Measurements of Negative-Muon Lifetimes in Light Isotopes*†

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Negative muons from the Carnegie Tech synchrocyclotron were stopped in the following targets: separated isotopes of lithium (Li^6 and Li^7) and boron (B^{10} and B^{11}), and natural beryllium, carbon, nitrogen, and oxygen. From an analysis of the resulting time spectrum of the decay electrons, the negative-muon lifetime in each of these substances was obtained. From a separate measurement of the μ^+ lifetime, (2.202 ± 0.003) μsec, the capture rates in the above elements were determined. They are (in units of 10^5/sec); $\lambda_{cap}(Li^6)=0.061\pm0.014$, $\lambda_{cap}(Li^7)=0.018\pm0.014$, $\lambda_{cap}(B^{10})=0.265\pm0.015$, $\lambda_{cap}(B^{11})=0.218\pm0.016$, $\lambda_{cap}(Be)=0.10\pm0.02$, $\lambda_{cap}(C)=0.397\pm0.013$, $\lambda_{cap}(N)=0.65\pm0.04$, and $\lambda_{cap}(O)=0.98\pm0.03$.

INTRODUCTION

We have recently measured the lifetimes of negative muons in separated isotopes of high-purity lithium (Li^6 and Li^7) and boron (B^{10} and B^{11}) and in natural beryllium, nitrogen, carbon, and oxygen. We have also remeasured the lifetime of the positive muon. Measurements of muon-capture rates in light elements and of the muon-capture isotope effect are of interest because of the information they may provide on the form of the weak interaction and on nuclear structure.[1,2] In addition to ordinary exclusion principle effects, a further inhibition of the capture rate in B^{11} relative to B^{10} may occur since the six neutrons of B^{11} complete the $p_{\frac{3}{2}}$ nuclear level.

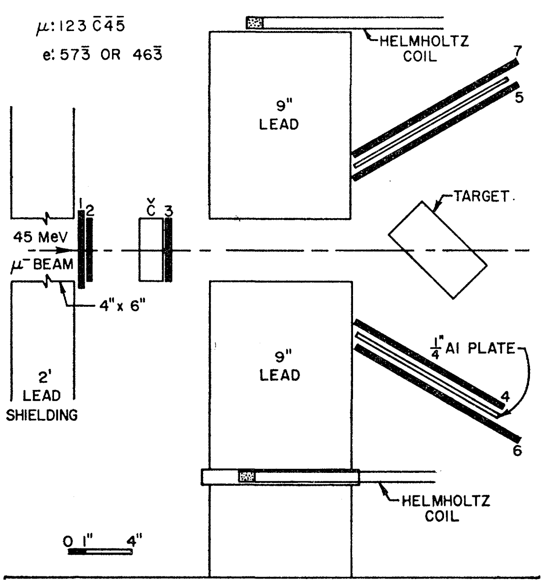

FIG. 1. Experimental arrangement.

METHOD AND ANALYSIS

The experiment was performed in two separate runs (I and II). The experimental arrangement used in most of these measurements is shown in Fig. 1. A 45-MeV muon beam (consisting of approximately 70% muons, 30% electrons, and a negligible number of pions) from the Carnegie Tech synchrocyclotron was collimated by a 4-in.×6-in. aperture in the lead shielding wall. Helmholtz coils cancelled the cyclotron fringing field at the location of the target. The geometry was designed to minimize a decay component arising from muons which stopped in the plastic scintillants and carbon-containing wrappings of the counters. For this purpose, also, the faces of electron counters 4 and 5 nearest the target were wrapped with silver foil and the Lucite light-pipes covered with $\frac{1}{4}$-in. lead sheets. Data occurring between time zero and 0.5 μsec were discarded in the analysis in order to exclude short-lived components arising from muons captured in heavy elements like lead and silver. The amplitude of an extraneous component due to muons stopping in carbon was found to be less than 0.2%. Muons were recorded as a $1+2+3+\bar{C}+\bar{4}+\bar{5}$ coincidence, the Čerenkov counter, C, serving to distinguish between electrons and muons and the anticoincidence counters 4 and 5 preventing time analysis of muons which scatter from the target into the electron telescopes. Decay electrons from muons which stopped in the target were observed in either of two telescopes, $(4+6+\bar{3}$ or $5+7+\bar{3})$, the anticoincidence of counter 3 preventing the counting of electrons from decay of muons stopping in 3. In run II, no anticoincidence was used in the electron telescopes and decay electrons were simply observed either as $(4+6)$ or $(5+7)$.

A muon coincidence initiated a timing gate which was subsequently closed by an electron count, if one was forthcoming, or by a 15-μsec delayed pulse from the initiating muon if one was not. The width of the gate, as determined by a train of 10-Mc/sec pulses, gave the time sequence in a $\mu-e$ event. The time-analysis apparatus used was essentially that reported in pre-

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[1] See, for example, L. Wolfenstein, in *Proceedings of the 1960 Annual International Conference on High-Energy Physics at Rochester* (Interscience Publishers, Inc., New York, 1960), p. 529; H. Uberall, Phys. Rev. **121**, 1219 (1960).
[2] H. Primakoff, Rev. Mod. Phys. **31**, 802 (1959).

vious publications,[3,4] except that the fast-timing gate circuit described in the first paper has since been transistorized insuring greater stability and a faster rise time, and protective circuits have been included to suppress distortions of the data which arise from multiple muon stops in the target. The time spectrum of decay electrons was recorded in the memory of a 256-channel RCL analyzer. A reduction to 5 of the cyclotron duty factor lowered the observed random background to approximately 0.2% of the peak in the decay curves. We believe that the general improvement in the equipment and running procedure make the present data more reliable than those we obtained previously.

The Li, B, and H_2O targets were encased in airtight, high-purity silver boxes, the faces of which were 0.001-in. thick. Water was used as the target in the O experiment, since muons which stop in H_2O are totally transferred to O atomic orbits in a characteristic time negligibly small compared to the mean life. The lithium and boron target boxes were filled with argon and a positive pressure was maintained within them throughout the experiment. In the lithium and boron measurements, each isotope target was alternated in the beam every 4 h in order to cancel any systematic effects due to geometry or electronic drifts. The time analyzer was regularly checked during the experiment for both linearity and channel width.

Two separate measurements were made of the muon disappearance rate in the lithium isotopes. In the initial run, the Li^6 target consisted of 15 sheets of enriched (95.6% Li^6, 4.4% Li^7) lithium metal, each sheet 7.5 in. $\times$7.5 in.$\times$0.1 in. Analysis of this material at the completion of the run showed a presence of about 2% oxygen, probably due to exposure to air during the process of sealing the target in its box.

For run II, a more highly enriched lithium target was obtained (99.32% Li^6, 0.68% Li^7) in the form of a very pure cast block 8 in.$\times$5.5 in.$\times$3.5 in. This target was more carefully sealed in its silver box which was also pressurized with argon. Because any oxide coating was minimized in the sealing process and because the narrow momentum spectrum of the muon beam employed (5 g/cm^2 at half-maximum) allowed us to minimize muon capture near the lithium faces, there was no appreciable muon capture on oxygen atoms.

Muon disappearance rates in nitrogen were measured in run II by stopping muons in a 5-liter copper Dewar filled with liquid nitrogen. Measurements performed with the Dewar empty showed the presence of negligible amounts of low-Z materials, probably carbon. The presence of substantial quantities of such low-Z elements could have confused the analysis of the disappearance rates in nitrogen. Analysis of the nitrogen data was begun at times greater than 0.7 μsec to allow muons captured in the copper Dewar to disappear.

Measurements of negative muon disappearance rates in carbon, oxygen, and Li^7 were repeated in both runs. Measurements of the free muon lifetime were performed in both runs. In run I, positive muons were stopped in carbon in the geometry shown in Fig. 1. Muon rates were varied over the range 200 to 1500/sec without observing rate dependent systematic effects. In run II, the free-muon lifetime was obtained by stopping π^+ mesons in carbon.

Protective devices in the timing circuitry permitted a simple analysis of the decay curves. The dead-time circuit in the gate stop input[3] was 20 μsec wide, whereas the maximum width of the fast-timing gate was 15 μsec. With such a dead-time circuit the probability of recording more than one stop pulse in the maximum period of the gate is zero so that, in the absence of correlated decay electrons, all channels become equally probable and the background is constant. When both random background and correlated muon decay electrons are present, then the probability of observing a decay electron in the interval dt at time t is $E\lambda_d e^{-\lambda t}dte^{-RT}$, where E is the efficiency of the electron detector, λ_d is the muon decay rate, λ is the muon disappearance rate, R is the instantaneous background rate, and T is the (20 μsec) dead time of the univibrator in the electron circuit.

The probability of a random count at time t in the interval dt must include: (a) the probability that no random count occurred in the interval T before dt, which would cause the dead-time univibrator to block, (e^{-RT}); (b) the probability that a random count arrived in the interval dt, (Rdt); (c) the probability that no-decay electron was observed in the interval of time t during which the gate was opened, namely, $[1-\lambda_d E e^{-RT}(1-e^{-\lambda t})/\lambda]$. The probability of observing a random count is then

$$Re^{-RT}dt[1-\lambda_d E e^{-RT}(1-e^{-\lambda t})/\lambda].$$

For the logic employed in this experiment, then, the background at time $t>0$ is the sum of a constant component and a component having the form $e^{-\lambda t}$. The constant background observed at time $t<0$ can thus be used as a check on the background at times $t>0$ as fitted by computer analysis.

Events in which more than one muon stopped in the target during a time measurement could have introduced an error since the first detected decay electron turned off the timing apparatus. In order to remove this bias, a protective circuit was installed to disable the time analyzer if such multistop events occurred. During run II the timing functioned properly; during run I, however, the protective circuit functioned so that only events in which a second particle arrived before the decay of the first were discarded rather than discarding all events in which a second muon arrived within a time T of the first, where T is the maximum width of the

[3] R. W. Findley, R. A. Reiter, and T. A. Romanowski, Nucl. Instr. Methods 9, 221 (1960).
[4] R. A. Reiter, T. A. Romanowski, R. B. Sutton, and B. G. Chidley, Phys. Rev. Letters 5, 22 (1960).

TABLE I. Negative muon lifetimes and capture rates.

Element	Lifetime (10^{-6} sec)	Capture rate λ_{cap}[a] (10^5 sec^{-1})	λ_{cap}/Z_{eff}^4[b] (10^2 sec^{-1})
Li^6	2.173±0.005[d]	0.061±0.014[d]	0.82±0.18[d]
Li^7	2.194±0.004[c]	0.018±0.011[c]	0.24±0.15[c]
Be	2.156±0.010[e]	0.10 ±0.02[e]	0.44±0.09[e]
	2.14 ±0.02[f]	0.18 ±0.10[f]	
B^{10}	2.082±0.006[e]	0.265±0.015[e]	0.48±0.03[e]
B^{11}	2.102±0.006[e]	0.218±0.016[e]	0.39±0.03[e]
C	2.025±0.004[c]	0.397±0.013[c]	0.37±0.01[c]
	2.043±0.003[g]	0.373±0.011[g]	
	2.041±0.005[h]	0.361±0.013[h]	
		0.404±0.011[i]	
N	1.927±0.013[d]	0.65 ±0.04[d]	0.34±0.02[d]
	1.86 ±0.02[f]	0.86 ±0.11[f]	
O	1.812±0.012[c]	0.98 ±0.03[c]	0.31±0.02[c]
	1.64 ±0.03[f]	1.59 ±0.14[f]	

[a] Capture rates in this experiment obtained using (4.541±0.008)×10 sec^{-1} as the free muon-decay rate.
[b] For all elements except boron and lithium, Z_{eff} taken from K. W. Ford and J. G. Wills, Nucl. Phys. **35**, 295 (1962). For boron, Z_{eff} taken from J. A. Wheeler, Rev. Mod. Phys. **21**, 133 (1949). For lithium we have interpolated $Z_{eff}=2.94$ from the calculations of Ford and Wills.
[c] Data obtained from both run I and run II of this experiment. Errors quoted are statistical only.
[d] Data obtained from run II only of this experiment. Errors quoted are statistical only.
[e] Data obtained from run I only of this experiment. Errors quoted are statistical only.
[f] See Ref. 6.
[g] See Ref. 4.
[h] See Ref. 5.
[i] See Ref. 19.

timing gate. The process actually recorded in run I, then, involved not only the probability of detecting a decay electron or a random-background count but also the probability that no second muon arrived at the target during the interval of time t that the timing gate was open. If the muon arrival rate is R, then this latter probability is simply e^{-Rt}.

Another source of time-dependent instrumental error consists of a muon stopping in the target during the dead time of the time analyzer prior to the arrival of the gate-opening mu. For the muon rates and decay-electron efficiency involved here, the error introduced is negligible.

The data of run I were thus fitted by a least-squares analysis to a function of the form $e^{-Rt}(Ae^{-\lambda t}+B)$, while the data of run II were fitted to the function $Ae^{-\lambda t}+B$. The total disappearance rate is given by λ and is the inverse of the mean life. In all cases, the data showed a good fit to the assumed time dependence. In the lithium and boron analyses, the above function was modified to permit successive corrections to the decay component arising from the less abundant isotope present in each of the targets. Our negative muon results are recorded in Table I along with previous measurements made on Be, C, N, and O[4–6] The amplitudes of the decay electron spectra were for B^{10} and B^{11}, about 25 000 each; for C, 35 000; for N, 2700; for O, 4000; for Be, 7500; for Li^6 and Li^7, about 30 000 each; and for the free-muon measurements, 50 000.

RESULTS

The following remarks may be made on the basis of the results reported here:

(1) The μ^- capture rate in Li^6 as measured in run I was $(0.103\pm0.014)\times10^5$ sec^{-1}. The Li^6 sample used in run I was in the form of 15 layers of the metal on which some LiO had formed. Subsequent analysis of the sample showed the presence of 2±1% oxygen by weight. We may assume the same stopping power per gram for LiO as for Li^6 and that the LiO forms about 2.8% of the total mass of the target and is situated in a muon beam of the same intensity as the pure Li^6. If one then assumes that O atoms in LiO have about twice the probability for *atomic* muon capture as do Li atoms in LiO, as is suggested by recent "Z-law" experiments,[7] then one obtains a corrected capture rate $\lambda_{cap}(Li^6)=(0.087\pm0.02)\times10^5$ sec^{-1}. Because the Li^6 sample of run I was analyzed for oxygen content at only two places over its large area, we list in Table I only the capture rate measured in the purer, more highly enriched Li^6 target used in run II, $\lambda_{cap}(Li^6)=(0.061\pm0.014)\times10^5$ sec^{-1}. The μ^- capture rate in Li^7, as measured in runs I and II, was $\lambda_{cap}(Li^7)=(0.018\pm0.011)\times10^5$ sec^{-1}. The rather low capture rate in Li^7 appears difficult to attribute to the inhibition caused by the presence of the "fourth" neutron in Li^7 or to hyperfine effects. Since hyperfine transitions in the muon-nucleus system proceed primarily through Auger electron ejection,[8,9] such transitions would be energetically impossible for the bound electrons in Li.

(2) The muon disappearance rate in Be, measured with greater precision, is in agreement with an earlier value.[6]

(3) The boron results show an inhibition of the muon-capture rate in B^{11} relative to that in B^{10}, an effect consistent with the exclusion principle. Transitions between the two hyperfine states in B^{10} or in B^{11} with the rates given by Winston and Telegdi[8] would imply the following: Our quoted mean lives in both B^{10} and B^{11} should be interpreted as being at most 0.4% less than the respective average lifetimes.

(4) The measured muon capture rate in nitrogen is smaller than a previously reported result.[6]

(5) The capture rate in O is substantially smaller than a previously-reported result,[6] and now falls below, rather than above, the "Primakoff line."[6] A theoretical

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[6] J. C. Sens, Phys. Rev. **113**, 679 (1959).
[7] J. F. Lathrop, R. A. Lundy, R. A. Swanson, V. L. Telegdi, and D. D. Yovanovitch, Nuovo Cimento **15**, 831 (1960); M. Eckhause, T. A. Filippas, R. B. Sutton, R. E. Welsh, and T. A. Romanowski, *ibid.* **24**, 666 (1962); Jagdish S. Baijal, Lawrence Radiation Laboratory Report, UCRL Report 10429, 1962 (unpublished).
[8] R. Winston and V. L. Telegdi, Phys. Rev. Letters **7**, 104 (1961).
[9] H. Uberall, Phys. Rev. **121**, 1219 (1961).

calculation of λ_{cap} in O^{16} by Burkhardt and Caine[10] gave $\lambda_{cap}=1.6\times10^5$ sec^{-1}, while Beltrametti and Fiorio[11] have calculated the rate for the capture process $O^{16}+\mu^- \rightarrow N^{15}+n+\nu$, $\lambda(O^{16},N^{15})=0.6\times10^5$ sec^{-1}. In order to correlate our measurement of λ_{cap} with the calculation of Beltrametti and Fiorio, one must increase their result by the percentage of μ^- capture leading to bound states or to emission of particles other than neutrons. In emulsions, Fry[12] has found that less than 10% of μ^- captures give visible charged products. If, as suggested by Shapiro and Blokhintsev,[13] about 10% of μ^- captures in O^{16} lead to bound states in N^{16} then the effect of both corrections would be to modify the calculations of Beltrametti and Fiorio to obtain λ_{cap} (μ^- in O^{16} to all final states) $\cong 0.72\times10^5$ sec^{-1}. Luyten *et al.*,[14] using our value for the O^{16} capture rate and Sens[6] value for the Ca^{40} capture rate, have derived coupling constants which agree for these muon absorption reactions to within 10% but which disagree by 50% with the value suggested by a universal Fermi interaction.

From recent measurements[15] of the hyperfine effect in μ^- capture in F^{19}, one can estimate the contribution to this capture due to the "outside" proton, and, hence, the contribution due to the "oxygen core." By correcting the core contribution by Z_{eff}[3] and by an estimate for the inhibition of capture due to the "outside" neutrons in F^{19}, one can estimate the capture rate for O^{16}. A result of about 1.1×10^5 sec^{-1} is obtained. One might expect this value to be an upper limit since no account has been taken of the distortion of the core in fluorine by the odd proton and since the hyperfine effect arising from this proton has been assumed to be maximal.

(6) The μ^+ lifetime measurements, performed as a check on the time analyzer, yielded 2.202 ± 0.004 μsec in both run I and run II. This value is in agreement with a recent determination by Lundy[16] (2.203 ± 0.003 μsec) but below an earlier measurement made here[4] (2.211 ± 0.003 μsec) under different conditions. In calculating capture rates, one should perhaps employ an average of all recent free-muon-lifetime measurements but, because of the varying conditions under which they have been obtained and the wide variations in results, we have not chosen to do so. Presumably, the more recent measurements, such as Lundy's, are more accurate because of the care given to elimination of instrumental distortions of the measured lifetimes. We have used the value, 2.202 ± 0.003 μsec, to obtain the capture rates listed in Table I. In the elements studied here it has been assumed that the decay rate of bound negative muons is equal to the decay rate of the positive muon. The muon capture rate is, thus, merely the difference between the total disappearance rate and the decay rate: $\lambda_{cap}=\lambda-\lambda_{decay}$.

(7) The μ^- lifetime in carbon is substantially lower than previous measurements.[4,5] If the μ^+ lifetime is actually lower than our previous measurement,[4] then we might expect also that the carbon lifetime should be somewhat lower than our earlier value. The quantity of greatest interest is the capture rate. If we use our latest value for the carbon lifetime and our value for the μ^+ lifetime (2.202 ± 0.003 μsec), we obtain the capture rate, λ_{cap}, given in Table I $(0.397\pm0.013)\times10^5$ sec^{-1}. As can be seen, this value is higher than the other counter values given in Table I. An independent method for obtaining λ_{cap} in carbon is by observation of μ^- mesons stopping in a propane bubble chamber. (In such experiments the quantity measured is essentially $\lambda_{cap}/\lambda_{decay}$, where λ_{decay} is the free decay rate, so that results quoted depend on the value of λ_{decay} used.) Previously published bubble chamber results are [17,18] $(0.44\pm0.04)\times10^5$ and $(0.36\pm0.04)\times10^5$ sec^{-1}, using values of λ_{decay} of 0.45×10^6 sec^{-1}. The large errors on these results overlap all the counter results given in Table I. However a new, more accurate measurement using a bubble chamber at Carnegie Tech,[19] in which more events were obtained and greater care taken in various corrections, particularly in the pion correction $(5\pm1.5\%)$, yields a value of $(0.404\pm0.011)\times10^5$ sec^{-1}, using $\lambda_{decay}=4.54\times10^5$ sec^{-1}. This result agrees considerably better with our new result than with previous measurements.

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