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Gamma Decays from the First $T=\frac{3}{2}$ Levels in ^{13}N and ^{13}C

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The reactions ^{11}B(^{3}He,n)^{13}N* ($T=\frac{3}{2}$) (γ) and ^{11}B(^{3}He,p)^{13}C* ($T=\frac{3}{2}$) (γ) have been used to study the γ-decay modes of the lowest $T=\frac{3}{2}$ states in ^{13}N and ^{13}C. Coincidences between neutrons and associated γ rays in the case of ^{13}N and between protons and γ rays in the case of ^{13}C were recorded in a two-dimensional array. For the γ decay of ^{13}N(15.07) and ^{13}C(15.11), we find $\Gamma_{\gamma 0}/\Gamma_{p0}=(12\pm2)\%$ and $\Gamma_{\gamma 0}/\Gamma=(0.53\pm0.06)\%$, respectively. When combined with previously available experimental information, these values yield $\Gamma=1.13\pm0.3$ and 4.7 ± 1.6 keV for the first $T=\frac{3}{2}$ levels in ^{13}N and ^{13}C, respectively. Additional information on γ branching ratios and particle decay for these levels is presented.

I. INTRODUCTION

The low-lying $T=\frac{3}{2}$ levels in the $4n+1$ series of light nuclei have in recent years been the subject of considerable investigation. Above mass 5, the lowest $T=\frac{3}{2}$, $T_z=\pm\frac{1}{2}$ levels in this series are bound against isospin-allowed particle decay and are quite narrow in spite of the large energy available for their decay into isospin-forbidden decay channels. Their structural simplicity has enabled them to be studied in reactions such as (^{3}He,p),[1–3] (^{3}He,n),[4,5] (p,t),[6] and (p, ^{3}He).[6] Their locations and several spin and parity assignments have come from these experiments. Resonant proton-scattering reactions,[7–10] which populate these levels by virtue of their isospin inpurities, have yielded some information on partial particle and γ widths.

Whereas particle decay from the levels is isospin-forbidden, γ decay is not. Among the sources of interest for studying these γ decays are: (1) In some cases $\Gamma_{\gamma 0}$ can be measured in (e,e')[11,12] experiments or by less direct means.[8] A supplementary measure of $\Gamma_{\gamma 0}/\Gamma$ then provides Γ,[13] a knowledge of which is useful both in the analysis of resonance scattering experiments through these levels and, in its own right, as some measure of the size of the isospin impurity in the nuclear wave functions. (2) $T=\frac{3}{2}$ to $T=\frac{1}{2}$ γ decays provide the interesting opportunity to test the prediction that $\Delta T=1$ γ transitions in conjugate nuclei should have equal strengths,[14] a rule which results from the absence of a contribution from the isoscalar part of the electromagnetic operator in such transitions. Deviations from this result should be sensitive to the amplitude of the isospin impurity, rather than the amplitude squared as is the case for the total widths.

The first $T=\frac{3}{2}$ levels in ^{13}C and ^{13}N (see Fig. 1), the analogs of the ground states of ^{13}B and ^{13}O, have spin assignment[8] $\frac{3}{2}^-$ with excitations and widths in ^{13}N and ^{13}C of 15.068 ± 0.008 MeV,[4] $\Gamma<2$ keV[9] and 15.114 ± 0.005 MeV,[1] $\Gamma<5$ keV,[1] respectively. The γ width to the ground states of ^{13}N and ^{13}C has been found to be $\Gamma_{\gamma 0}=27\pm5$ eV,[8] which can be combined with the $E2/M1$ intensity ratio[8] of $0.009_{-0.008}^{+0.018}$ to yield $\Gamma_{\gamma 0}(M1)=27\pm5$ eV. For the ^{13}C case, $\Gamma_{\gamma 0}(M1)=25\pm7$ eV.[11]

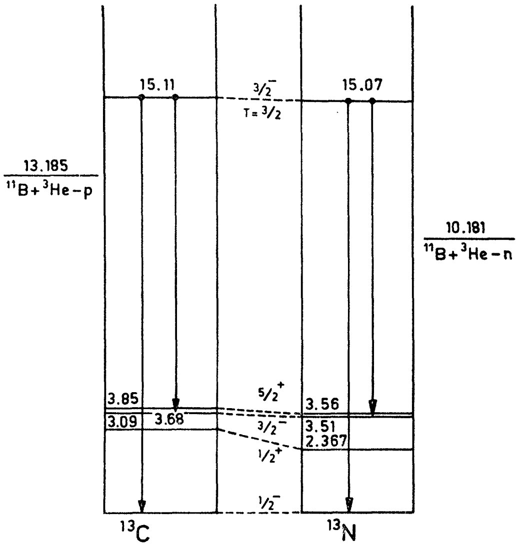

FIG. 1. Partial energy-level diagram for ^{13}C and ^{13}N. The ground states have been aligned.

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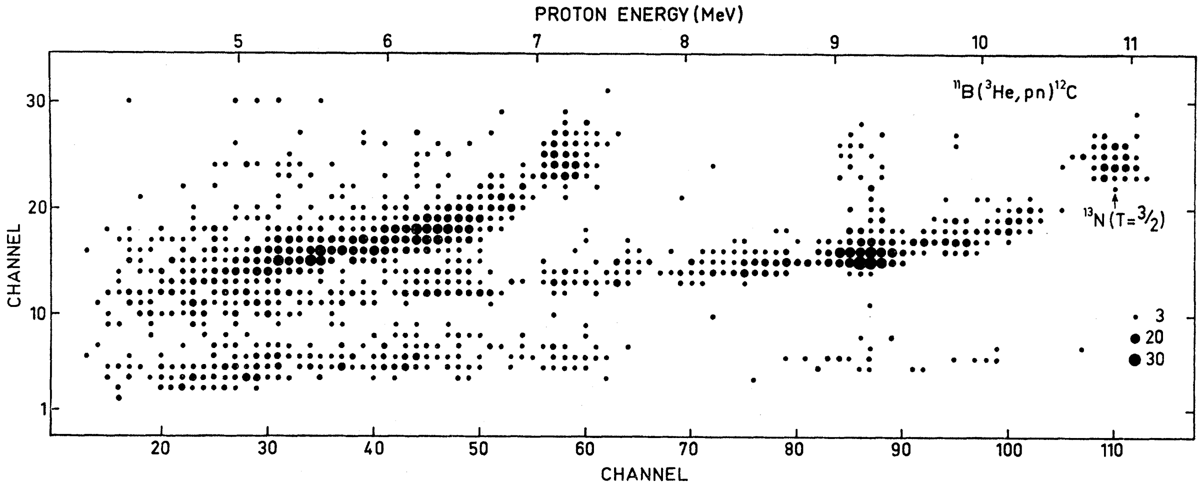

FIG. 2. Neutron time of flight versus proton energy spectrum from ^{3}He+^{11}B, $E(^3\mathrm{He})=7.3$ MeV, $\theta_n=0°$, $\theta_p=125°$. The time calibration is 1 nsec/ch, with a flight path of 29.6 cm. The proton group from the ^{12}C(g.s.) decay of ^{13}N(15.07, $T=\frac{3}{2}$) is indicated. Number of counts is indicated by size of dots.

These results are in excellent agreement with the isospin selection rule mentioned above.

The present experiment was undertaken in order to provide values for $\Gamma_{\gamma0}/\Gamma$, from which total widths for both levels may be deduced, and to provide branching ratios $(\Gamma_{\gamma2}+\Gamma_{\gamma3})/\Gamma_{\gamma0}$ in ^{13}C to compare with those found by Dietrich *et al.*[8] for ^{13}N. To these ends the reactions ^{11}B(^{3}He,n) and ^{11}B(^{3}He,p) were used to populate the first $T=\frac{3}{2}$ levels in ^{13}N and ^{13}C, respectively, and the ensuing γ rays were detected in coincidence with the protons and neutrons that populated the states.

II. ^{13}N DECAY

Insofar as the careful study of the ^{13}N 15.07-MeV level γ decay by Dietrich *et al.*[8] has provided values for relative branching ratios from this level, the present experiment was directed toward a determination of $\Gamma_{\gamma0}/\Gamma$.

A ^{11}B target of 400 μg/cm^2 evaporated onto a 0.025-mm tantalum foil was bombarded by a 7.3-MeV ^{3}He^{++} beam from the 5.5-MeV Van de Graaff accelerator of the Centre de Recherches Nucléaires. A target current of typically 30 nA was delivered to a 2-mm-diam beam spot. The neutrons were detected in an Ne102 plastic scintillator, 5 cm thick by 12.7 cm diam. The γ rays were detected in a 10.16×10.16-cm NaI crystal, the front surface of which was located 7.6 cm from the target spot. The neutron velocity was determined from its time of flight, using the γ-ray detection as the time zero. A two-dimensional analyzer was used to record neutron flight time versus the energy of the coincident γ ray.

The ratio $\Gamma_{p0}/\Gamma=0.20\pm0.02$ for the decay of the ^{13}N 15.07-MeV level to the ^{12}C ground state (g.s.) has previously been measured using the reaction ^{11}B(^{3}He,n)-^{13}N(15.07)(p) ^{12}C(g.s.).[15] In the absence of a pulsed beam it was not feasible to normalize our coincidence spectra to the yield from a singles spectrum of the ^{11}B(^{3}He,n)^{13}N(15.07) reaction. We have chosen instead to measure the ratio of the number of γ rays from the ^{13}N 15.07-MeV level to the number of protons from this level to the ^{12}C ground state. The value of $\Gamma_{\gamma0}/\Gamma_{p0}$ was then multiplied by Γ_{p0}/Γ to yield $\Gamma_{\gamma0}/\Gamma$.

The protons were detected in a silicon surface-barrier detector 1-mm thick collimated by a 2-mm-diam circular aperture located 3 cm from the target. A two-dimensional analysis of neutron flight time versus proton energy was made, in which the group from ^{11}B(^{3}He,n) ^{13}N(15.07)(p) ^{12}C(g.s.) stood out clearly as a resonant group along the kinematically allowed line for events leaving ^{12}C in its ground state (Fig. 2). A p-n coincidence spectrum was taken before and after the γ-n coincidence spectrum and normalized to the p-n spectrum using the deuteron group from ^{11}B(^{3}He,d)-^{12}C(g.s.), the latter appearing clearly in the surface-barrier-counter singles spectrum.

The geometry chosen for the p-n coincidence work was $\theta_n=0°$, $\theta_p=125°$; for the γ-n coincidence, $\theta_n=0°$, $\theta_\gamma=125°$. Under these conditions the axial symmetry and even parity of the angular correlation of both protons and γ rays ensure that the correlation may be expressed as a sum of even-l Legendre polynomials. The spin $\frac{3}{2}$ of the ^{13}N 15.07-MeV level further eliminates terms higher than $P_2(\cos\theta)$. Thus by measuring at the zero of $P_2(\cos\theta)$ one avoids the necessity of doing a detailed angular correlation.

Figure 3 shows a γ-n coincidence spectrum. The γ-γ line is due to coincidences between γ rays detected in the NaI crystal and their associated pair and Compton γ rays detected in the plastic scintillator. The slope of the coincidence lines is due to slewing in the γ-ray timing. The time difference between the γ-γ and γ-n lines was used to calculate the neutron velocity

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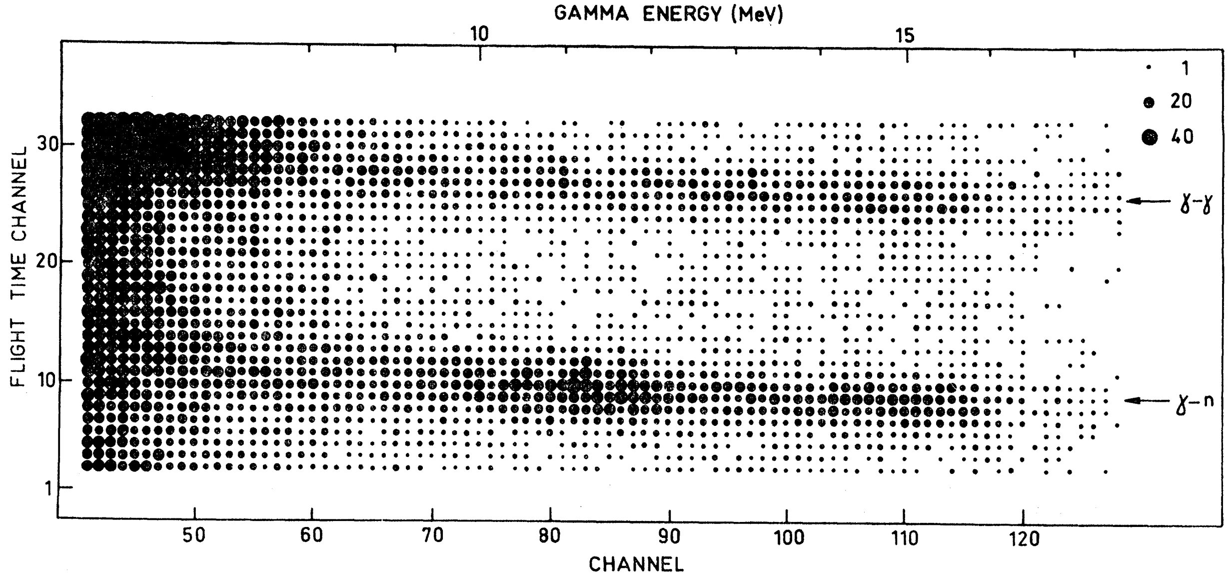

FIG. 3. Neutron time of flight versus γ energy spectrum, taken under the same conditions as the spectrum of Fig. 2, except that the γ spectrum is stored on the ordinate in place of the proton spectrum, and time of flight now increases downward. Number of counts is indicated by size of dots.

and to determine that the γ-n coincidence came from the decay of a state in ^{13}N at 15.2±0.2-MeV excitation.

The summed γ spectrum from the decay of the ^{13}N 15.07-MeV level, after subtraction of random coincidences, is shown in Fig. 4. Standard shapes in the NaI-photomultiplier assembly of 12-, 13-, and 16-MeV γ rays were measured using the reactions $^{11}\mathrm{B}+p$ and $^{15}\mathrm{N}+p$, and were used in fitting the curves shown in Fig. 4. With the help of these shapes and a prior knowledge of the relevant γ energies, we have extracted yields for γ rays of 15.1, 11.5, and 12.7 MeV, although the last of these is certainly problematical with our resolution. Absolute efficiencies of the NaI detector were calculated by numerical integration on an IBM 360 computer. The spectral shape from each γ was assumed to be flat below the half-energy point in extracting absolute yields from the NaI spectrum. Our values for the relative yields of ^{13}N(15.07) to ^{13}N(g.s.) and ^{13}N(3.56+3.51), along with an upper limit for decay to ^{13}N(2.37), are shown in Table I. It should be pointed out that the values found by Dietrich *et al.*[8] for the relative branching ratios are more precise than those that we have been able to obtain with our poorer resolution. The 12.7-MeV γ ray may also come from the decay of the ^{12}C 12.71-MeV level following the proton decay of the ^{13}N 15.07-MeV level to the ^{12}C 12.71-MeV state. Since the fraction of ground-state γ decays from the ^{12}C 12.71-MeV level is known to be (2.5±0.5)% (see Sec. III), an upper limit for the relative decay of the ^{13}N 15.07-MeV level to the ^{12}C 12.71-MeV level may be deduced to be $\Gamma_{p(12.71)}/\Gamma < 0.17$. For the ground-state decay we find $\Gamma_{\gamma_0}/\Gamma_{p_0} = 0.12 \pm 0.02$. This value can be combined with $\Gamma_{\gamma_0}\Gamma_{p_0}/\Gamma = 5.5 \pm 0.8$ eV[8] and $\Gamma_{p_0}/\Gamma = 0.20 \pm 0.02$[15] to yield $\Gamma_{\gamma_0}/\Gamma = (2.4 \pm 0.5)\%$ and $\Gamma = 1.13 \pm 0.3$ keV.

III. ^{13}C DECAY

The 15.11-MeV level in ^{13}C was populated in the reaction $^{11}\mathrm{B}(^{3}\mathrm{He},p)\,^{13}\mathrm{C}(15.11)$ and the ensuing γ rays were detected in coincidence with the protons. The bombarding energy used was 6.98 MeV, the target and beam conditions being otherwise those described in Sec. II. The proton counter was a 1-mm-thick silicon surface-barrier detector, and the γ rays were detected in a 12.7×10.16-cm NaI crystal mounted on an XP-1040 photomultiplier tube. A time resolution of 20 nsec was used. The geometry required for the coincidence

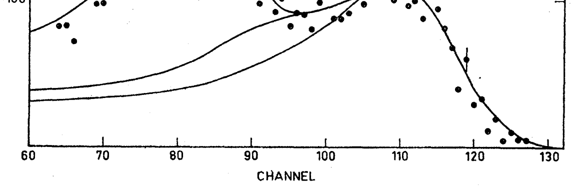

FIG. 4. High-energy portion of a summed γ spectrum from the decay of the 15.07-MeV, $T=\frac{3}{2}$ level in ^{13}N.

TABLE I. Comparison of ^{13}N (15.07-MeV) and ^{13}C (15.11-MeV) decays.

^{13}N		^{13}C	
$\Gamma_{\gamma 0}(15.07 \rightarrow 0.0)$ (eV)	27 ± 5[a]	$\Gamma_{\gamma 0}(15.11 \rightarrow 0.0)$ (eV)	25 ± 7[b]
$\Gamma_{\gamma}(15.07 \rightarrow 2.367)/\Gamma_{\gamma 0}$	<0.20 <0.14[a]	$\Gamma_{\gamma}(15.11 \rightarrow 3.09)/\Gamma_{\gamma 0}$	0.25 ± 0.10
$\Gamma_{\gamma}(15.07 \rightarrow 3.51+3.56)/\Gamma_{\gamma 0}$	0.81 ± 0.12 0.84 ± 0.08[a]	$\Gamma_{\gamma}(15.11 \rightarrow 3.68+3.85)/\Gamma_{\gamma 0}$	0.79 ± 0.10
$\Gamma_{p}(12.71)/\Gamma$	<0.17[c]		
$\Gamma_{\gamma 0}/\Gamma$	0.024 ± 0.005	$\Gamma_{\gamma 0}/\Gamma$	0.0053 ± 0.001
Γ (keV)	1.13 ± 0.3	Γ (keV)	4.7 ± 1.6

[a] From Ref. 8.
[b] From Ref. 12, and assuming intensity ratio $E2/M1 = 0.009_{-0.008}^{+0.018}$.
[c] Using γ-yield ratio $Y(12.7\text{ MeV})/Y(15.07\text{ MeV}) < 0.14$.

measurements was $\theta_p = 0°$, $\theta_\gamma = 125°$. Correspondingly, the proton detector, collimated by a 7-mm-diam circular aperture 4 cm from the target, was centered on the beam axis, subtending an angle extending to ±5° with the beam. The incoming beam and He-isotope reaction products were ranged out by the 0.025-mm-thick tantalum target support.

In order to properly normalize the coincidence spectra, it was necessary to have a singles charged-particle spectrum in which the proton group from ^{11}B(^{3}He,p) ^{13}C(15.11) could be separated. Poor energy resolution and inability to distinguish protons from deuterons made this impossible in the singles spectra obtained with the arrangement used in the coincidence work. High-resolution singles spectra were accordingly taken with self-supporting 50-μg/cm^2 ^{11}B targets using a 30-μ surface-barrier silicon detector in a dE function for particle identification. Figure 5 shows the resulting proton and deuteron spectra taken simultaneously at an angle of 6° to the beam. The small anomaly on the side of the ^{13}C(15.11) group appeared consistently at 6°, 8°, and 10° and is yet unidentified. Because the singles spectra could not be measured in the region between 0° and 5°, the ratio of the yield from ^{11}B(^{3}He,p)-^{13}C(15.11) to that from ^{11}B(^{3}He,d) ^{12}C(4.44) was extrapolated from the 6°–10° region to find the average value over the aperture used during the coincidence measurements. This ratio increased 8% in going from 10° to 6°. The ^{12}C(4.44) deuteron group was used to appropriately normalize the coincidence spectra.

In Fig. 6 we show a two-dimensional coincidence spectrum in which γ energy is displayed as a function of particle energy, the result of 14 h of measurement. γ rays from the decay of the ^{13}C 15.11-MeV and the ^{12}C 12.71-MeV levels are seen in particle energy channels 14 and 4, respectively. The summed γ spectrum from

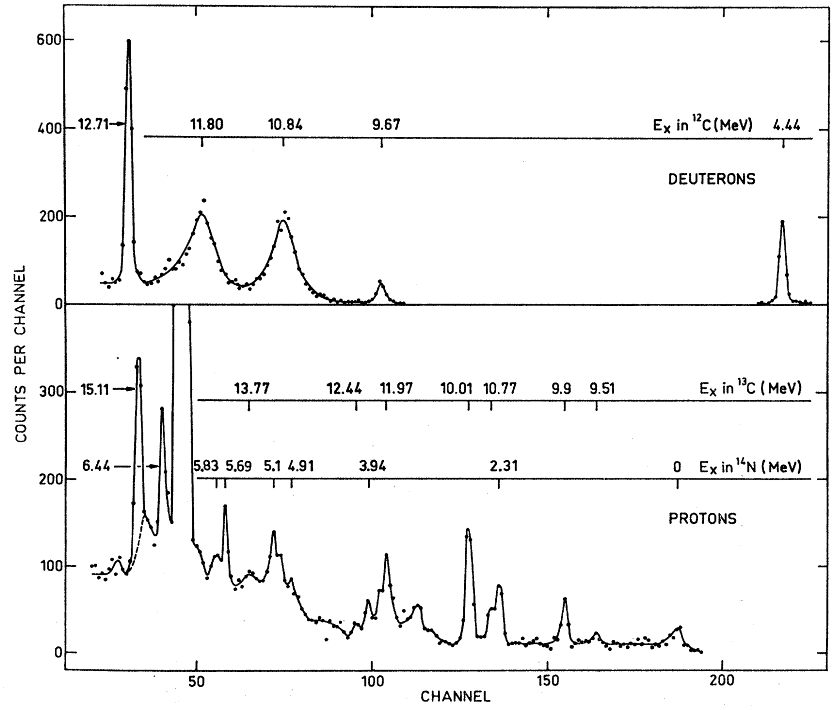

FIG. 5. Proton and deuteron spectra from the reactions ^{11}B(^{3}He,d) and ^{11}B(^{3}He,p) taken at $E(^3\text{He}) = 6.98$ MeV and an angle of 6°. Groups in ^{14}N come from ^{12}C(^{3}He,p), and the proton group in channel 47 is from ^{1}H(^{3}He,p) carbon and hydrogen being target contaminants.

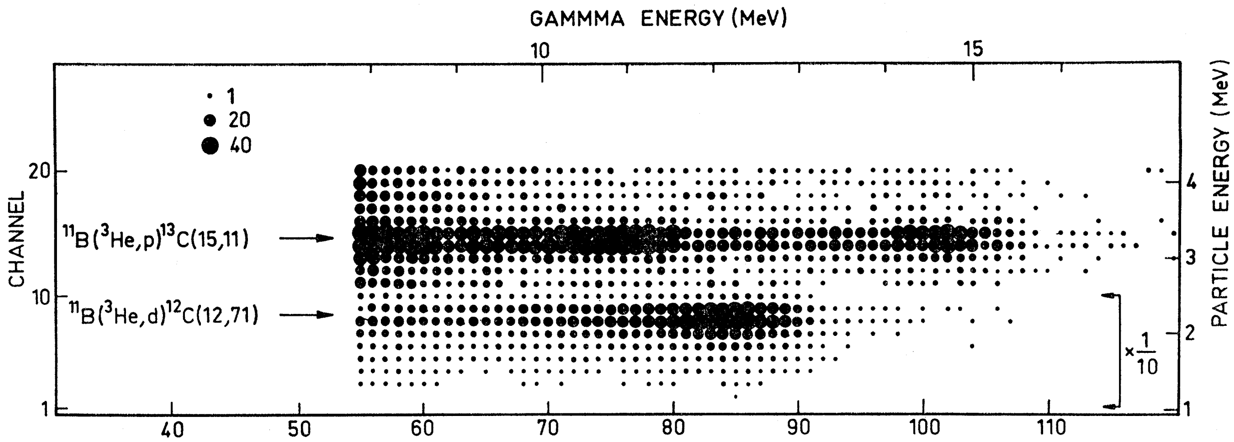

FIG. 6. Particle energy versus γ-ray energy spectrum from ^{3}He+^{11}B, $E(^3\mathrm{He})=6.98$ MeV, $\theta_p=0°$, $\theta_\gamma=125°$. Number of counts is indicated by size of dots.

the decay of the ^{13}C 15.11-MeV level, after subtraction of the appropriately normalized randoms spectrum, is shown in Fig. 7. The solid curves and the corresponding branching ratios shown in Table I were produced using prior knowledge of the relevant γ energies and the procedure described in Sec. II. As in the case of ^{13}N, the size of the weak decay toward the ^{13}C 3.09-MeV level is difficult to assess properly. We remark here that the neutron decay of the 15.11-MeV level via the 12.71-MeV level in ^{12}C is energy-forbidden.

The inclusion of the ^{12}C(12.71) peak in both our singles and coincidence spectra allows us to calculate $\Gamma_{\gamma 0}/\Gamma=(2.5\pm0.5)\%$, for this level. This value is in good agreement with the value previously measured $\Gamma_{\gamma 0}/\Gamma=(2.7\pm0.7)\%$,[16] thus providing an internal check on our experimental procedure. For the decay of the ^{13}C 15.11-MeV state, we find $\Gamma_{\gamma 0}/\Gamma=(0.53\pm0.1)\%$. This value can be combined with $\Gamma_{\gamma 0}(M1)=25\pm7$ eV and the intensity mixing ratio[8] (supposed the same in ^{13}N and ^{13}C) of $E2/M1=-0.009_{-0.008}^{+0.018}$ to yield $\Gamma=4.7\pm1.6$ keV for the first $T=\frac{3}{2}$ level in ^{13}C.

IV. DISCUSSION

That the isospin-forbidden decays from the first $T=\frac{3}{2}$ levels in ^{13}C and ^{13}N have quite different characters has been established previously from a comparison of their relative proton and neutron decays, respectively, to the ground and 4.44-MeV states of ^{12}C.[15] This difference

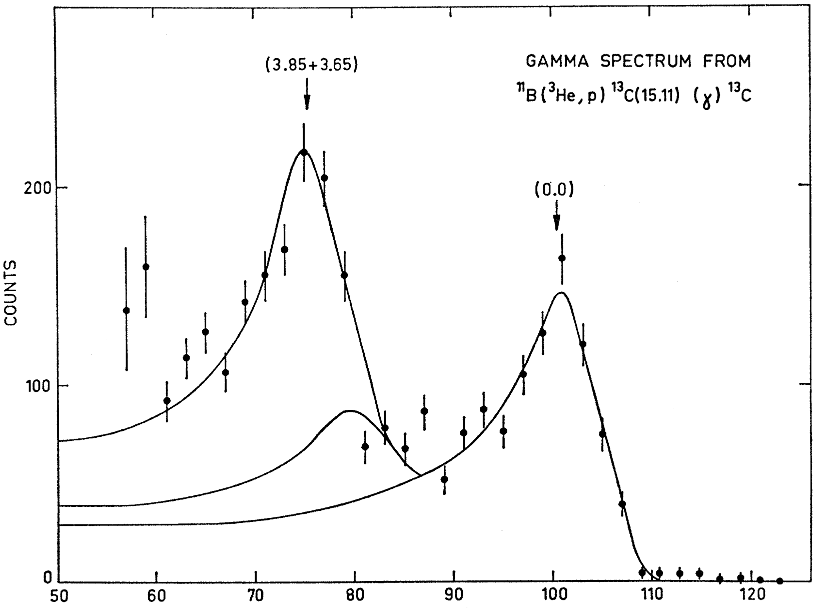

FIG. 7. High-energy portion of a summed γ spectrum from the decay of the 15.11-MeV, $T=\frac{3}{2}$ level in ^{13}C.

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[16] E. K. Warburton and H. O. Funsten, Phys. Rev. 128, 1810 (1962).

has pointed out that the mixture of more than one $T=\frac{1}{2}$ level into the $T=\frac{3}{2}$ states is probably important. The T_z dependence of the impurity may be attributed to possible variations in the two nuclei of the separation between the relevant $T=\frac{3}{2}$ and $T=\frac{1}{2}$ levels and to the expected T_z dependence of the isospin-nonconserving matrix elements. The rather dramatic difference in total widths for ^{13}N and ^{13}C observed here (Table I) further substantiates the lack of mirror symmetry in the second-order wave functions. Note that the difference in widths cannot be simply attributed to differing channel energies in the two cases, since this effect would produce a larger width for the ^{13}N decay. The only theoretical calculations of total widths available are, to our knowledge, those by Ghinocchio,[17] who obtains between 1.4 and 4.5 keV for ^{13}N, in rough agreement with the measured values.

A summary of experimental information on the isospin-allowed γ decays is shown in Table I. The resolution of decays to the $\frac{3}{2}^-$ and $\frac{5}{2}^+$ levels has not been accomplished in either ^{13}C or ^{13}N, although decay to the $\frac{5}{2}^+$ level is expected to be much weaker than that to the $\frac{3}{2}^-$.[17] Such separation should be feasible in the ^{13}C case where the γ energies differ by 170 keV; the appropriate experiment is in preparation. The present data are in entire agreement with the prediction that $\Delta T=1$ decays in mirror nuclei have equal strengths—within large experimental errors, however. The absence of experimental information on the $T=\frac{1}{2}$, $\frac{3}{2}^-$ levels near 15 MeV in $A=13$ precludes any estimate of the precision needed to detect the effects of isospin impurities in these $T=\frac{3}{2}$ levels. The situation in ^{9}Be is slightly better, where shell-model calculations predict $\frac{3}{2}^-$ levels of $T=\frac{3}{2}$ and $T=\frac{1}{2}$ at 14.39 and 12.76 MeV, respectively, both with appreciable components of [3,2] ^2P (in an LS-coupled basis) wave functions.[18] If one identifies these levels with those experimentally identified at 14.39 MeV ($\Gamma=0.46\pm0.17$ keV)[12] and 13.7 MeV ($\Gamma=600$ keV),[19] and correspondingly takes 600 keV as the width of the "typical" admixed $T=\frac{1}{2}$ level, one may estimate the square of the amplitude α of the isospin impurity into the $T=\frac{3}{2}$ state as $\alpha^2\sim0.8\times10^{-3}$ or $\alpha\sim3\times10^{-2}$. Under the tacit assumption that the impurities in $A=13$ are of a similar magnitude, one might therefore expect variations from the isospin selection rule for γ decays examined here of the order of a few percent. The present data are not sufficiently accurate to detect such deviations. More accurate data, such as might be obtainable with the use of large NaI scintillators, would be of great interest in this respect. Furthermore, it is clear from the above discussion that any detailed understanding of the isospin purity of these $T=\frac{3}{2}$ states must await experimental information on the $T=\frac{1}{2}$ levels in the same excitation region and having the same spin and parity.

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