long-lived α-emitting isomeric state of Bi^{210}, leading to a half-life of $(2.6\pm0.8)\times10^6$ years. This long life is in agreement with the expected properties, relative to α and β decay, of a high-spin state of Bi^{210}.

I. INTRODUCTION

The absorption cross section of bismuth for thermal neutrons is extremely small, constituting only a fraction of a percent of the scattering cross section. Early measurements[1] of the activation cross section, i.e., the cross section for activation of the five-day Bi^{210} (RaE), resulted in a value of about 15 mb. On the other hand, the absorption cross section, which is measured by some phenomenon sensitive to the disappearance of neutrons, gave somewhat higher values, of the order of 30 mb. However interfering effects of the large scattering cross section in the absorption measurements, as well as the possible contribution of impurities, made it seem likely that the true absorption could easily be the same as the activation cross section, i.e., about 15 mb.

It soon became clear that the difference between absorption and activation was not a result of impurities because the preparation of samples of increasing purity, as evidenced by chemical analysis, did not give rise to any decrease in absorption cross sections. The measured values lay in the 30–35-mb range regardless of the sample origin and degree of purification. In 1948, measurements of bismuth absorption were made by Langsdorf[2] with the "pile oscillator," and his value for pure bismuth was again about 30 mb. However, because of the interfering effects of scattering in the pile, it was felt by Langsdorf that some apparent absorption could result from neutron scattering and that the correct absorption of bismuth, after correction for this scattering effect, could be as low as the activation value.

A series of measurements of the absorption and activation cross sections was carried out by Palevsky, Hughes, and Eggler[3] in 1950 to investigate the possibility of a real difference between these cross sections, the experiments being performed in the graphite pile to study the effect of scattering on the absorption cross section. These measurements showed that there was indeed a distinct difference between the cross section for activation of the 5-day RaE and the absorption, indicating the formation of a hitherto undetected activity in bismuth in addition to the well-known five-day period. At about the same time a long-lived α-emitting activity was found in pile-irradiated bismuth by Newman, Howland, and Perlman,[4] and it seemed quite likely that the difference between absorption and activation could be attributed to the formation of the long-lived state. To investigate this possibility, as well

* Work carried out under contract with the U. S. Atomic Energy Commission.
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