The following broad conclusions can be drawn from the new data: (a) The electromagnetic size of the tritium nucleus is smaller than that of He^3. (b) Among the four form factors measured, namely, $F_{ch}(H^3)$, $F_{mag}(H^3)$, $F_{mag}(He^3)$, and $F_{ch}(He^3)$, the first three are quite similar but not exactly equal to each other. (c) The fourth form factor, $F_{ch}(He^3)$, is different from the others and indicates that the charge structure in He^3 is larger in size than any of the other three density distributions. (d) Because in any reasonable model, $F_{ch}{}^n$, the neutron's electric form factor, is folded into two of the above four measured form factors, it is possible, in principle, to find a set of values of $F_{ch}{}^n$ in addition to those found in the past by making scattering measurements on the deuteron. We are now in the process of making such determinations of $F_{ch}{}^n$.

We have also made a rough attempt to fit the form factors of tritium and He^3 with the usual type of model analysis. In this way we find that the rms charge radius of tritium is approximately 1.68×10^{-13} cm, while the rms magnetic moment radius is 1.63×10^{-13} cm. Errors in these determinations are less than $\pm 10\%$. The corresponding new results for He^3 are that the charge radius is $(1.97 \pm 0.10) \times 10^{-13}$ cm and the magnetic radius is $(1.69 \pm 0.10) \times 10^{-13}$ cm. The latter values are to be compared with the older values[1] of 2.07×10^{-13} cm ($\pm 10\%$) and 1.68×10^{-13} cm ($\pm 10\%$). In the above calculations a Gaussian model was used in fitting all the curves except that of $F_{ch}(He^3)$ for which a hollow exponential model was used. In reference 1 we have already seen that the radii are relatively insensitive to the choice of models which fit the data approximately.

After further refinement of the above data, we hope to analyze the results in terms of body form factors for the nuclei He^3 and H^3. At that stage we expect that theory can provide nuclear models fitting our data. In fact, both Schiff[4] and Levinger[5] have already developed some ideas in this direction. It is also well known that results such as those given in this paper can be used to sharpen up considerably the choice of wave functions previously used in variational calculations made on H^3 and He^3.

We wish to acknowledge gratefully the assistance we have received from the staffs of the Los Alamos Scientific Laboratory and Stanford University in helping us to overcome the health and safety problems connected with the handling of the tritium targets. In this connection we are particularly indebted to Mr. Morris Engelke of Los Alamos and Mr. Carl Irwin of Stanford. We are especially grateful to Dr. J. B. M. Kellogg and to Dr. Norris Bradbury of the Los Alamos Laboratory for the enthusiastic support they gave to this joint project. We wish to thank most heartily Mr. Hall Crannell for his gracious assistance in applying his computer program to our data.

*This work was supported in part by the Office of Naval Research, the U. S. Atomic Energy Commission, and the U. S. Air Force Office of Scientific Research.

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μ CAPTURE IN OXYGEN*

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(Received 2 July 1963)

This note reports the results of measurements of the capture of negative muons by O^{16} to the four bound states of N^{16}:

$$\mu^- + O^{16} \to N^{16} + \nu_\mu .$$

In our experiment, we are concerned with several distinct μ-capture transitions between discrete states of O^{16} and N^{16}. The properties of these nuclei have been extensively studied both theoretically and experimentally, so that one might hope that detailed measurements would provide useful information about the basic weak interaction involved,

$$\mu^- + p \to n + \nu_\mu .$$

In particular, one of the μ-capture transitions

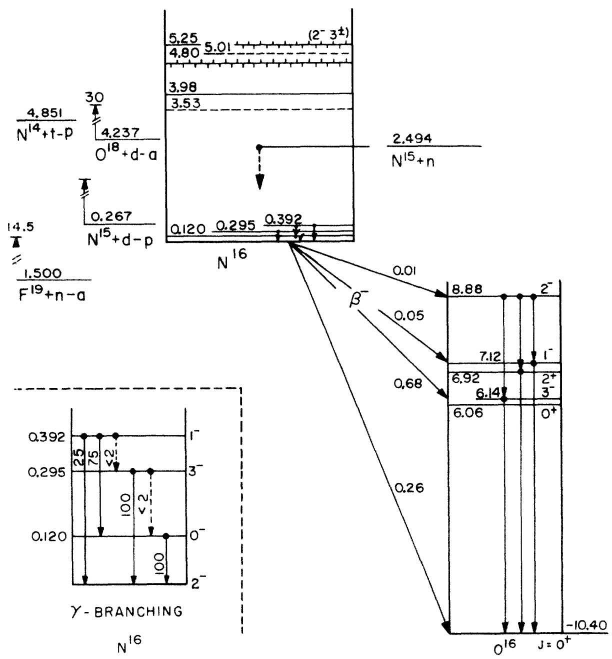

FIG. 1. Energy levels of N^{16} (see reference 3).

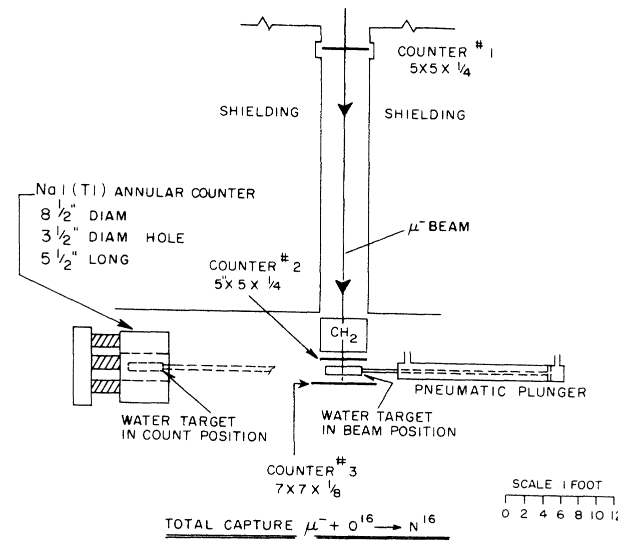

FIG. 2. Apparatus for measuring the total capture rate to all four bound states of N^{16}.

measured is from the 0^+ ground state of O^{16} to a 0^- state of N^{16} and the rate calculated for this transition is very sensitive to the assumed magnitude of the induced pseudoscalar constant (g_P). Goldberger and Treiman,[1] and Wolfenstein,[2] have calculated a value of $g_P \approx 8g_A$, but there has been little experimental verification of this prediction.

Figure 1 shows the level structure of N^{16} and O^{16}. The four relevant states of N^{16} are all within 400 keV of the ground state.[3] The total muon capture rate to all these four states together was determined by observing the beta and subsequent gamma decay:

$$N^{16} \rightarrow O^{16*} + e^- + \bar{\nu}_e; \quad O^{16*} \rightarrow O^{16} + \gamma \text{ (6.14 MeV)}.$$

Specifically, the number of 6.14-MeV gamma rays per stopped muon in oxygen provides a measure of this rate. (The possibility that a muon would be captured to one of the higher unbound states and then decay by gamma rather than neutron emission to one of our four bound states was estimated to be negligible compared to the direct capture to these states.) Figure 2 shows the arrangement of the apparatus for this part of the experiment. A low-energy muon beam from the Columbia University Nevis cyclotron was slowed down and stopped in our water target (2.5 g/cm^2). Since the half-life of N^{16} is long, 7.4 sec, we were able to use a pneumatic plunger to move the target alternately from a position in the beam, where it was irradiated for 10 sec, to a position inside a large annular NaI(Tl) crystal, where the 6.14-MeV gamma-ray activity was measured for 10 sec. This cycle was repeated several hundred times; and then, to assess the background, enough extra absorber was added to that already in the beam to stop the muons in front of the water target and the entire process repeated. The crystal was 5.5 in. long, 8.5 in. in diameter with a 3.5-in. diameter hole, and it was viewed by six photomultiplier tubes whose mixed output was fed into a multichannel pulse-height analyzer.

The absolute efficiency of the NaI crystal for the detection of the 6.14-MeV gamma ray was measured at the Columbia University Van de Graaff generator using the resonant reaction

$$F^{19} + p \rightarrow O^{16*} + \alpha; \quad O^{16*} \rightarrow O^{16} + \gamma \text{ (6.14 MeV)}.$$

For a proton energy of 340 keV, 97% of the reactions go to the 6.14-MeV excited state of oxygen, so that for every alpha particle emitted, approximately one 6.14-MeV gamma ray is emitted. By using a solid-state detector, whose efficiency is 100% for alpha detection, in an accurately known geometry, we were able to calibrate the NaI crystal absolutely.

Figure 3 shows the arrangement of the apparatus used in the second part of the experiment—the measurement of the individual rates to the excited bound states of N^{16} by observing the nuclear de-

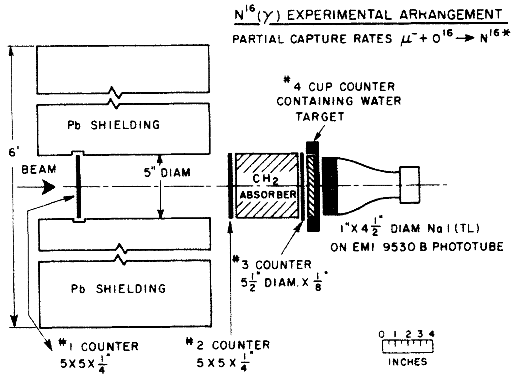

FIG. 3. Apparatus for measuring the rates to each of the three excited bound states of N^{16}.

excitation gamma rays. The muons were again stopped in a water target, 2.5 g/cm^2, which was completely surrounded by scintillation counters (counters No. 3 and No. 4) arranged to detect any decay electrons coming from the water. Since 80% of the stopped muons decayed and thus could not possibly have been captured, no event was recorded if a count was seen in either No. 3 or No. 4 counters within 16 μsec of a stopping muon, thus greatly reducing one source of background, bremsstrahlung from the decay electrons. Mesonic x rays, another large potential source of background, were eliminated by timing. The low-energy gamma rays were detected by a NaI(Tl) crystal (1 in. thick by 4.5-in. diameter) mounted on an EMI-9530B phototube, whose output was connected to the multichannel analyzer.

The over-all efficiency of the apparatus was measured as a function of energy using the mesonic x rays of oxygen, magnesium, and aluminum. There is good evidence, both experimental[4,5] and theoretical,[6] that these elements give one K mesonic x ray for each stopping muon. For magnesium and aluminum, discs were used and so spaced that they approximated the x-ray stopping power of the water. The physical arrangement of the apparatus was left unchanged during these x-ray runs, but all the mesonic x-ray rejection features of our electronics were switched off.

The observed spectra of the x rays and the nuclear gamma rays were analyzed in the usual manner. Radioactive sources were used to determine line shapes for all energies, and these shapes plus an assumed background were fitted to the experimental curves. This analysis, straightforward in the case of the x rays, was much more difficult in the case of the nuclear gamma rays because of the large background. The uncertainty in the nature of the background limited the accuracy to which we knew the number of counts in the lines to about 5%, even though our statistical uncertainty was only about 2%.

The de-excitation of the N^{16} first excited state (120 keV) followed a growth and decay law, since it was fed by muon capture (mean lifetime[7] of 1.8 μsec) and the level has a half-life of 5.7 μsec.[3] We observed this behavior by storing in four separate parts of the pulse-height analyzer the pulses arriving in each of four successive 4-μsec intervals (these intervals were generated each time a muon stopped in the target). Since the growth and decay curve is easily calculated, we were able to compare the measured intensity as a function of time with that calculated from this curve; we have obtained satisfactory agreement.

The experimental results are listed in Table I. The capture rate to the 3^- state was too small to be seen in this experiment, and this agrees with theoretical predictions. Several theoretical estimates have been made of the capture rates measured here.[8-11] The treatment by Duck is the most ambitious in that it starts with the complete Hamiltonian of Fujii and Promakoff,[12] including the velocity-dependent terms, and uses the intermediate-coupling shell-model wave functions rather than the simple j-j wave functions. The other authors either use a simplified theory only, or start with the simplified theory and then proceed to make large corrections for the terms omitted. Duck makes two complete sets of calculations, first using a set of wave functions that he has calculated for N^{16} and then using the set calculated by Elliot and Flowers.[13] The difference between the two sets of wave functions is presumably computational, since the physical parameters on which they are based are virtually identical. Not surprisingly, the rates calculated

Table I. Experimental results. The disappearance rates were calculated using a total disappearance rate in oxygen[a] of $(0.551 \pm 0.003) \times 10^6$ sec^{-1}.

State	Percent of stopped muons captured	Disappearance rate (λ) (sec^{-1})
1^-	0.314 ± 0.018	$(1.73 \pm 0.10) \times 10^3$
0^-	0.120 ± 0.019	$(0.66 \pm 0.11) \times 10^3$
2^-	1.23 ± 0.13	$(6.76 \pm 0.71) \times 10^3$
3^-	Unobserved	
Total	1.66 ± 0.13	$(9.15 \pm 0.71) \times 10^3$

[a]See reference 17.

using the two sets of wave functions disagree. Several of the authors[9,10] point out that if pure j-j coupling is used, the ratio of the rates to the states $0^-/1^-$ is completely independent of all nuclear parameters. Some insensitiveness still persists when admixtures are included in the calculations. Indeed, the discrepancy between the values of this ratio as calculated by the two sets of wave functions is much smaller than the discrepancy between the rates to either the 1^- or the 0^- states.

Figure 4 shows the comparison between our results and the theoretical predictions. [The basic assumptions of these calculations include $g_V(\mu\ \text{capture}) \approx g_V(\mu\ \text{decay})$ and $g_A = -1.23 g_V$.] It is obvious that, on the basis of the calculations made, the value of the pseudoscalar constant required by the experimental results is higher than that predicted by the theory.[1,2] Our experiment suggests a value for g_P of about $15 g_A$, but the precision of this value is limited by uncertainties in the wave functions of the nuclear states involved.[14]

Some hint of a large value of g_P is provided by other recent experiments: μ capture in hydrogen[15-17] and the asymmetry of neutron emission when complex nuclei capture polarized muons.[18]

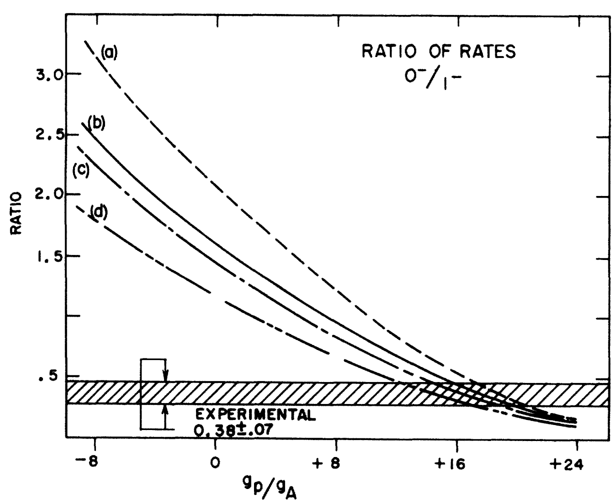

FIG. 4. Ratio of the rates $0^-/1^-$. The four curves are based on the calculations of Duck[8]: (a) using his wave functions and not including weak magnetism terms in the Hamiltonian, (b) using his wave functions and including weak magnetism terms in the Hamiltonian, (c) using Elliot and Flowers' wave functions and not including weak magnetism terms in the Hamiltonian, and (d) using Elliot and Flowers' wave functions and including weak magnetism terms in the Hamiltonian.

We wish to thank those who helped in the experiment, especially Dr. A. Knipper and Mr. E. Hyman; also Mr. C. Nissim-Sabat and Mr. E. Bogart for their help in the calibration of the NaI crystal at the Van de Graaff generator.

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*Work supported in part by the U. S. Office of Naval Research.

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