vector polarization of the recoil deuteron can be written in the form[1]

$$\vec{P} = [A(L\vec{K}^* + \vec{K}L^*) + Bi(L\vec{K}^* - \vec{K}L^*) + Ci(\vec{K}\times\vec{K}^*)] \times (\alpha LL^* + \beta\vec{K}\cdot\vec{K}^* + \gamma|\hat{Q}\cdot\vec{K}|^2)^{-1}. \quad (1)$$

If the relative phase between the $S$ and $D$ states is zero or 180° (the positive value of the deuteron quadrupole moment precludes 180°), then $A=0$, and for elastic scattering of unpolarized electrons with no observation on the final spin state the quantities $L\vec{K}^*-\vec{K}L^*$ and $\vec{K}\times\vec{K}^*$ are zero if one-photon exchange is assumed. This is easily seen if we write $L$ and $\vec{K}$ explicitly in terms of the electromagnetic form factors as[2]

$$L = G_E A_t \quad (2)$$

$$\vec{K} = G_M \vec{Q}\times\vec{A}/2M, \quad (3)$$

where $A$ is given, apart from multiplying factors, by

$$A_\mu = (\bar{u}_{p_2}\gamma_\mu u_{p_1}), \quad (4)$$

where $p_1(E_1,\vec{p}_1)$ and $p_2(E_2,\vec{p}_2)$ denote the initial and final electron momenta. It is also easily seen that after summing and averaging over the electron spins we have

$$L\vec{K}^* + \vec{K}L^* = 8G_E G_M(E_2+E_1)\vec{p}_1\times\vec{p}_2/2M, \quad (5)$$

which is not zero. If $\delta$ denotes the relative phase between the $S$ and $D$ states, the coefficient $A$ is given by

$$A = -(3\sqrt{6})\,\mathrm{Re}\langle D|j_2|S\rangle \times \tan\delta[2\,\mathrm{Re}\langle D|j_2|S\rangle - 2^{-1/2}\langle D|j_2|D\rangle]. \quad (6)$$

Explicit expressions for the coefficients $\alpha$ and $\beta$ in (1) can be found in Ref. 1. Under the assumption of one-photon exchange $\vec{Q}\cdot\vec{K}$ is zero.

This note is expected to be of interest in the context of the recent experimental study[3] of the recoil-deuteron polarization to test time-reversal invariance in electromagnetic interactions.[4] It may be emphasized that although we do not introduce in the nucleon current any $T$-nonconserving term like $(P_\mu'-P_\mu)F_3$ in the notation of Bernstein, Feinberg, and Lee[5] (and all the particles are treated on the mass shell), we still obtain nonzero polarization for the recoil deuteron if there is a difference of phase between the $S$ and $D$ states of the deuteron. The possible origin of this phase difference is clearly beyond electromagnetism even if it exists. The negative result of the experiment[3] could either be due to the absence of $T$ nonconservation and the zero value of the phase difference $\delta$ or due to an accidental cancellation of the two effects.

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## PARTIAL CAPTURE RATES OF MUONS BY $^{16}O$ LEADING TO EXCITED NUCLEAR STATES OF $^{15}N$†

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Partial interaction rates have been measured for the muon capture reaction $\mu^- + {}^{16}O \to {}^{15}N^* + n + \nu$ leading to the excited states at 6.323 MeV ($\frac{3}{2}^-$), 5.270 MeV ($\frac{5}{2}^+$), and 5.299 MeV ($\frac{1}{2}^+$). The total observed transition rate to excited states of $^{15}N$ is in good agreement with predictions attending recent calculations of the total capture rate. The distribution of the excitation among the three levels is very similar to that observed from the photoproton and photoneutron reactions on $^{16}O$.

Comparison of calculations with measured nuclear capture rates of muons within the framework of the universal Fermi interaction has proven rather difficult. Interpretations are complicated either by molecular effects, in hydrogen, or by nucleon-nucleon interactions, in all other nuclei. The success of the giant-dipole model in reconciling theoretical[1-4] and experimental[5,6] capture rates of muons by $^{16}O$ is well known. Aside from the total capture rate itself, however, the only evidence for the validity of the model as applied to $\mu^-$ capture was the small likelihood of capture leading to particle-stable states of $^{16}N$.[7-9]

Largely to encourage a search for further experimental evidence for the model, Raphael, Überall, and Werntz made detailed calculations of final-state distributions following $\mu^-$ capture. We report here the observation of the capture rate to the $\frac{3}{2}^-$ (6.323-MeV) level[10] of $^{15}N$ at approximately the high intensity predicted. We furthermore observe a significant number of transitions to the even-parity levels of $^{15}N$. These transitions are predicted in the simple electric-dipole–capture models. However, they are also observed[11-13] in the photoexcitation of $^{16}O$.

The experiment was performed in the meson cave at the Berkeley 184-in. cyclotron. A muon beam defined by a 4-in. square counter telescope was stopped in a 2-in.-thick water target. The target was viewed at 90° by a Ge(Li) detector. Beginning 200 nsec after each muon stopping a 2-$\mu$sec gate was generated. Gamma rays detected by the Ge(Li) detector during this gate were analyzed in a 1024-channel pulse-height analyzer. To reduce background from decay electrons a plastic scintillator in anticoincidence was placed between the water target and the Ge(Li) detector.

The efficiency of our detector was determined by using the muonic $K\alpha$ x rays from Pb. Targets of three different thicknesses of Pb were used to permit correction for $\gamma$-ray absorption. The targets, each made of lead foil uniformly dispersed between thin sheets of Lucite, were so constituted and spaced as to have the same total stopping power and dimensions as the water target. The muonic x rays were detected in prompt coincidence with the muon stopping. The 6.130-MeV $^{16}O$ line was used for in situ energy calibration and stabilization.

Background was measured by analyzing the $\gamma$-ray spectrum from the detector, uncorrelated with stopping muons, but during the beam pulse. In the energy region of interest the only background $\gamma$ observed was the 6.130-MeV $^{16}O$.

In the course of the experiment two Ge(Li) detectors were used. In the early part of the experiment we used a coaxial detector of nominal intrinsic volume of 35 $cm^3$ that gave an energy resolution of about 30 keV at 6 MeV. After we had accumulated about half our final data, a reasonably large, higher resolution detector became available. This was a planar detector having a volume of about 12 $cm^3$ and a resolution of approximately 12 keV at 6 MeV. The data shown in Fig. 1 were taken with this planar detector.

All experimental results are based on the observed intensities of the double-escape (de) peaks ($E_\gamma$−1.022 MeV). With the planar detector 29 $\pm 1$ $K\alpha$ x rays from lead were detected per $10^6$ stoppings in lead. Assuming a yield of 0.913 $K\alpha$ x rays per $\mu^-$ stopping in lead,[14] we had an efficiency for detecting lead $K\alpha$ x rays of $(3.17 \pm 0.11) \times 10^{-5}$. The efficiency of the coaxial detector was greater, $(4.32 \pm 0.24) \times 10^{-5}$. On the basis of the analysis by Cline[15] we assumed the efficiency to be independent of energy over the range of interest. This analysis indicated that for the size of detectors we were using the de-peak detection efficiency goes through a broad maximum in the neighborhood of 6 MeV. An extrapolation error for our range of energies of more than 10% seems unlikely.

The area under the broad 6.322-MeV (de) $\gamma$ peak (5.300 MeV) was determined by subtracting from the total area under this peak an average "base-line" area. The area under the sharp 5.269-MeV peak was determined in the same way. The 5.298-MeV peak area was obtained by first subtracting the 5.269-MeV peak area and then finding the net area of the remaining broad peak. This contribution is small (Fig. 1), but about $2\frac{1}{2}$ standard errors above background.

The variations in widths of the peaks are completely consistent with the known level-lifetime limits and the slowing-down time.[16] That is, the 6.323- and 5.299-MeV levels, having lifetimes on

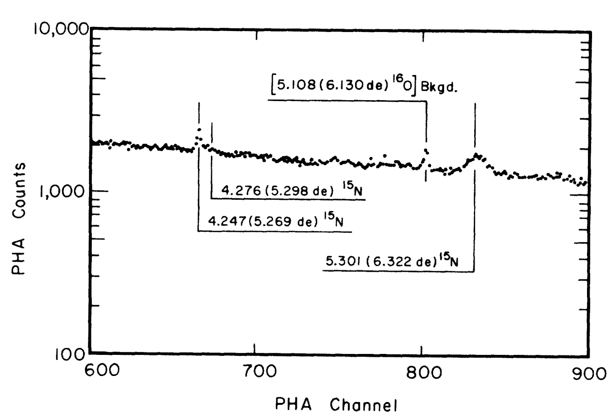


FIG. 1. Pulse-height spectrum of $\gamma$ rays following $\mu^-$ stoppings in an $H_2O$ target. The peak labeled "bkgd" disappears after background subtraction. The designation de indicates ($E_\gamma$−1.022) MeV.

the order of $10^{-14}$ sec,[17] decay while the $^{15}N$ nucleus is still recoiling. However, the 5.270-MeV level, with a lifetime on the order of $10^{-10}$ sec,[17] is sufficiently long lived that the $^{15}N$ nucleus has already slowed down before decay. The slowing-down time for the $^{15}N$ nucleus is approximately $10^{-12}$ sec.[16] The observed Doppler broadening of the short-lived levels is somewhat larger than would be expected if one assumed only recoil from an 80-MeV neutrino. The additional contribution to the broadening can be attributed to the recoiling neutron. (A 3-MeV neutron, for example, has the same momentum as an 80-MeV neutrino. Each independently can produce here a Doppler broadening of about 60 keV full width.) Analysis of the shape of such Doppler-broadened peaks has been proposed by Grenacs et al.[18] as a means of determining the angular correlation between nuclear orientation and the direction of neutrino emission. Analysis of the 6.322-MeV peak shape is in progress and will be reported elsewhere together with a more complete discussion and description of the experiment.

The observed $\gamma$-ray yields are shown in Table I. What fraction, if any, of the observed level populations are not direct but result from cascading we cannot say. Within the limits of energy range (up to 7.5 MeV) and resolution of our measurements we have no evidence of other excited $^{15}N$ levels (nor for higher production-threshold final products such as $^{14}N$* or $^{15}C$*). For example, neither the 3.924-MeV transition (from the 9.223- to the 5.299-MeV level) nor the 7.300-MeV transition to the ground state is observable above background.

Column three gives the absolute yield of $\gamma$ rays per $\mu^-$ stop on $^{16}O$. In addition to the counting statistics, the error quoted includes also uncertainties due to corrections for gate widths and delays, $\mu^-$ stoppings in scintillators and target-container walls, and detection efficiency. Each of these corrections contributed an uncertainty of about 3%; these uncertainties have been combined quadratically with the counting uncertainty. The partial capture rates $\lambda_c$ are determined by multiplying the absolute $\gamma$-ray yields by the total $\mu^-$ disappearance rate, $\lambda = \lambda_a + \lambda_D$, where $\lambda_a = (0.97 \pm 0.03) \times 10^5$ sec$^{-1}$,[5] and $\lambda_D = (0.4549 \pm 0.0002) \times 10^6$ sec$^{-1}$[19]; $\lambda_a$ is the total absorption rate and $\lambda_D$ is the decay rate.

The coaxial detector resolution was inadequate to allow separation of the $\gamma$ rays from the $\frac{1}{2}^+$ and $\frac{5}{2}^+$ levels. The results show, therefore, only the sum of these. In addition, an insufficient amount of background data was taken with the coaxial detector, so all background corrections were based on the planar detector results and on the assumption that the relative background was the same for both detectors.

The measured transition rate to the $\frac{3}{2}^-$ level of $^{15}N$, $(2.50 \pm 0.23) \times 10^4$ sec$^{-1}$, can be compared with theoretical values of $5.2 \times 10^4$ sec$^{-1}$ and 3.0 $\times 10^4$ sec$^{-1}$ obtained, respectively, from the calculations by Balashov et al.[2] and by Raphael, Überall, and Werntz.[3] We are not aware of theoretical predictions of the transition rates to the $\frac{5}{2}^+$ and $\frac{1}{2}^+$ levels. Their presence suggests a more complicated initial interaction than a single-parti-

Table I. Observed $\gamma$-ray yields.

| $J^\pi$ | $E_\gamma$ (MeV) | $\gamma$ rays per $\mu^-$ stopping in $^{16}O$ | $\lambda_c \times 10^{-6}$ (sec$^{-1}$) | Branching ratio $\lambda_c/\lambda_a$ |
|---|---|---|---|---|
| | | Planar detector ($4.306 \times 10^9$ $\mu^-$ stoppings) | | |
| $\frac{5}{2}^+$ | 5.269 | $0.0161 \pm 0.0025$ | $0.0089 \pm 0.0014$ | $0.092 \pm 0.014$ |
| $\frac{1}{2}^+$ | 5.298 | $0.0127 \pm 0.0054$ | $0.0070 \pm 0.0030$ | $0.072 \pm 0.031$ |
| $\frac{3}{2}^-$ | 6.322 | $0.0445 \pm 0.0055$ | $0.0246 \pm 0.0030$ | $0.254 \pm 0.031$ |
| | | Coaxial detector ($2.917 \times 10^9$ $\mu^-$ stoppings) | | |
| $\frac{5}{2}^+ + \frac{1}{2}^+$ | | $0.0178 \pm 0.0039$ | $0.0098 \pm 0.0022$ | $0.101 \pm 0.023$ |
| $\frac{3}{2}^-$ | | $0.0460 \pm 0.0052$ | $0.0254 \pm 0.0029$ | $0.262 \pm 0.030$ |
| | | Average of coaxial plus planar detectors | | |
| $\frac{5}{2}^+ + \frac{1}{2}^+$ | | $0.0232 \pm 0.0042$ | $0.0128 \pm 0.0023$ | $0.132 \pm 0.024$ |
| $\frac{3}{2}^-$ | | $0.0452 \pm 0.0042$ | $0.0250 \pm 0.0023$ | $0.258 \pm 0.024$ |

cle, single-hole (first-forbidden electric dipole).[20] These levels are also observed along with the $\frac{3}{2}^-$ level following giant-dipole-resonance photoexcitation.[11-13] The photoabsorption experiments all have results similar to ours in the sense that the predominant excitation observed is the $\frac{3}{2}^-$ level. The two even-parity levels, $\frac{1}{2}^+$ and $\frac{5}{2}^+$, are also produced by giant-resonance photoexcitation, but for the final state $^{15}N^* + p$ with somewhat less probability than observed here. On the other hand the branching ratios to the mirror levels of $^{15}O^* + n$ are quite similar to those we observe. It would appear, therefore, that the experimental picture of muon capture in $^{16}O$ is very similar to that in photoexcitation, and that successful theoretical interpretation of one, particularly with regard to the even-parity levels, would also explain the other.

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