Precision Measurements of Gamma-Ray Energies in the Region from 2.3 to 7.1 MeV*

C. CHASMAN, K. W. JONES, R. A. RISTINEN,† AND D. E. ALBURGER
Brookhaven National Laboratory, Upton, New York
(Received 28 February 1967)

Precision energy measurements have been made on γ rays in the region from 2.3 to 7.1 MeV by means of Ge(Li) detectors and a gain-stabilized pulse-height analyzer system. The transitions studied include certain non-Doppler-broadened γ rays occurring in the reactions $C^{12}(He^3,p)N^{14}$, $N^{14}(d,p)N^{15}$, $N^{14}(d,n)O^{15}$, and $F^{19}(p,\alpha)O^{16}$ and the γ rays emitted in the radioactive decays of B^{12}, C^{15}, O^{14}, and N^{16}. In most cases energy calibrations were made with mixed sources and the extension to higher energies depended on the assumption of 1022.01 keV for the energy separation between full-energy-loss and two-escape peaks. The γ-ray energies in keV, with the nucleus from which they originate in parentheses, were determined to be the following: 2312.68±0.10 (N^{14}), 2792.68±0.15 (N^{14}), 4438.91±0.31 (C^{12}), 5104.87±0.18 (N^{14}), 5240.53±0.52 (O^{15}), 5270.60±0.46 (N^{15}), 5299.03±0.43 (N^{15}), 6129.96±0.46 (O^{16}), and 7117.02±0.49 (O^{16}).

I. INTRODUCTION

THE recent introduction of Ge(Li) γ-ray detectors has provided a new and versatile method for measuring γ-ray energies to a high degree of precision. While radioactive sources emitting γ rays with accurately known energies, that is, with uncertainties of a few hundred eV, are available up to about 3 MeV, the situation has been substantially worse at higher energies, where the uncertainties have been greater than 1 keV. Since high-precision measurements can be of great importance in nuclear spectroscopy, we have attempted to determine more precisely the energies of various γ rays that can be produced rather easily with an electrostatic accelerator. In addition to the application to nuclear spectroscopy the 6.13-MeV γ ray from O^{16} has been used extensively as a standard for the determination of μ-mesonic x-ray energies.[1] The O^{16} γ ray occurs in the β decay of 7-sec N^{16}, an activity which can be made readily via the $O^{16}(n,p)N^{16}$ reaction in samples of ordinary water exposed to the high-energy neutrons produced by cyclotron irradiation. In nuclear reaction work the 6.13-MeV γ ray has the desirable property of being emitted from a state that is sufficiently long-lived that there are no Doppler effects due to the motion of the emitting O^{16} nucleus. Finally, the 7.12-MeV γ ray in O^{16} determines the energy of the 7.12-MeV O^{16} level which is only slightly less than the Q value for the $C^{12}(\alpha,\gamma)O^{16}$ reaction of 7.1615±0.0004 MeV.[2] This reaction may be important during the helium-burning state in the evolution of massive stars, and a precise knowledge of the level energy is useful in determining the reaction rate.[3]

II. GENERAL METHODS

The γ-ray energies that we have determined are based on the energy values of γ rays from radioactive isotopes that have been measured elsewhere. A summary of these primary standards and their energies is given in Table I. We have extended the measurements to higher energies in two different ways. In the first method a measurement is made with a Ge(Li) γ-ray detector of the energy difference between the full-energy-loss peak of a standard γ ray and the two-escape peak of a γ ray that has an energy approximately 1 MeV greater than that of the standard. The sequence used in our first method consisted entirely of radioactive sources, i.e., the series Co^{56}-B^{12}-C^{15}-N^{16} with γ-ray energies of 3.3, 4.4, 5.3, and 6.1, 7.1 MeV, respectively. Measurements on mixed sources of successive pairs of these activities allowed the calibration to be extended from 3.3 to 7.1 MeV. A summary of the reactions used for forming the activities, as well as other pertinent information, is given in the first four lines of Table IIA. Incidental to the main purpose of the present work were the precise

TABLE I. Energies of γ rays from radioactive sources used for calibration.

Source	Energy (keV)			Reference
Co^{60}	1173.23±0.040,	1332.48±0.046		a
Co^{60}	1173.25±0.08,	1332.56±0.05		b
Na^{22}	1274.58±0.10			b
Na^{22}	1274.52±0.07			c
Na^{24}	2753.92±0.12			a
Co^{56}	3201.9 ±0.3,	3202.3 ±0.5,	3202.3±0.5	d,e,f
Co^{56}	3253.65±0.15,	3254.0 ±0.5,	3254.0±0.5	d,e,f
Co^{56}	3273.2 ±0.3,	3272.8 ±0.6,	3273.6±0.4	d,e,f
Co^{56}	3452.1 ±0.4,	3452.5 ±1.0,	3452.6±0.5	d,e,f

[a] G. Murray, R. L. Graham, and J. S. Geiger, Nucl. Phys. **63**, 353 (1965).
[b] D. H. White and D. J. Groves, Argonne National Laboratory Conference on Slow-Neutron Capture γ-ray Spectroscopy, 1966, Report No. ANL 7282 (unpublished).
[c] W. W. Black and R. L. Heath, Nucl. Phys. **A90**, 650 (1967).
[d] C. Chasman and R. A. Ristinen, Phys. Rev. **159**, 830 (1967).
[e] H. Petterson, O. Bergman, and C. Bergman, Arkiv Fysik **29**, 423 (1965).
[f] K. W. Dolan, D. K. McDaniels, and D. O. Wells, Phys. Rev. **148**, 1151 (1966).

* Work performed under the auspices of the U. S. Atomic Energy Commission.
† On leave 1966–67: University of Colorado, Boulder, Colorado.
[1] See, for example, T. T. Bardin, R. C. Barrett, R. C. Cohen, S. Devons, D. Hitlin, E. Macagno, C. Nissim-Sabat, J. Rainwater, K. Runge, and C. S. Wu, Phys. Rev. Letters, **16**, 429 (1966).
[2] J. H. E. Mattauch, W. Thiele, and A. H. Wapstra, Nucl. Phys. **67**, 1 (1965).
[3] See the discussion by P. A. Crean and T. K. Alexander, Can. J. Phys. **43**, 721 (1965).

TABLE II. Summary of reactions used to produce the γ rays of interest and the associated calibration γ rays.

Method of production of unknown γ ray	E_γ (keV)	E_γ-$2m_0c^2$ (keV)	Method of production of calibration lines	Energies of calibration γ rays (keV)
A.				
$B^{11}(d,p)B^{12}(\beta^-)C^{12*}(\gamma)C^{12}$	4440	3420	$Co^{56}(\beta^+)Fe^{56*}(\gamma)Fe^{56}$	3202,3254,3273,3452
$C^{14}(d,p)C^{15}(\beta^-)N^{15}(\gamma)N^{15}$	5300	4280	$B^{11}(d,p)B^{12}(\beta^-)C^{12*}(\gamma)C^{12}$	4440,4440-m_0c^2
$N^{15}(d,p)N^{16}(\beta^-)O^{16*}(\gamma)O^{16}$	6130	5108	$C^{14}(d,p)C^{15}(\beta^-)N^{15}(\gamma)N^{15}$	5300,5300-m_0c^2
$N^{15}(d,p)N^{16}(\beta^-)O^{16*}(\gamma)O^{16}$	7120	6098	$N^{15}(d,p)N^{16}(\beta^-)O^{16*}(\gamma)O^{16}$	6130,6130-m_0c^2
$C^{14}(d,n)N^{15*}(\gamma)N^{15}$	5270	4248	$C^{14}(d,p)C^{15}(\beta^-)N^{15*}(\gamma)N^{15}$	5300-$2m_0c^2$,5300-m_0c^2
$N^{14}(d,n)O^{15*}(\gamma)O^{15}$	5240	4218	$N^{14}(d,p)N^{15*}(\gamma)N^{15}$	5270-$2m_0c^2$,5270-m_0c^2
B.				
$C^{12}(He^3,n)O^{14}(\beta^+)N^{14*}(\gamma)N^{14}$	2310	1288	$Co^{60}(\beta^-)Ni^{60*}(\gamma)Ni^{60}$ $Na^{22}(\beta^+)Ne^{22*}(\gamma)Ne^{22}$	1173,1274,1332
$C^{12}(He^3,p)N^{14*}(\gamma)N^{14}$	2790	1768	$Na^{24}(\beta^-)Mg^{24*}(\gamma)Mg^{24}$	2754,2754-m_0c^2 2754-$2m_0c^2$
The energy of the N^{14} 5.11-MeV level is given by the sum of the two above γ rays after correction for recoil effects.				
$C^{12}(He^3,p)N^{14*}(\gamma)N^{14}$	5104	...	precision pulser	
$F^{19}(p,\alpha)O^{16*}(\gamma)O^{16}$	6130	5108	precision pulser	

energy measurements of the N^{15} and O^{15} transitions listed in the 5th and 6th lines of Table IIA.

A second method used for determining the energy of the 6.13-MeV transition in O^{16} depended on finding a reference γ ray of about 5 MeV whose energy in turn could be established by measuring cascade transitions. An energy level that meets these requirements is the 5.11-MeV state in N^{14}. This energy level is sufficiently long lived so that the Doppler effects are negligible in a nuclear reaction and it has the excellent feature of emitting cascade and crossover transitions with comparable intensities, i.e., $I(5.11 \rightarrow 2.31) = 33\%$ and $I(5.11 \rightarrow 0) = 67\%$. Furthermore, the level is strongly populated in the $C^{12}(He^3,p)N^{14}$ reaction at $E_{He^3} = 2.2$ MeV and at this bombarding energy the resulting γ-ray spectrum is simple. The $5.11 \rightarrow 2.31$ transition was measured with respect to a Na^{24} standard. The $2.31 \rightarrow 0$ transition on the other hand cannot be measured accurately in the (He^3,p) reaction because of the Doppler broadening of the γ rays associated with the direct population of the 2.31-MeV state. For this measurement the 2.31-MeV γ ray was observed in the positron decay of O^{14} and compared with primary standards.

The determination of the energies of the two-cascade γ rays from the 5.11-MeV state of N^{14} allows one to establish the energy of the ground-state transition and then compare it with the 6.13-MeV O^{16} transition. The complete sequence in this second method is summarized in Table IIB.

III. EXPERIMENTAL PROCEDURES

The γ rays were detected with planar-type Ge(Li) γ-ray detectors with an area of about 6 cm^2 and a depletion depth of 5–7 mm and hence a volume of about 4 cc. The detector was placed at 90° to the beam from the Brookhaven electrostatic accelerator. Pulses from the detector were amplified in a low-noise preamplifier and an ORTEC model 220 biased-amplifier system. The pulse-height analysis was performed in a Victoreen 1600-channel pulse-height analyzer that had been equipped with digital stabilization of the analog-digital converter zero and conversion gain. The reference pulses were supplied by two ultra-stable temperature-controlled pulsers. Integrating and clipping-time constants of 1 μsec were used in the main amplifier as a compromise between the best settings for optimum resolution and for optimum performance at high-counting rates. The effects of pulse pileup on detector line shape were minimized by requiring the total counting rate from the detector to be 5000 cps or less. With this system it was possible to obtain resolutions at energies around 5–6 MeV of 8–12 keV full width at half-maximum (FWHM) for counting periods up to 40 h long.

For all but one of the energy comparisons measured in this work the runs were carried out with mixed sources of γ rays. With this method drifts in the electronics or other experimental conditions have a minimal effect on the measurement of the energy separation between a given pair of lines.

The energy calibration of the system was made by use of a pair of peaks from the full-energy-loss, one- and two-escape peaks which are associated with every γ ray investigated. Such a calibration assumes that the energy separation between appropriate pairs of these peaks is always $m_0c^2 = 511.006 \pm 0.006$ keV.[4] Since at high energies the photoelectric cross section becomes very small, the full-energy peaks are largely formed by multiple Compton scattering and/or photoelectric absorption of the 511-keV annihilation quanta following pair production. On the other hand, the two-escape peak results from summing the electron-hole pairs formed by the stopping electron and positron. It is thus not immediately obvious that the line shapes for the peaks are indeed identical or that they are necessarily separated by a pulse-height difference exactly equivalent to m_0c^2. We were unable to find any differences in the shapes of these lines, but it must be emphasized that

[4] E. Richard Cohen and Jesse W. M. DuMond, Rev. Mod. Phys. **37**, 537 (1965).

the success of this experiment does rest on this assumption for establishing the energy dispersion of the analyzer and in assigning energy differences between full-energy and two-escape peaks.

Once the energy dispersion of the pulse-height analyzer is established the energy difference between the unknown and standard γ rays must be found. Rather than attempt a detailed investigation of the linearity of the detection system an auxiliary calibration was performed with a precision pulser under the same condition as the actual run.[5] Pulser lines were inserted at channels as close as possible to the actual peak position, and a linear interpolation was then performed to find the pulser-dial setting corresponding to the peak position. The pulser dial could be read to an accuracy corresponding to 0.1 keV and was linear to 40 ppm. Because the interpolations were made over restricted energy ranges the uncertainties from nonlinearities in the electronic system were of negligible importance. Energy differences could then be calculated by use of the equivalent pulser-dial values.

The positions of the peaks in the analyzer spectrum were determined in two ways. A computer program[6] which did a least-squares fit with a Gaussian peak and either a polynomial or exponential background was used to determine the centroid of each peak. As an additional check each peak was also analyzed by hand using a method which has been previously applied to β spectrometer data.[7] Here the technique used was to determine the midpoint of the peak as a function of the peak height. The smooth curve connecting the midpoints was then extrapolated to the peak maximum and the point of intersection was taken as the peak position. The results obtained by the computer analysis and the hand-fitting procedure were in good agreement. We have chosen to use the computer analysis for the results quoted here since it gives the most consistent way of handling the data. It does have the drawback that the line shapes are not exactly Gaussian and the fits are therefore not exact. However, all the γ lines for a given run have about the same energies and differences in line shapes were not observed. If analysis is done in a consistent way, any systematic errors introduced in the determination of the energy differences should be negligibly small.

In measurements of the energy of γ rays produced in nuclear reactions the lifetime of the emitting nuclear state is often so short that a significant Doppler broadening and Doppler shift can be observed; in many cases the size of the effect is several times the energy resolution of the Ge(Li) γ detector. This problem was circumvented in the present work by producing the γ rays from the β decay of radioactive nuclei. In cases where this was done a mechanical beam chopper[8] was used to pulse the beam. Activation times of about 3 msec were used, followed by a 1-msec interval for the electronics to stabilize, a 12-msec counting interval, and finally a 1-msec interval before the next activation period to ensure there were no counts from the direct beam-induced reactions. No degradation of the energy resolution of the detector was noticed that could be ascribed to the high counting rate during the "beam-on" part of the cycle. The detector and associated electronics thus recover in less than 1 msec after the high counting rate experienced during the bombardment time.

In the simultaneous measurement of the γ rays from a short-lived activity and from a long-lived standard the reference source was simply placed near the Ge(Li) detector during the target bombardment. However, for the simultaneous measurement of two short-lived activities the target holder was designed so that two different target materials could be bombarded at the same time. The target holder could be adjusted vertically by means of a screw so as to change the relative amounts of the two targets exposed to the beam, thereby varying the relative strengths of the induced activities.

In this series of measurements there was only a single case where the comparison of two lines required non-simultaneous or sequential measurements: the N^{14} $5.10 \rightarrow 0$ full-energy-loss peak and the O^{16} $6.13 \rightarrow 0$ two-escape peak. It was necessary in this case to change both the target and the type of bombarding particle and to make a number of pairs of comparison runs in order to average out small electronic shifts.

In the following section the experimental results obtained with the equipment and methods described here are presented. In one case a detailed description of the analysis of the data is also given.

IV. EXPERIMENTAL RESULTS AND ANALYSIS

In this section a discussion of the energy determination of each γ ray investigated is given. For the first case, the 4.44-MeV γ ray from the first excited state of C^{12}, a more detailed discussion is given to illustrate the methods used in the analysis of the data.

4.44-MeV γ Ray from C^{12}

The 4.44-MeV γ ray from C^{12} is emitted from a short-lived level and was therefore studied by observing it in the β decay of B^{12} which was produced by the $B^{11}(d,p)B^{12}$ reaction. A thick target of B^{11} was used with a 0.009-μA beam of 1.5-MeV deuterons. Absorbers of Be, C, Pb, and Cu were placed between the target and the detector to reduce the bremsstrahlung from the slowing of high-energy β rays emitted in the decay of B^{12}. The calibration source of Co^{56} was a thin plate

[5] The technique used has been described previously by D. E. Alburger, C. Chasman, K. W. Jones, and R. A. Ristinen, Phys. Rev. **136**, B913 (1964).

[6] M. A. Mariscotti, Nucl. Instr. Methods **50**, 309 (1967).

[7] G. Murray, R. L. Graham, and J. S. Geiger, Nucl. Phys. **63**, 353 (1965).

[8] D. E. Alburger, Phys. Rev. **131**, 1624 (1963).

placed between the Cu absorber and the detector cryostat.[9] Co^{56} is a convenient calibration source since it gives lines at 3202, 3254, 3273, and 3452 keV (see Table I). The energy spectrum obtained is shown in Fig. 1. The energy dispersion used was 0.43 keV/channel and the detector resolution was ~8.6 keV FWHM. Figure 2 shows an expanded view of the regions around the Co^{56} peaks used for the energy calibration and the B^{12} peak. The solid line shown is the computer fit to the peaks.

Pulser-calibration lines were placed at nominal energies of 3202.0, 3254.0, 3416.0, 3451.0, and 3548.0. We shall refer to such pulser values hereafter as a pulser-dial value.

TABLE III. Summary of data analysis for 4.44-MeV C^{12} line: a typical case.

Peak energy (keV)	Peak position (channel)	Equivalent dial reading
	A. γ-ray lines	
3201.9	488.07±0.11	3203.51±0.06
3253.65	604.40±0.07	3255.02±0.06
3273.2	649.05±0.19	3274.80±0.10
4438-$2m_0c^2$	972.53±0.11	3418.12±0.06
3452.1	1051.93±0.30	3453.51±0.15
	B. Pulser	
3202.0	484.65±0.09	
3254.0	602.10±0.10	
3416.0	967.78±0.08	
3451.0	1046.29±0.10	
3548.0	1263.91±0.08	

C. Equations for best fits to energy–versus–dial-reading Co^{56} values of Petterson *et al.* (see Table II).

$E_\gamma = (-1.39\pm14.59) + (1.0000\pm0.004) \times$ Pulser-dial Eq. 1

Co^{56} values of Dolan *et al.* (see Table II).

$E_\gamma = (-4.78\pm9.01) + (1.0011\pm0.003) \times$ Pulser-dial Eq. 2

Co^{56} values of Chasman and Ristinen (see Table II).

$E_\gamma = (-3.12\pm6.72) + (1.0005\pm0.0021) \times$ Pulser dial Eq. 3

D. Energy of C^{12} 4.44-MeV γ ray

$E_\gamma = 4438.82\pm0.77$ (from Eq. 1)

$E_\gamma = 4439.17\pm0.42$ (from Eq. 2)

$E_\gamma = 4438.73\pm0.34$ (from Eq. 3)

E. Average γ-ray energy $= 4438.91\pm0.31$ keV

Tables IIIA and IIIB list the various γ-ray and pulser lines and give the centroid of each peak with an uncertainty as determined by the computer fit to the data. The pulser lines closest to each of the γ-ray peaks were used to determine the average dial-reading/channel in the neighborhood of each γ-ray peak and from the difference in channel number between the two peaks an equivalent dial reading could be found for each γ-ray peak. The relationship between pulser-dial setting and energy is presumably linear to within the linearity of the pulser (0.004%) and passes quite accurately through zero at zero energy. This property is not relied upon, but a least-squares fit of a straight line to the calibration lines is made and the resulting equation used

[9] C. Chasman and R. A. Ristinen, Nucl. Instr. Methods **34**, 250 (1965).

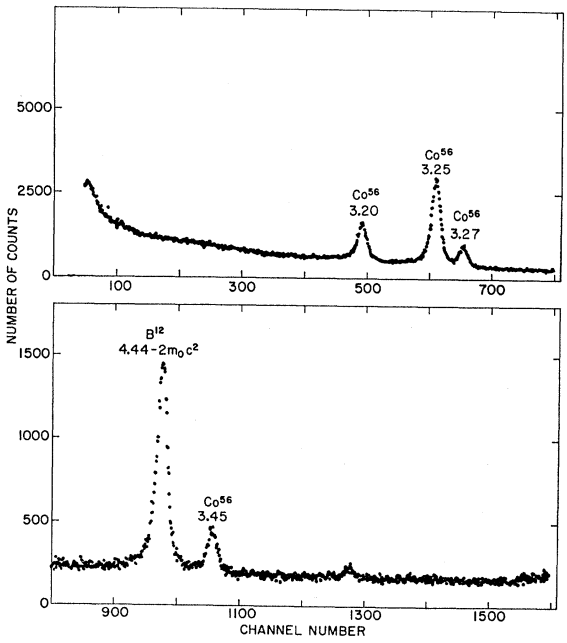

FIG. 1. Pulse-height spectrum obtained with mixed sources Co^{56} and B^{12}. The energy dispersion is 0.43 keV/channel.

to find the energy of the unknown and the associated uncertainty. The equations of the least-squares fits adjusted to the energy values given in Ref. d, e, and f of Table I are given in Table IIIC. The resulting

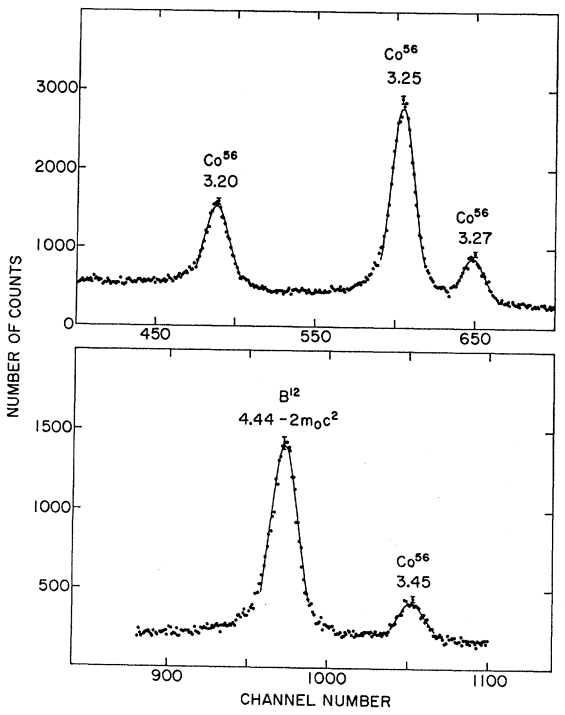

FIG. 2 An expanded view of the data shown in Fig. 1. The solid curve is the computer fit to the peaks assuming an exponential background and a Gaussian line shape for each peak.

values for the C^{12} 4.4-MeV γ ray are given in Table IIID. (Note here the assumption that the two-escape peak can be compared directly with the full-energy-loss peak of another line.) A final value of 4438.91±0.31 keV is adopted for the γ-ray energy. Our value is in agreement with a recent measurement by Kolata, Auble, and Galonsky,[10] who obtained a value of 4439.8±0.5 keV for the level energy or 4438.9±0.5 keV for the γ-ray energy.

5.30-MeV γ Ray from N^{15}

The lifetime of the N^{15} 5.30-MeV state is short so that advantage was taken here of the β decay of C^{15} which populates this level rather strongly. A chopped-deuteron-beam current of 0.04 μA with an energy of 2.2 MeV was used to bombard a target which consisted of a thick deposit of B^{11} adjacent to a C^{14} target. C^{15} and B^{12} were thus produced when the beam struck both the B^{11} and C^{14} targets. By adjusting the vertical position of the target holder relative to the beam the strengths of the two activities (each in equilibrium with the beam) could be adjusted so as to result in suitable relative intensities of the lines to be measured.

The spectrum obtained in this bombardment is shown in Fig. 3. It can be seen that the two-escape peak of the 5.30-MeV line falls between the full-energy-loss and one-escape peaks of the B^{12} 4.44-MeV line. Using procedures similar to those already discussed a value of 860.12±0.3 keV is found for the energy difference of the B^{12} 4.44-MeV line and the N^{15} 5.30-MeV line and hence a value of 5299.03±0.43 keV for the energy of the N^{15} line. This compares well with recent values of 5299±1, 5298.3±0.35, and 5298.2±1.5 keV quoted by Warburton *et al.*,[11] Greenwood,[12] and Bartholomew *et al.*[13]

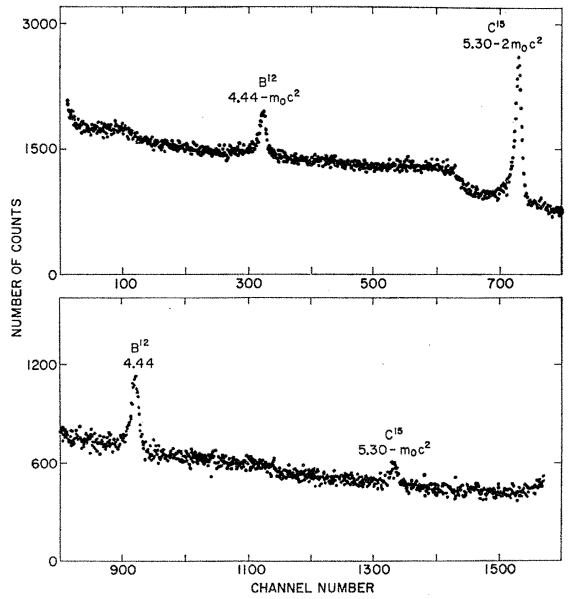

FIG. 3. Pulse-height spectrum obtained with mixed sources of B^{12} and C^{15}. The energy dispersion is 0.85 keV/channel.

[10] J. J. Kolata, R. Auble, and A. Galonsky (to be published); private communication from A. Galonsky.

6.13-MeV γ Ray from O^{16}—Method I

The energy of the 6.13-MeV γ ray can be measured conveniently by comparison with the 5.30-MeV N^{15} line since the two-escape peak of the oxygen line falls between full-energy-loss and one-escape peaks of the nitrogen line. Because of the Doppler-shift problem with the nitrogen line, the chopped-beam technique was again used. A 0.002-μA beam of 2.9-MeV deuterons bombarded a split of C^{14} and TiN^{15} and produced C^{15} and N^{16} by the $C^{14}(d,p)C^{15}$ and $N^{15}(d,p)N^{16}$ reactions. The lines occurring in the decays of the resulting activities were displayed with the results shown in Fig. 4. From the average of four runs a value of 831.45±0.20 keV is found for the energy difference of the two lines and a value of 6130.48±0.48 keV for the energy of the oxygen γ ray. Since the energy of this γ ray was also measured by an independent set of reactions, we shall defer comparison with other results to the section dealing with the mean value obtained for our two measurements.

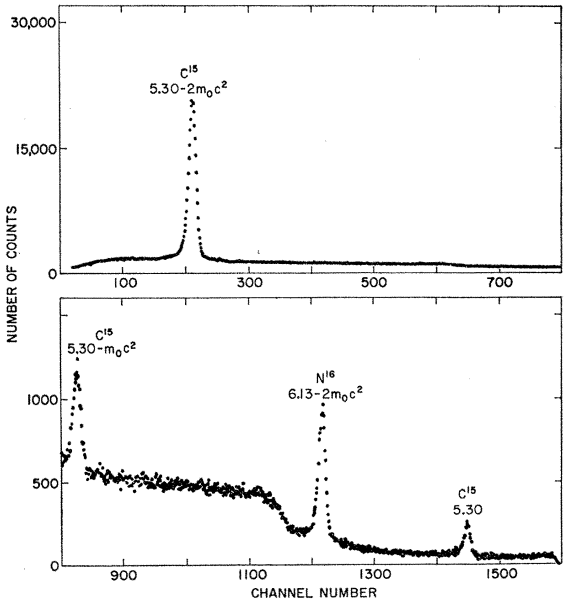

FIG. 4. Pulse-height spectrum obtained with mixed sources of C^{15} and N^{16}. The energy dispersion is 0.85 keV/channel.

5.27-MeV N^{15} and 5.24-MeV O^{15} γ Rays

The 5.27-MeV N^{15} and 5.24-MeV O^{15} γ rays and the 5.30-MeV N^{15} line from the C^{15} β decay were produced

[11] E. K. Warburton, J. W. Olness, and D. E. Alburger, Phys. Rev. **140**, B1202 (1965).

[12] R. C. Greenwood, Argonne National Laboratory Report No. ANL-7282, 1966 (unpublished).

[13] G. A. Bartholomew, E. D. Earle, and M. R. Gunye, Can. J. Phys. 44, 2111 (1966).

by the bombardment of a split target of ZrN and C^{14} with a 0.0045-μA beam of 3.0-MeV deuterons. The lifetimes for the 5.27-MeV N^{15} and 5.24-MeV O^{15} levels are long so that they can be observed directly as sharp lines in the $N^{14}(d,p)N^{15*}$ and $N^{15}(d,n)O^{15*}$ reactions. The levels at 5.19 and 5.30 MeV in O^{15} and N^{15}, respectively, are Doppler broadened in the $N^{14}(d,n)O^{15}$ and $N^{15}(d,p)N^{15}$ reactions because of their short lifetimes. The C^{14} target was used to produce simultaneously C^{15} via the $C^{14}(d,p)C^{15}$ reaction so that a sharp unshifted line from the N^{15} 5.30-MeV level, produced in the β decay, is obtained for reference purposes. The region around the two-escape peaks of the spectrum obtained is shown in Fig. 5. It may be noted that the sharp 5.30-MeV peak is superposed on the Doppler-broadened 5.30-MeV component and that the very broad 5.19-MeV line is just discernible to the left of the sharp lines. (A discussion has been given by Warburton *et al.*[14] on the interpretation of this spectrum.) The one-escape peaks, which are not shown in Fig. 5, were also observed and from their positions the energy calibration was established.

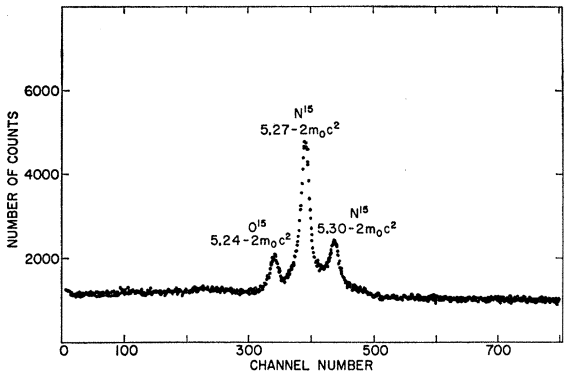

FIG. 5. Pulse-height spectrum obtained by bombardment of a split target of ZrN and C^{14} with a 0.0045-μA beam of 3.0-MeV deuterons. The energy dispersion is 0.61 keV/channel.

Our analysis of these data indicates that the energy splitting of the 5.30–5.27-MeV doublet in N^{15} is 28.43 $\pm$0.15 keV, which gives an energy of 5270.60$\pm$0.46 keV if our value of 5299.03$\pm$0.43 keV is used for the upper line. The energy splitting of the 5.24-MeV O^{15} line and the 5.30$\pm$0.42-MeV N^{15} line is 58.50$\pm$0.28 keV which gives an energy of 5240.53$\pm$0.52 keV for the O^{15} line. These splittings have been measured recently by Alexander, Litherland, and Broude,[15] who find a value of 28.5$\pm$3 keV for the splitting between the N^{15} levels and a difference between the N^{15} 5.27-MeV and O^{15} 5.24-MeV lines of 29$\pm$1 keV. Other measurements of the N^{15} line have been made by Greenwood[12] and Bartholomew *et al.*[13] Their values are 5269.6 $\pm$0.35 and 5270.5$\pm$1.5 keV, respectively.

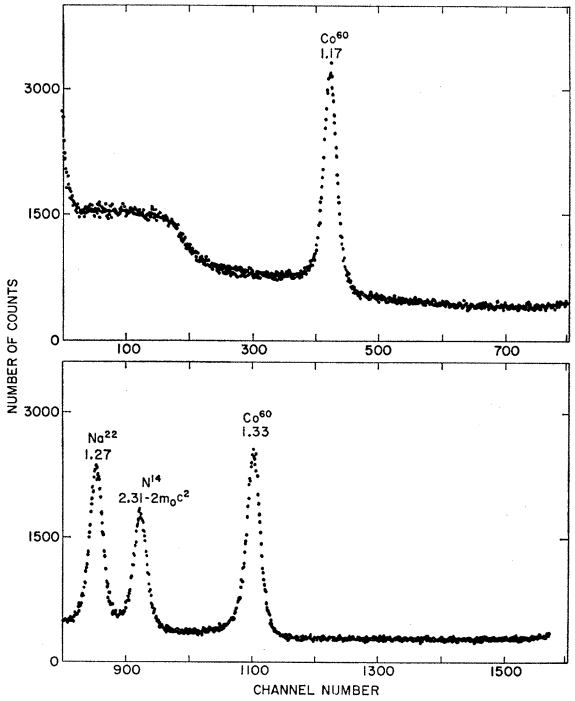

FIG. 6. Pulse-height spectrum obtained with mixed sources of O^{14}, Na^{22}, and Co^{60}. The energy dispersion is 0.24 keV/channel.

2.31-MeV N^{14} γ Ray

The 2.31-MeV N^{14} level is short lived, and its γ ray is Doppler broadened when produced by the C^{12}-$(He^3,p)N^{14}$ reaction. We therefore used a chopped He^3 beam of 0.04 μA at 2.0-MeV energy to produce O^{14} by the $C^{12}(He^3,n)O^{14}$ reaction. The 2.31-MeV N^{14} level is then populated in the positron decay of O^{14}. Calibration sources of Co^{60} and Na^{22} were run simultaneously to provide the energy calibration. Fortunately, the two-escape peak of the N^{14} line lies between the Na^{22} and Co^{60} peaks which means that a very small interpolation is necessary to find the energy of the unknown.

Analysis of the spectrum from this run, shown in Fig. 6, gives a value of 2312.68$\pm$0.10 keV for the γ-ray energy. After correction for the effect of nuclear recoil a value of 2312.89$\pm$0.10 keV is found for the level energy. This is in good agreement with the value listed in the compilation of Ajzenberg-Selove and Lauritsen[16] of 2312.0$\pm$1.2 keV.

2.79-MeV N^{14} γ Ray

The 2.79-MeV N^{14} γ ray was observed in the direct spectrum of the reaction $C^{12}(He^3,p)N^{14*}$ produced by a 0.25-μA beam at 3.0 MeV. A Na^{24} source was used for

[14] E. K. Warburton, K. W. Jones, D. E. Alburger, C. Chasman, and R. A. Ristinen, Phys. Rev. Letters, **14**, 146 (1965).

[15] T. K. Alexander, A. E. Litherland, and C. Broude, Can. J. Phys. **43**, 2310 (1965).

[16] F. Ajzenberg-Selove and T. Lauritsen, Nucl. Phys. **11**, 1 (1959).

calibration. In the spectrum shown in Fig. 7 both full-energy and both two-escape peaks are seen clearly. In addition, on an enlarged scale, the one-escape peaks can be seen so that the energy calibration is very well determined. The energy separation between the 2.79 N^{14} line and the Na^{24} line is found to be 38.76±0.10 keV which gives an energy of 2792.68±0.15 keV for the N^{14} line.

6.13-MeV O^{16} γ Ray (Method II and Mean Value)

The 2.31- and 2.79-MeV N^{14} γ rays cascade from a level at 5.10 MeV. When the 2.79-MeV γ-ray energy is corrected for nuclear recoil and added to the level energy of the 2.31-MeV state, the energy of the 5.11-MeV level is 5105.87±0.18 keV. This level also decays to the ground state of N^{14}, and after a recoil-energy correction it is found that the γ-ray energy is 5104.87±0.18 keV. Since this energy differs by only 3–4 keV from the energy of the two-escape peak of the oxygen 6.13-MeV line, an accurate measurement can be made of the oxygen relative to the nitrogen energy. The awkward feature of this comparison is that the separation between the two lines is so small that the mixed-source technique used in all the previous cases is no longer possible. Even aside from this point, there would be a technical difficulty in simultaneously bombarding two targets with two different types of beams, at least with the reactions that we used. Consequently, we made separate runs on the two lines with the resultant possibility of instabilities in the detection playing a large role.

The lines were produced with the $F^{19}(p,\alpha)O^{16*}$ and $C^{12}(He^3,p)N^{14*}$ reactions with a beam energy of 2.2 MeV and currents of 0.05 and 1.0 μA, respectively. While our He-ion beams are normally produced by using an ion-source bottle that has never been exposed to hydrogen, in this case a regular hydrogen bottle was installed and a helium discharge was struck in it. It was possible to obtain not only the He^{3+} beam but a contaminant proton beam of sufficient strength for this work. Carbon and CaF_2 targets were mounted back-to-back on a rotatable holder. The change from C+He^3 to CaF_2+p could be made in less than 1 min by rotating the target, changing the deflecting-magnet setting and refocusing for the desired beam current. The energy calibration was found by use of a precision pulser calibrated on the O^{16} line as well as from the positions of the one-escape peaks. Because of the small energy difference the energy calibration does not have to be known with great precision. Two separate sequences of determinations were made at different times. Figure 8 shows portions of the energy spectra obtained around region of interest in a typical run. Table IV summarizes the results of the various determinations. A value of 2.82±0.21 keV is found for the separation and hence a value of 1024.83±0.21 keV for the energy difference between the O^{16} and N^{14} γ rays.

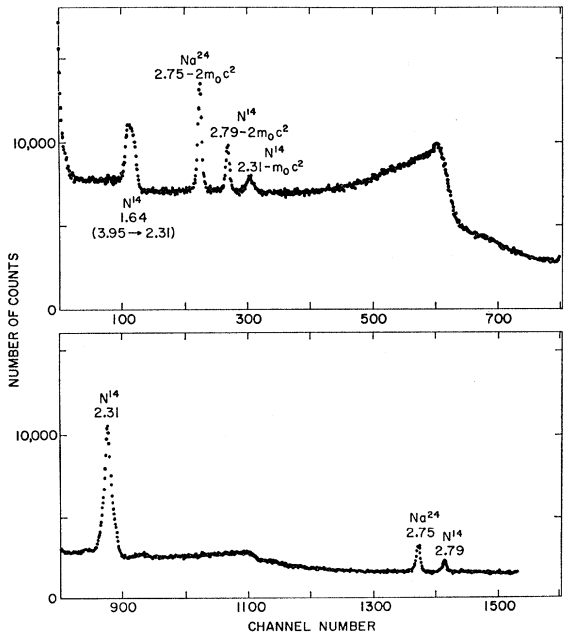

FIG. 7. Pulse-height spectrum produced by bombardment of a carbon target with a 0.25-μA He^3 beam at an energy of 3.0 MeV. The Na^{24} calibration source was run simultaneously. The one-escape peaks for the Na^{24} and 2.79-MeV N^{14} lines were also observed, but cannot be seen well here because of the scale used for the figure. The energy dispersion is 0.89 keV/channel.

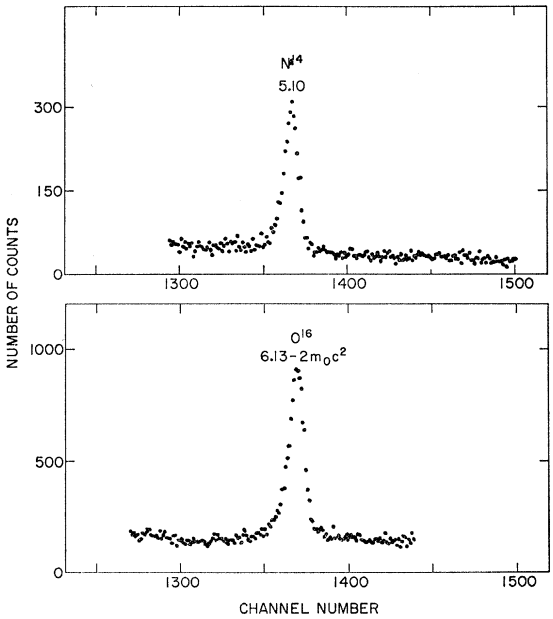

FIG. 8. The upper portion of the figure shows the full-energy-loss peak of the 5.10-MeV N^{14} line produced by bombardment of a carbon target with a 1.0-μA He^3 beam at an energy of 2.0 MeV. The bottom portion of the figure shows the two-escape peak of the 6.13-MeV O^{16} line produced by bombardment of a CaF_2 target with a 1.05-μA beam of 2.2-MeV protons. As pointed out in the text, this comparison is the only one where it was not possible to run all lines of interest simultaneously. The energy dispersion is 0.84 keV/channel.

TABLE IV. Summary of measurements of energy difference between 6.13-MeV O^{16} and 5.11-MeV N^{14} γ rays.

	Run 1		Run 2	
	Position of O^{16} line (channel)	Position of N^{14} line (channel)	Position of O^{16} line (channel)	Position of N^{14} line (channel)
	1369.7 ±0.2[a]	1366.1 ±0.2	455.1 ±0.2	450.0 ±0.2
	1369.8 ±0.2	1366.5 ±0.2	455.0 ±0.2	450.9 ±0.2
	1370.0 ±0.2	1367.2 ±0.2	454.3 ±0.2	450.0 ±0.2
	1369.7 ±0.2	1365.9 ±0.2	454.1 ±0.2	450.1 ±0.2
Average	=1369.80±0.10[b]	1366.43±0.30	454.63±0.30	450.25±0.20
Difference	= 3.37±0.30		4.38±0.40	
Energy dispersion	= 0.84 keV/channel		0.64 keV/channel	
Energy difference between peaks	= 2.83±0.30 keV		2.80±0.30 keV	
Energy difference between γ rays	= 1024.84±0.30 keV		1024.81±0.30 keV	
Average energy difference between γ rays	= 1024.83±0.21 keV			

[a] Uncertainties for the channel numbers are for the uncertainty in the centroid of the peak only.
[b] The external uncertainty is given for the average channel number.

Based on the value of the N^{14} γ ray given above the energy of the O^{16} γ ray is 6129.70±0.28 keV. This agrees reasonably well with the value of 6130.48±0.48 keV found by Method I. The weighted average of the two results gives our best value for the oxygen γ ray as 6129.96±0.46 keV. (The external uncertainty of the two measurements is given.) By correcting for recoil the O^{16} excitation energy is then 6131.22±0.46 keV. Other measurements of this γ-ray energy have been made by Berg and Kashy,[17] Greenwood,[18] and Coté.[19] The values obtained were 6127.8±1.2, 6128.9±0.4, and 6128.5±1.0 keV, respectively. All of the results are in agreement with the work of Browne[20] and Michael who obtained 6131±4 keV for the level energy in a study of the $N^{14}(He^3,p)O^{16}$ reaction.

7.12-MeV O^{16} γ Ray

The two-escape peak of the 7.12-MeV γ ray is about 35 keV below the full-energy-loss peak of the 6.13-MeV O^{16} line, so that an accurate determination of the energy can be made relative to the 6.13-MeV line using the 6.13-MeV full-energy and one-escape peaks for the energy calibration. The 7.12-MeV line must be observed in the β decay of N^{16} with the chopped-beam technique because of the short lifetime of the energy level.

The 0.04-μA beam of 2.2-MeV deuterons was used to produce N^{16} by means of the $N^{15}(d,p)N^{16}$ reaction. N^{16} decays by β-ray emission to both the 6.13-MeV state of O^{16} (68%) and to the 7.12-MeV state (5%). Although the 6.13- and 7.12-MeV transitions differ in intensity by a factor of about 14 and 6.13-MeV full-energy-loss and 7.12-MeV two-escape peaks turn out to have comparable pulse-spectrum amplitudes because of the efficiency of the Ge(Li) detector. The γ-ray spectrum is shown in Fig. 9.

The energy difference between the two peaks shown in Fig. 9 is 35.0±0.15 keV, and the energy difference between the 7.12- and 6.13-MeV γ rays is thus 987.06 ±0.16 keV, which makes the energy of the 7.12-MeV γ equal to 7117.02±0.49 keV, based on the mean value of the 6.13-MeV γ energy quoted above. Crean and Alexander[3] performed an identical experiment and found the γ-ray energy separation to be 987.3±3 keV. Correction of our γ-ray energy for recoil gives an O^{16} level energy of 7118.72±0.49 keV, which is in agreement with the value of 7115±3 keV reported by Browne and Michael.[20]

V. DISCUSSION

A summary of our results is given in Table V. In connection with Method I one might ask why only successive pairs of mixed sources were measured rather than

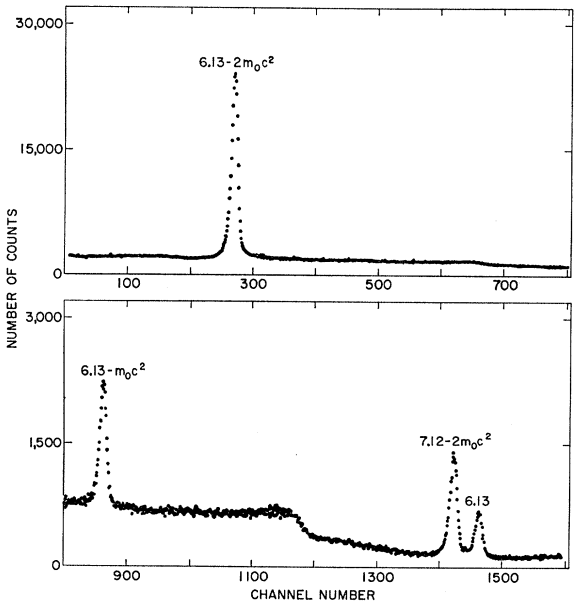

FIG. 9. Pulse-height spectrum obtained in the decay of an N^{16} source to the 6.13- and 7.12-MeV levels in O^{16}. The energy dispersion is 0.86 keV/channel.

[17] R. E. Berg and E. Kashy, Nucl. Instr. Methods **39**, 169 (1966).
[18] R. C. Greenwood, Phys. Letters, **23**, 482 (1966).
[19] R. E. Coté (private communication).
[20] C. P. Browne and I. Michael Phys. Rev. **134**, B133 (1964).

TABLE V. Summary of results.

γ-ray energy difference (keV)	Nucleus and transition	γ-ray energy (keV)	Level energy (keV)
	C^{12} (4.44 → 0)	4438.91±0.31	4439.79±0.31
5.30(N^{15})-4.44(C^{12})=860.12±0.30	N^{15} (5.30 → 0)	5299.03±0.43	5300.03±0.43
6.13(O^{16})-5.30(N^{15})=831.45±0.20	O^{16} (6.13 → 0)	6130.48±0.48[a]	6131.74±0.48[a]
	N^{14} (2.13 → 0)	2312.68±0.10	2312.89±0.10
2.79(N^{14})-Na^{24}=38.76±0.10	N^{14} (5.11 → 2.13)	2792.68±0.15	
	N^{14} (5.11 → 0)	5104.87±0.18[b]	5105.87±0.18
6.13(O^{16})-5.11(N^{14})=1024.83±0.21	O^{16} (6.13 → 0)	6129.70±0.28[c]	6130.96±0.28
7.12(O^{16})-6.13(O^{16})=987.06±0.16	O^{16} (7.12 → 0)	7117.02±0.49[d]	7118.72±0.49
5.30(N^{15})-5.27(N^{15})=28.43±0.15	N^{15} (5.27 → 0)	5270.60±0.46	5271.59±0.46
5.30(N^{15})-5.24(O^{15})=58.50±0.28	O^{15} (5.24 → 0)	5240.53±0.52	5241.51±0.52
	O^{16} (6.13 → 0)	6129.96±0.46[e]	6131.22±0.46[d]

[a] Method I.
[b] Derived from energies of 2.13- and 2.79-MeV γ rays.
[c] Method II.
[d] Based on the mean energy of O^{16} 6.13-MeV γ ray found from the two determinations.
[e] Mean energy for O^{16} 6.13-MeV γ ray. The external uncertainty is given.

three or even four sources at the same time. The reason for this is that in the 4–7 MeV energy region the intensity of the two-escape peak from the size detector that we used (about 4 cc) is larger than the full-energy-loss peak by a factor of about 10. Thus if one were, for example, to use three sources and try to compare the C^{12} (4.44) peak with the N^{15} (5.30–1.022) peak, and at the same time compare the N^{15} (5.30) peak with the O^{16} (6.13–1.022) peak, the intensities of the 4.44-, 5.30-, and 6.13-MeV γ rays would have to be roughly in the ratio 100:10:1 in order that the two members of each pair of lines have comparable intensities. Such intensity ratios can be achieved, but because of considerations of Compton backgrounds and total counting rates, a three-source intercomparison of this sort was not feasible, let alone a four-source measurement.

As larger Ge(Li) detectors are made, the detector volume may be reached eventually where the full-energy and two-escape peaks are of comparabe intensity in the 4–7-MeV region. In such a case one might imagine the simultaneous measurement in a single run of all the lines in the combined sources $Co^{56}+B^{12}+C^{14}+N^{16}$. A dispersion of ~0.5 keV per channel would then require an analyzer of ~8000 channels in order to cover the 3–7-MeV range.

In the one sequential measurement reported in Method II, i.e., the N^{14} 5.10-MeV full-energy-loss peak and the O^{16} 6.13-MeV two-escape peak, the average variation in all successive pairs of runs amounted to 0.25 keV. It would appear that even with our present stabilized-analyzer system there are electronic instabilities that limit the accuracy in the determination of an unknown in the region of 6 MeV to ~±0.3 keV if compared sequentially with a calibration line. Thus a substantial increase in the accuracy of the high-energy calibration lines will become of value for measuring unknown lines when detector resolution has been increased and when the electronics pulse-height stability has been improved.

ACKNOWLEDGMENTS

We are indebted to Professor D. H. Wilkinson for suggesting the sequence of measurements used in the second determination of the 6.13-MeV O^{16} γ energy, to Dr. M. Mariscotti for the computer analysis of the data, and to Professor A. Galonsky for communicating the results of Ref. 10 on C^{12} prior to publication. The stabilizer used was developed by R. L. Chase and M. A. Poole.