neutrinos/cm^2 sec; unfortunately, the energies of the neutrinos produced are small,[23] $\lesssim 250$ MeV. Nevertheless, perhaps several events per day of reaction (1) may be expected.

The question is how to identify these. Characteristic features of reaction (1) are the following:

(a) The lepton energy is given by $E_l = \nu - \delta$, i.e., it is independent of emission angle. The initial neutrinos are not monochromatic; their spectrum is known from calculation, however, and the leptons in Eq. (1) would have a spectrum equal to the neutrino spectrum, for $\nu \gtrsim 300$ MeV; below that, their spectrum is known from folding.

(b) The lepton angular distribution is more forward than in reaction (31), where angles below 20° are largely depressed owing to the exclusion principle.[19,20,24]

[24] S. M. Berman, in *Proceedings of the International Conference on Theoretical Aspects of Very High-Energy Phenomena* (CERN, Geneva, 1961), p. 7; B. Goulard and H. Primakoff, Phys. Rev. **135**, B1139 (1964).

(c) The excited dipole state will decay in a characteristic fashion,[14] i.e., $\rightarrow {}_7N^{12}+\gamma$, ${}_7N^{12*}+\gamma$, ${}_6C^{11}+p$, ${}_6C^{11*}+p$. The emitted particles have characteristic energies, given by the dipole state excitation energy Δ less the sum of the rest energies of the pair of final particles above the ${}_7N^{12}$ rest energy, with the excitation energy of the residual nucleus subtracted if it is formed in an excited state.

In total, there seems to be a good chance to observe the excitation of the giant dipole and related collective modes by neutrinos, even though the cross section is smaller than that of the direct (elastic) reactions. After the now-contemplated construction of high-intensity accelerators or "pion factories," the observation should be rather easy.

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Quadrupole-Dipole Mixture of the N^{14} 3.95 → 0 Gamma-Ray Transition

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The quadrupole-dipole mixing ratio of the 4% gamma-ray branch from the N^{14} second excited state at 3.95 MeV to the ground state has been determined using the $C^{12}(He^3,p)N^{14}$ reaction and an He^3 beam of 5 MeV. Gamma rays due to the decay of the 3.95-MeV level were detected in coincidence with protons of the right energy to populate the 3.95-MeV level. The protons were detected in a surface-barrier counter at 0° with respect to the He^3 beam, and the populations of the magnetic substates were fixed from a simultaneous observation of the transition to the 0^+, 2.31-MeV level. Two regions of values for the mixing ratio x consistent with the experiment were found, namely, $-0.5 \leq x \leq -0.2$ and $-5 \leq x \leq -2$.

I. INTRODUCTION

THE extremely long lifetime of C^{14} is an experimental fact which has not received an unambiguous explanation despite several extensive efforts.[1–5] The crucial point is that the cancellation between the various contributions to this matrix element which must take place in order to reach the long lifetime of C^{14} cannot be achieved with a pure s^4p^{10} configuration and a conventional shell-model interaction, i.e., a central interaction between the particles together with a single-particle spin-orbit force. Two possible explanations for this cancellation have been advanced.[1] In one the s^4p^{10} configuration is assumed to be pure and the necessary modification of the s^4p^{10} wave function is achieved by introducing a small (but in this case non-negligible) tensor interaction between the nucleons.[2–4] In the other the cancellation is attributed to destructive interference between the contribution to the matrix element from s^4p^{10} and the contribution from admixtures of the doubly excited configurations generated by raising two p-shell nucleons into the $2s$ and $1d$ shells.[5] At the pres-

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[2] B. Jancovici and I. Talmi, Phys. Rev. **95**, 289 (1954).
[3] J. P. Elliott, Phil. Mag. **1**, 503 (1956).
[4] W. M. Visscher and R. A. Ferrell, Phys. Rev. **107**, 781 (1957).
[5] E. Baranger and S. Meshkov, Phys. Rev. Letters **1**, 30 (1958).

ent time it is not clear which of these explanations (or a combination of both) is correct.

The sign and magnitude of the quadrupole-dipole mixing ratio

$$x = \langle J_f \| E2 \| J_i \rangle / \langle J_f \| M1 \| J_i \rangle$$

of the gamma transition from the second excited state of N^{14} to the ground state depends sensitively on the presence of a tensor force but is not too sensitive to admixtures of the doubly excited configuration. Thus its determination can provide useful information for the theoretical understanding of the long lifetime of C^{14}. A measurement of the mixing ratio x is described in the present paper. Its significance for the near-vanishing of the C^{14} β-decay matrix element will be discussed in a forthcoming paper.

The 3.95-MeV state of N^{14} decays approximately 96% to the $J^{\pi}=0^+$, 2.31-MeV first excited state,[6] and therefore, gamma rays of 1.64 and 2.31 MeV dominate the spectrum due to its decay. In order to determine the mixing ratio x for the extremely weak 3.95-MeV gamma-ray branch to the ground state from an observation of the angular distribution of this gamma ray, great care has to be taken to correct for random coincidences and contributions due to summing of 1.64- and 2.31-MeV gamma rays. The reaction $C^{12}(He^3,p)N^{14}$ was used to populate the 3.95-MeV level. Gamma rays due to the decay of this level were selected for observation by gating the gamma-ray detection equipment with signals produced by protons of the right energy to populate the 3.95-MeV level. The populations of the magnetic substates of the 3.95-MeV level were determined from an observation of the angular distribution of the $3.95 \rightarrow 2.31$ transition. Since this transition must be of pure multipole order, observation of its distribution determines the populations of the substates uniquely.[7] The experimental procedure and the evaluation of the data are described in Sec. II. The results for the mixing ratio x are given in Sec. III together with the value obtained for the branching ratio.

II. EXPERIMENTAL PROCEDURE AND DATA EVALUATION

The reaction $C^{12}(He^3,p)N^{14}$ was used with a fast-slow proton energy selective coincidence experiment. An He^3 beam of 5.0 MeV was supplied by the Freiburg University 5.5-MeV Van de Graaff generator. An Ortec SBCJ 050-1000 surface barrier counter detected the protons at 0° with respect to the He^3 beam and at an approximate distance of 6 cm from the target. A spectrum of the protons is shown in Fig. 1.

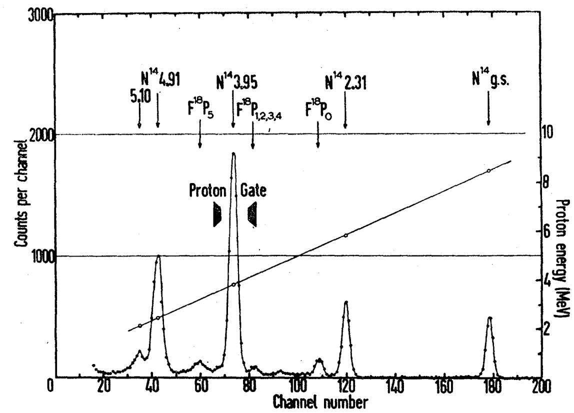

FIG. 1. Spectrum of protons in the reaction $C^{12}(He^3,p)N^{14}$ at a bombarding energy $E_{He^3}=5.0$ MeV obtained with a surface barrier counter using an approximately 140-μg/cm²-thick natural carbon target. The small oxygen contamination of the target causes the peaks due to the reaction $O^{16}(He^3,p)F^{18}$, which also are labeled.

The target consisted of an approximately 140-μg/cm² thick film of natural carbon deposited on a 20-mg/cm²-thick copper foil. A further foil of this thickness was used to shield the counter against scattered particles while the first foil served simultaneously as the main beam stopper. The energy resolution of the proton detection equipment including the electronics was approximately 100 keV.

A 4-×4-in. NaI(Tl) crystal mounted to rotate around the target on a Dumont 6364 photomultiplier tube was used to detect the gamma rays. Measurements were taken at 0° and 90° with respect to the He^3 beam in runs with the front face of the gamma-ray detector at two different distances from the target (23 and 46 cm). The effective solid-angle ratio for these two distances is $\Omega(23\text{ cm}):\Omega(46\text{ cm})=3.4$ for all the gamma-ray energies in question.

Proton-gamma coincidences were established using "trailing edge" coincidence techniques. A fast-slow coincidence unit of the Cosmic Radiation Laboratories, type 801, served to measure real and random coincidences separately and a Laben 512-channel pulse-height analyzer was programmed to record these spectra in two different subgroups. The coincidence resolving times of the two circuits were $2\tau=60$ and 75 nsec. The role of the two circuits measuring real and random coincidences was interchanged in the middle of each measurement in order to average out the differences in the circuits.

Each run consisted of four measurements: two at 0° and two at 90° with respect to the He^3 beam. Three runs were made with the gamma-ray counter at a distance of 23 cm from the target and a beam of 0.14 μA. The total integrated charge for these runs was 9.6 mC, corresponding to approximately 20-h running time. The number of detected protons populating the 3.95-MeV level and yielding coincidence signals for gamma-ray detection was approximately 8×10^6. One further run was made with the detector distance of 23 cm and a beam of 0.07 μA. The total integrated charge for this run

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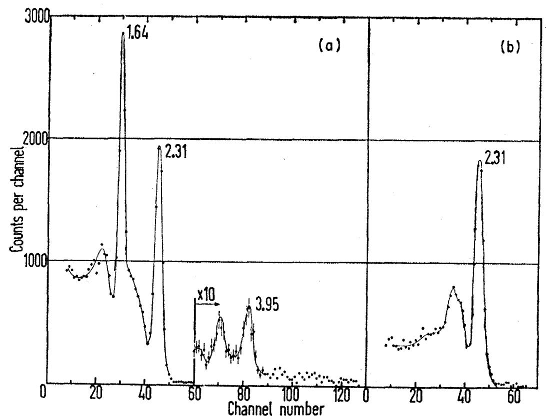

FIG. 2. (a) Spectrum of the gamma rays in coincidence with protons populating the 3.95-MeV level in N^{14} (compare Fig. 1 for the proton gate setting). The spectrum is obtained with a 4-×4-in. NaI(Tl) crystal and displayed on a Laben 512 channel analyzer. (b) Gamma-ray spectrum in coincidence with protons populating the 2.31-MeV level in N^{14}.

was 3.36 mC corresponding to approximately 3×10^6 detected protons and 14-h running time.

Three runs were made with the detector at 46 cm and with a beam of 0.14 μA. The total integrated charge was 18 mC corresponding to 36-h running time. The number of protons collected in the gate during these three runs was 16×10^6. Checks on the stability of the proton and gamma-ray detection equipment and on the target were made in between the runs. The gamma-ray detection device was stabilized electronically.

In Fig. 2(a) the sum of all coincidence gamma-ray spectra obtained in the runs at 0° with the gamma-ray detector at a distance of 23 cm is shown. In order to evaluate the correct number of counts due to the 1.64-MeV gamma ray in this and the corresponding 90° summed spectra, a further experiment was done of which the result is displayed in Fig. 2(b). The single-channel analyzer gate was set on the proton group populating the 2.31-MeV level and the gamma-ray spectrum was recorded. In this manner the correct shape of the spectrum due to an isolated 2.31-MeV gamma ray is obtained as shown in Fig. 2(b). After proper normalization, this spectrum can be subtracted from the spectrum shown in Fig. 2(a) to yield the correct number of counts in the 1.64-MeV line.

The evaluation of the data from the spectra obtained in the three sets of runs described above was done in two different ways. The total number of random coincidences in the spectra obtained in the three sets of runs varies between 4 and 1% of the total number of counts in the real coincidence spectra, depending of course on the conditions (current and distance) each set was taken at. More importantly, the contribution of the random coincidences to the pulse-height region of the full-energy loss and one-escape peaks of the 3.95-MeV gamma ray varied between 10 and 25%. Thus a careful correction for randoms was necessary. This correction was made in two ways. In what shall be called method R, the simultaneously recorded random-coincidence spectra were subtracted from the spectra of real coincidences. In method S, a normalized singles spectrum (recorded at the start of each measurement) was subtracted from the sum of the real coincidence spectra. The normalization was made to the number of counts in the sum of the real coincidence spectra above channel 90, i.e., above the 3.95-MeV gamma-ray line.

The latter procedure (method S) was introduced because the random spectra had an intensity in the pulse-height region above channel 90 which was, on the average, about 70% of that in the real coincidence spectra in this pulse-height region. Method S was partially justified by the fact that the shape of the spectra above channel 90 was closely proportional to that of the single spectra. The failure of the randoms to account for all the counts in the pulse-height region above the 3.95-MeV level is probably due to real coincidences with the background underlying the proton group populating the 3.95-MeV level. If so, the fact that the high pulse-height region of the coincidence spectra has a similar shape to the singles spectra is accidental. In any case, the procedures R and S yielded two limiting final answers which differ by less than the uncertainties imposed by statistics.

After the background corrections via method R or S had been made, the analysis of the 0° and 90° spectra from the three sets of runs (summed for each set) was carried out in the following manner. The contribution due to the 2.31-MeV gamma ray in each of the spectra was determined using the 2.31-MeV gamma-ray spectrum displayed in Fig. 2(b). In this manner, the intensity of the 1.64-MeV gamma ray could be accurately determined. Two small corrections were applied to the intensities of the gamma rays. There were a correction of about 1% for that fraction of the 3.95-MeV gamma-ray spectrum which underlay the 2.31- and 1.64-MeV peaks, and an almost negligible correction for the difference of absorption of the three gamma rays in the target chamber walls, etc. The pulse-height regions from channels 27 to 35, 36 to 55, and 56 to 90 [see Fig. 2(a)] were used in the analysis of the 1.64-, 2.31-, and 3.95-MeV gamma rays, respectively. Finally, a correction was made for contributions to the 3.95-MeV gamma-ray intensity due to summing of the 1.64- and 2.31-MeV gamma rays. This was done with negligible error by folding numerically the 1.64- and 2.31-MeV gamma-ray spectra after having separated them in the manner described above and using the counts in the proton window for normalization. It is found that in the 23-cm runs, between 6% and 12% of the intensity of the 3.95-MeV gamma-ray line (depending on the angle) was due to summing. At 43 cm the correction was between 1% and 5%.

The intensity ratio $I(0°)/I(90°)$ was obtained by normalizing to the intensity of the isotropic 2.31-MeV gamma ray since this procedure was more reliable and accurate than relying on the integrated charge. The combined results of all the runs for the intensity ratio $I(0°)/I(90°)$ are 0.752 ± 0.025 and 1.42 ± 0.10 for the 1.64- and 3.95-MeV gamma rays, respectively. This ratio uniquely characterizes the angular distributions since the 3.95-MeV level has $J=1$. The anisotropies are then $-(0.248\pm0.025)$ and $+(0.42\pm0.10)$; while the coefficients, $A_2(J_1J_2)$, for the $1^+\rightarrow 0^+$, $3.95\rightarrow 2.31$ and $1^+\rightarrow 1^+$, $3.95\rightarrow 0$ transitions are $A_2(10)=-(0.180\pm0.017)$ and $A_2(11)=+(0.25\pm0.05)$, where the angular distribution of these two transitions is given by $W(\theta)=1+A_2(J_1J_2)P_2(\cos\theta)$. The uncertainties, which are mainly due to statistics, are root-mean-square errors including all the sources of error mentioned in this section.

A convenient way of extracting a value for the mixing ratio x for the $3.95\rightarrow 0$ transition from these data is to form the ratio $f(x)=-2A_2(11)/A_2(10)$. From the values given above for $A_2(11)$ and $A_2(10)$, this ratio is 2.8 ± 0.6. We note that the correction to the $A_2(J_1J_2)$ coefficients due to the finite solid angle subtended by the gamma-ray detector drops out to first order when this ratio is taken, and since this correction was small to begin with the uncertainty from this source is negligible.

III. THE MIXING RATIO AND BRANCHING RATIO OF THE $3.95\rightarrow 0$ TRANSITION

From the observed relative intensities of the 1.64-, 2.31-, and 3.95-MeV gamma rays, the branching ratio of the $3.95\rightarrow 0$ transition is found to be $(3.8\pm0.5)\%$. This value is arrived at using only the number of events in the full-energy-loss peaks of the gamma rays. The peak-to-total ratios and the total efficiencies of the 4-×4-in. NaI(Tl) cyrstal for the gamma rays in question were taken from the tables of Miller *et al.*[8] The photofraction also was determined experimentally and the average of the tabulated and experimental values was used. The error is mainly due to the mean-square error on the 3.95-MeV gamma-ray intensity and partly due to uncertainties in the peak-to-total ratios and to uncertainties in the subtraction of the underlying background of the 3.95-MeV full-energy-loss peak. This value is in good agreement with previous determinations.[6]

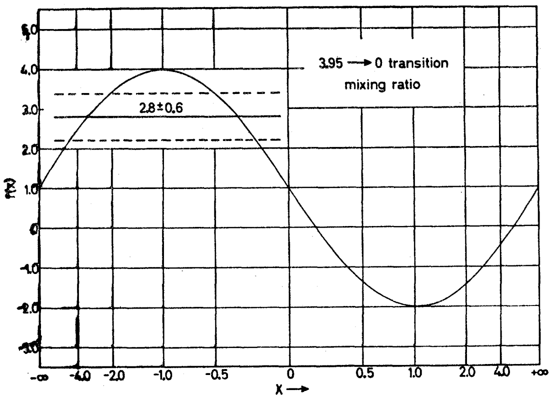

FIG. 3. The function $f(x)=(1-6x+x^2)/(1+x^2)$ versus the $E2/M1$ amplitude ratio x in the $3.95\rightarrow 0$ transition. The experimental value of $f(x)$ determined from the angular distributions of the $3.95\rightarrow 0$ and $3.95\rightarrow 2.31$ transitions is $f(x)=2.8\pm0.6$ and corresponds to $-5\leq x\leq -2$ or $-0.5\leq x\leq -0.2$.

The function $f(x)$ which was evaluated experimentally to be 2.8 ± 0.6 is given theoretically by[7] $f(x)=(1-6x+x^2)/(1+x^2)$ with the phase convention of Litherland and Ferguson.[9] The function $f(x)$ is shown plotted against x in Fig. 3. Also shown in Fig. 3 is the region of $f(x)$ allowed by the experiment. Two regions of x are selected by the experiment. These are $-0.5\leq x\leq -0.2$ and $-5\leq x\leq -2$.

A theoretical prediction for the absolute value of x can easily be obtained from the wave functions given by Elliott or by Visscher and Ferrell. These wave functions are derived assuming a pure s^4p^{10} configuration and a tensor interaction sufficient to reproduce the very small C^{14} β-decay matrix element. The two calculations predict identical values of $|x|$ namely $1.53(1+2\beta)$, where β takes collective enhancement into account according to the weak coupling scheme, is zero for no collective enhancement, and is expected to have a value of $\simeq 0.5$. It would appear that, if the wave functions used are suitable, the experimental result gives a preference for collective enhancement and is in agreement with $\beta\simeq 0.5$. A more detailed analysis of the measured value of x (including its phase as well as its magnitude) will be made in a forthcoming paper.

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