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Ernest O. Lawrence Radiation Laboratory

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A measurement of the muon capture rates from the ground state of O^{16} to states of known spin and parity in N^{16} has been suggested as a method for determining the value of the induced pseudoscalar coupling constant.[1-3] This form of coupling exists in the general weak-interaction Hamiltonian of Goldberger and Treiman because of the presence of strongly interacting particles. They predict that this coupling constant has a value of approximately 8 g_A if the induced pseudoscalar coupling is introduced via a one-pion intermediate state.[4] Since the induced pseudoscalar coupling is proportional to the mass of the lepton involved, the effect is more likely to be observed in muon capture than in beta decay.

Observation of the basic muon-nucleon interaction, muon capture in hydrogen, is experimentally difficult. Therefore, one observes capture in complex nuclei and hopes that knowledge of the nuclear physics of the reaction will allow the determination of the muon-proton interaction. Experimental evidence[5] for the existence of a pseudoscalar interaction comes from observation of the angular distribution of neutrons following capture of polarized muons, the muon capture rates in H, He^3, and C^{12}, and from results of radiative capture in Ca^{40}. The partial-capture rates in O^{16} have been measured recently at Columbia,[6] by using a method different from that reported here.

Figure 1a shows the level and decay scheme[7] for muon capture in O^{16} leading to the low-lying states of N^{16}. Theoretical calculations show that the capture rate from the ground state ($J^P = 0^+$) of O^{16} to the excited state (0^-) of N^{16} is very sensitive to the induced pseudoscalar interaction. Capture into the 0^- state is identified by looking for the 120-keV gamma ray which is emitted when the 0^- level decays to the ground state. However, the 0^- state can also be fed by direct capture to the 1^- state followed by a cascade gamma ray of 276 keV. The transition rate into the 0^- state is then found by measuring the number of 120- and 276-keV gammas emitted per stopped muon. Capture can occur into the higher excited states of N^{16} that are above the threshold for neutron emission, but a knowledge of the level widths leads one to believe that decay by gamma-ray emission from these higher states can be regarded as negligible for the purposes of the present experiment.

This experiment was conducted in the summer of 1963 at the Berkeley 184-Inch Cyclotron. Muons were identified by a time-of-flight system and brought to rest in a 1-in.-thick, 2-1/2-in.-diam water cell, where some were captured by the O^{16} nucleus with a characteristic muon mean life of 1.81 μsec.[8] Figure 1b shows the experimental arrangement. A stopping muon was registered electronically by a coincidence between the time-of-flight system and counter 3, with no count in counter 5. The muons were stopped at a rate of 250/sec. After a stopped muon was identified, the sodium iodide crystal was used to look for delayed gamma rays from the water target.

The apparatus was designed to display the energy spectra of delayed gamma rays for different time intervals. The data were collected in five time bins which were spaced 0 to 4, 4 to 8, 8 to 12, 12 to 16, and 30 to 34 μsec after the arrival of the muon in the target. We refer to these time bins as τ_1, τ_2, τ_3, τ_4, and τ_5 respectively. The 276-keV gamma ray appears with the lifetime characteristic of muon capture in O^{16} and consequently should be expected mainly in τ_1 and τ_2. The 0^- level is metastable with a lifetime of 8.26 μsec,[9] and therefore the time distribution of the 120-keV gamma rays displays a buildup and decay, and is present in all time bins. The purpose of bin τ_5 is to display the shape and magnitude of the random background. Only a small fraction of 120-keV gammas persists in τ_5, and a correction for it can be made easily. Figure 2a shows the pulse-height distributions in τ_1, τ_2, τ_3, and τ_4.

The pulse-height spectrum in τ_1 contains the 120-keV, 276-keV, and possibly the 396-keV line (1^- to 2^- transition). The line at 206 keV comes from the reaction I^{127} (n, n') I^{127*} in the NaI crystal produced by the neutrons from muon capture. The background arises from high-energy products of muon capture in O^{16} which deposit only part of their energy in the NaI. This background has the O^{16} lifetime of 1.81 μsec, and makes analysis of the data in τ_1 very difficult. In τ_3 and τ_4 the background is almost entirely random in nature, and can be removed accurately by using τ_5.

To improve the peak-to-background ratio for the 276-keV line, we used the correlated 120-keV gamma ray which follows it. Those events in τ_1 which were followed by a 120-keV gamma ray in τ_2, τ_3, or τ_4 were displayed separately in a new bin, τ_6. This additional requirement removed most of the background from under the 276-keV peak. The result obtained is shown in Fig. 2b.

The absolute efficiency of the sodium iodide detector was measured by using mu-mesic X-rays and radioactive sources of known activity. The mu-mesic X-rays were from the K-series in oxygen, sodium, magnesium, and aluminum. The thickness of the X-ray targets were calculated to give the same absorption as water for escaping X-rays, and in some cases the geometry of the target was extended in order to approximate more closely the solid angle used in the experiment proper. The target could be removed from the apparatus and replaced by an identical cell containing a known amount of radioactive substance dissolved in water. There were four of these cells, containing Co^{57}, Cr^{51}, Hg^{203}, and Be^{7}. Both methods of calibration were used periodically as checks on the apparatus. The efficiency curve obtained from these data is shown in Fig. 3.

After subtraction of background in the time bins, there are 30,000 120-keV events in τ_2, 17,600 in τ_3, and 11,500 in τ_4 for 150×10^6 muons stopped in the target. This gives 0.46×10^{-2} for the number of 120-keV gamma rays per stopping muon. The number of 276-keV gamma rays is obtained by fitting a background plus the known shape of the 279-keV line from the Hg^{203} calibration source to the data. There are 950 ± 50 events under the photopeak, giving 1.8×10^{-3} 276-keV gammas per stopping muon. From these numbers the partial-capture rates given in Table I can be determined. The results are compared with the Columbia experiment, which used a different method of background analysis and did not make a correlation requirement for identification of the 276-keV gamma ray.

In principle, the pseudoscalar coupling constant can be computed when the $0^+ \to 0^-$ transition rate is known. However, as shown in Table I, the several theoretical calculations that have been made disagree with each other.[1-3] In the present state of the theory, the only firm conclusion is that the pseudoscalar coupling constant is positive. For a more precise evaluation, one needs not only the proper Hamiltonian, but also a good O^{16} wave function. Some velocity terms (order $\underline{p}/m$) must be included in the Hamiltonian because of the high momentum transfer (~100 MeV/c) involved in muon-capture reactions. This contrasts with β decay, where the momentum transfer is small, making the velocity terms negligible. Also, the 0^- wave function is not a pure jj coupling configuration, but has a small component whose amplitude is not well known. Since the transition rate is sensitive to the magnitude of this small component, more calculations are required. These calculations are in progress at Berkeley in collaboration with Dr. Vincent Gillet.

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FOOTNOTES AND REFERENCES

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Table I. Muon capture rates in O^{16}

N^{16} final state	Capture rates (10^3 sec^{-1})			
	Experimental		Theoretical[a]	
	Berkeley	Columbia	Ericson and Sens[b]	Duck[c]
0^-	1.6 ± 0.2	1.1 ± 0.2[d]	1.00	$0^-/1^- \approx 0.95$
1^-	1.4 ± 0.2	1.73 ± 0.10[e]	2.01	

a. Conserved vector current and $g_P = 8g_A$ is used.

b. See reference 3.

c. See reference 2.

d. This rate has been revised from that given by Cohen et al. in Phys. Rev. Letters 11, 134 (1963). We thank the Columbia group for allowing us to publish this number.

e. They assume a 1^- to 0^- branching ratio of 0.75.

FIGURE LEGENDS

Fig. 1. (a) Level and decay scheme[7] for the muon-capture reaction in O^{16}; (b) counter arrangement for measuring capture rates in O^{16}.

Fig. 2. Sodium iodide pulse-height spectra (a) in time bins τ_1 through τ_4 for 150×10^6 muons stopping in the target and (b) in time bin τ_6, which requires a correlation between a delayed 120-keV gamma ray and a count in bin τ_1.

Fig. 3. Total NaI counter efficiency obtained from mu-mesic X-rays and radioactive sources dissolved in water.

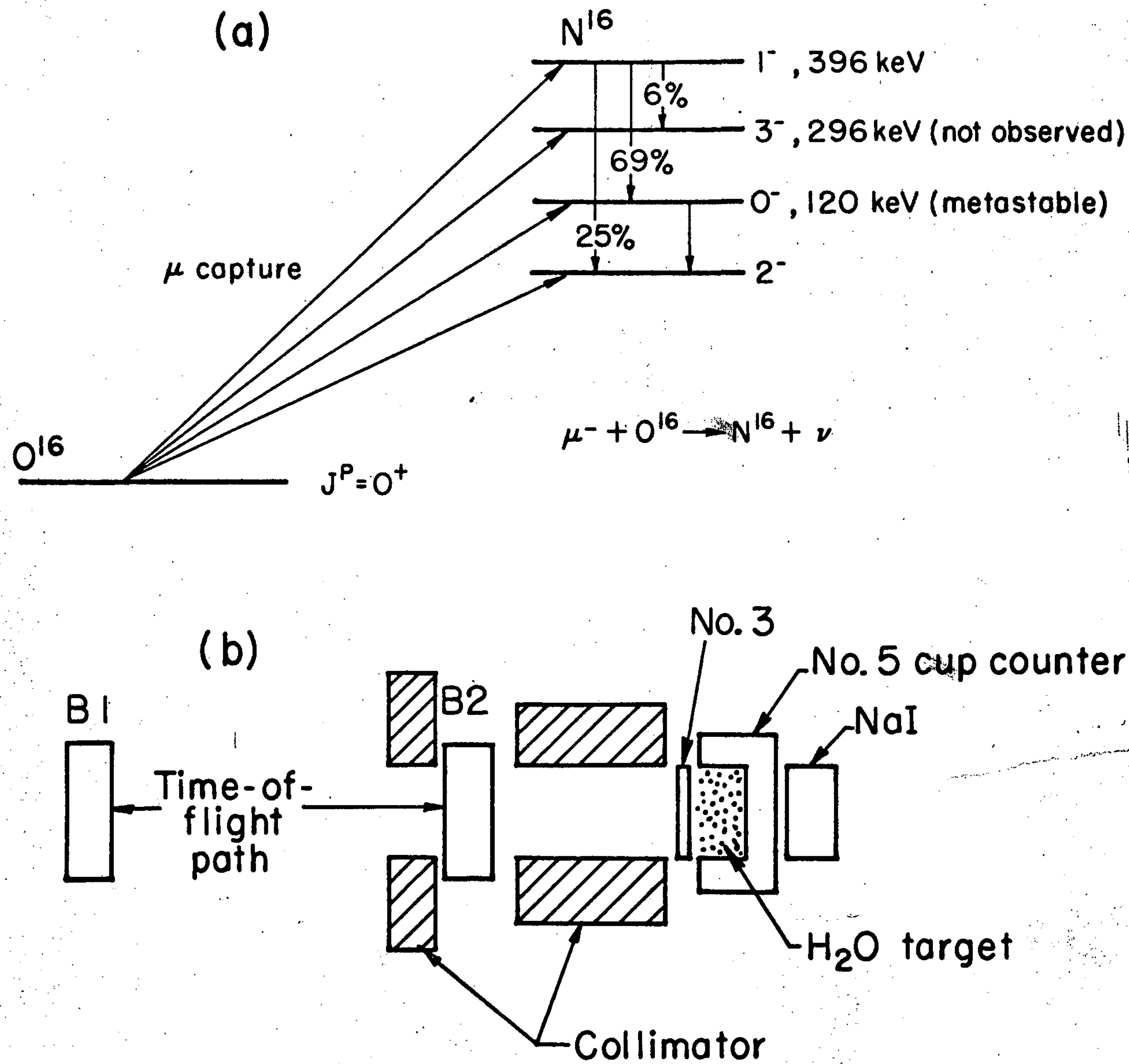

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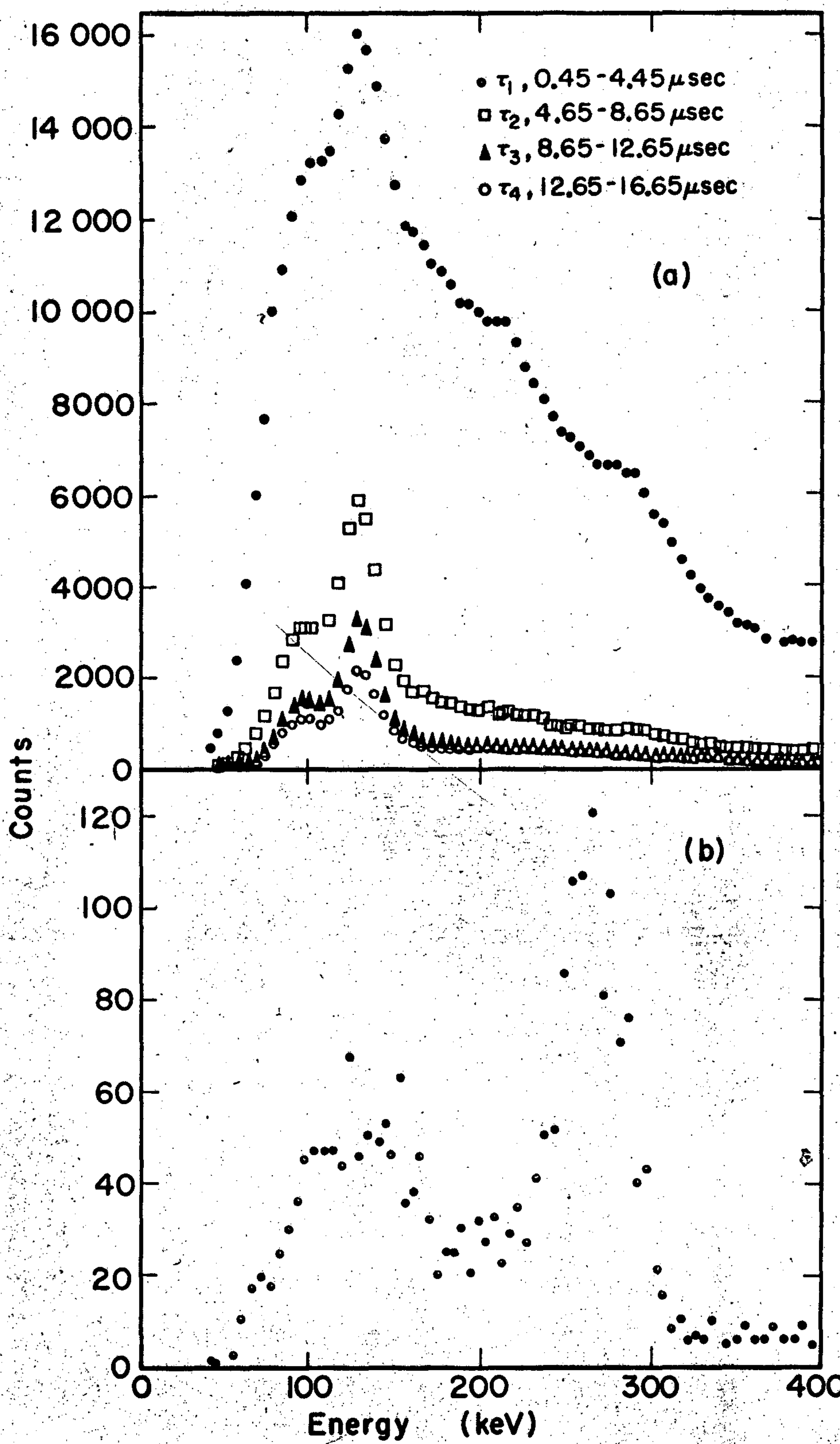
Fig. 1



MU-33344

Fig. 2

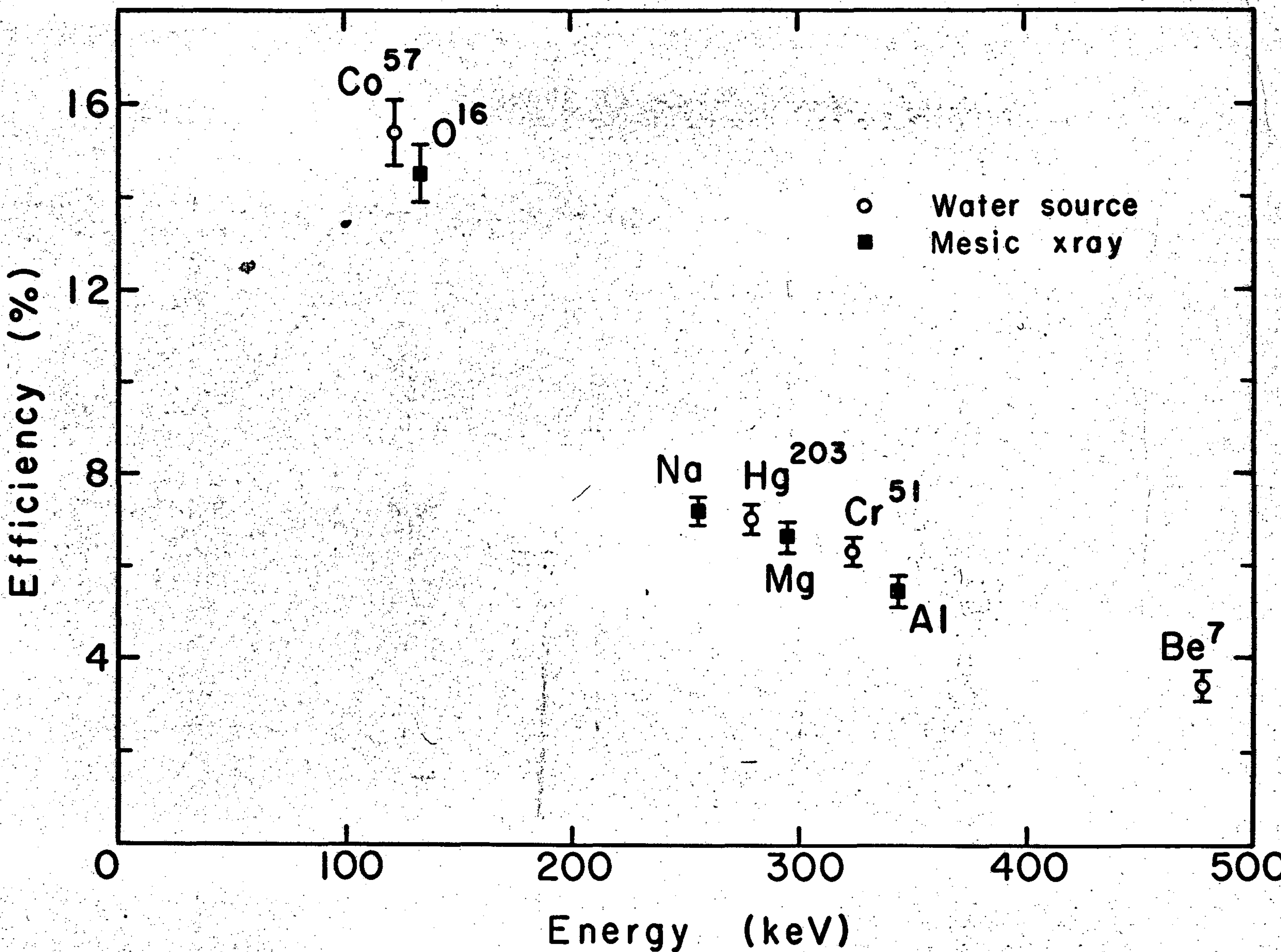


Fig. 3

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