

Total nuclear capture rates for negative muons

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The lifetime of negative muons has been measured in 50 elements plus 8 isotopes. For light elements the accuracy of 2 to 3 ns is a significant improvement over most previous measurements. In heavier elements the accuracy is 1 to 2 ns, which is comparable to, or better than, previous results, with reasonable agreement in most cases. For ^{18}O , Sc, Dy, and Er there were no previous data. The total capture rates have been deduced and compared to various calculations.

I. INTRODUCTION

The capture of negative muons by nuclei via the weak interactions has been studied for many years. It was hoped that the information could be used to study the weak interactions themselves, but, in fact, the major difficulty has been the understanding of nuclear effects. Unfortunately, the total capture rate is not simple to calculate as the final nucleus is excited to an unknown energy, which from the theoretical point of view is a critical parameter. However, from the experimental point of view the measurement is straightforward, as it is simply the determination of the muon lifetime when stopped in the relevant material. This number is often needed in other experiments, so precision measurements of the lifetime continue to have their usefulness.

The present experiment was motivated by the problems that existed among the measurements of the muon lifetime in light elements. Of particular concern was the Carnegie experiment of Eckhause *et al.*,¹ which had obtained a μ^- lifetime in ^6Li of 2173 ± 5 ns and in ^7Li of 2194 ± 4 ns, which were surprisingly different. They used their own measurement of the lifetime of the positive muon (2202 ± 3 ns) to calculate the capture rates of 6100 ± 1400 and 1800 ± 1100 s^{-1} , respectively. These rates were discussed by Lodder and Jonker,² who showed that the difference should be about 1500 s^{-1} . For the light elements the capture rate is proportional to the difference between the lifetime of the μ^+ and the μ^- in the material. It was therefore disconcerting that their μ^+ lifetime was shorter than an earlier measurement of 2211 ± 3 ns (Ref. 3), yet longer than the presently accepted value of 2197.03 ± 0.04 ns (Refs. 4 and 5). The earlier measurements were limited by the poor duty cycle of the old synchrotrons and by the quality of the electronic equipment. It seemed prudent therefore to reinvestigate this problem.

At about the time this present experiment was being performed, an experiment at the ALS, Saclay,⁶ also remeasured the lifetime in ^6Li (2175.3 ± 0.4 ns) and ^7Li (2186.8 ± 0.4 ns), thus obtaining a better accuracy than the present experiment, but our results are in good agreement

with these values. The same group⁷ also measured the muon lifetime in Be, C, and N with a similar precision to our own; beryllium and carbon are in agreement, but the results for nitrogen are incompatible, although there is a possible explanation for this. We should also note that these measurements were not the principal goal of their experiment and there may have been some unknown systematic error; furthermore, the group does not intend to publish these particular measurements.

The theoretical approaches rest on the classical work of Primakoff.⁸ The prototypic weak absorption reaction



becomes more complicated in the nuclear environment; for example,



where ${}^{12}\text{B}^*$ represents boron 12 in an excited state. The main difficulty lies in the mean excitation energy of the residual nucleus^{9,10} in which the giant dipole excitations are very important. Bernabéu¹¹ proposed a model which avoids the uncertainty of the neutrino energy and Kohyama and Fujii¹² used this model to calculate the total capture rates. Mukhopadhyay reviewed the subject a few years ago,¹³ as did Cannata *et al.*,¹⁴ and there is a continuing interest.¹⁵⁻²⁴ For the hydrogen isotopes the capture of muons is complicated by molecular effects²⁵ and we shall avoid a direct discussion of this topic. Similarly, in the very heavy elements (the actinides) the measurements are complicated by fission induced during the atomic cascade with the muon sometimes sticking to a fission fragment. We shall not discuss this in any detail, since a recent paper covers this topic more thoroughly²⁶ and so we shall limit ourselves to simply reporting our results.

II. EXPERIMENTAL METHOD

The experiment was performed at the M20 channel at TRIUMF when the proton beam was only 20 μA . As we shall see, the muon intensity was more than adequate, but the advantage of a 100% duty cycle was critical. Back-

the lighter elements special runs were taken using brass plates with the same stopping power. This makes the carbon background stand out, and then the background amplitude can be fixed in the analysis.

The data acquisition system was basically that of the μ SR (muon spin rotation) group at TRIUMF, but more vetos were used than is typical for their normal operation, because care must be taken to ensure that no second muon interferes with the measurement. Thus, events were rejected if another muon arrived before or after the muon being studied. A veto gate 32 μ s before and after was used for the light elements, 16 μ s for the heavier targets.

Similarly, events were rejected if two electrons were detected within this time gate after a start. With no rejection the lifetime is 20 ns too low at a stop rate of $4 \times 10^3/s$. Initially, muon rejection was defined using (1,2,3), but at high rates the apparent lifetime dropped by about 3 ns; however, by defining a premuon or second muon by (1,2,3,4,5), no rate effect was observed. Note that all μ^- data were taken with a stopping rate of less than 1000/s, and often much less, so these tests were rather extreme.

The electronic configuration is shown in Fig. 2 and a summary of event definition is as follows:

INCIDENT MUON (entering target region)=(1,2,3) ,
 STOPPED MUON (stop in target)=(1,2,3,4,5) ,
 START (GOOD MUON) (no premuon rejection)=(1,2,3,4,5,G1) ,
 STOP (GOOD ELECTRON)=(5,6) or (5,7) or (5,8) or (5,9) .

Event rejected if

PREMUON=(1,2,3,4,5) within 16 (32) μ s before START ,
 SECOND MUON=(1,2,3,4,5) within 16 (32) μ s after START ,
 TWO COINCIDENT (or SLOW) MUONS=(2',3) with S2 pulse height > 600 mV ,
 SECOND ELECTRON=two STOPS within 16 (32) μ s after START .

Gate created by

STOPPED MUON (pileup gate)=G1 (muon gate 16 or 32 μ s) ,
 TWO COINCIDENT (or SLOW) MUONS (Pile up gate)=G2 ,
 GOOD MUON (normal gate)=G4 (gate for pattern unit) ,
 GOOD ELECTRON (normal gate)=G5 (ELECTRON gate) ,
 End of (G1+G5)=G6 (protection of muon logic) ,

[Note that the 32 (16) μ s gate was used for measurements of lifetimes longer (shorter) than 300 ns] .

The clock used a 1 GHz scaler and was developed at TRIUMF. It was checked against a time calibrator (ORTEC 650) and with positive muons; the value obtained for the μ^+ lifetime averaged over all the test runs is 2197.0 ± 0.7 ns, to be compared with the present world average of 2197.03 ± 0.04 ns.^{4,5}

Events were recorded as four time histograms for each counter S6–S9 (i.e., single events were not stored). Each histogram contained 2000 channels in either 16 ns bins (light elements) or 8 ns bins (heavy elements) At the end of the run the histograms were transferred from the disk of the on-line computer (a PDP 11/40) to magnetic tape for analysis on the UBC Amdahl 470 V/6.

The histograms were analyzed with MINUIT to fit the decay in question, the decay from oxygen for the oxide targets, a carbon background, and a constant background. A spectrum is shown in Fig. 3 for Cr_2O_3 to illustrate the most complex case (granular chromium was also used).

The flat background at the end was first determined

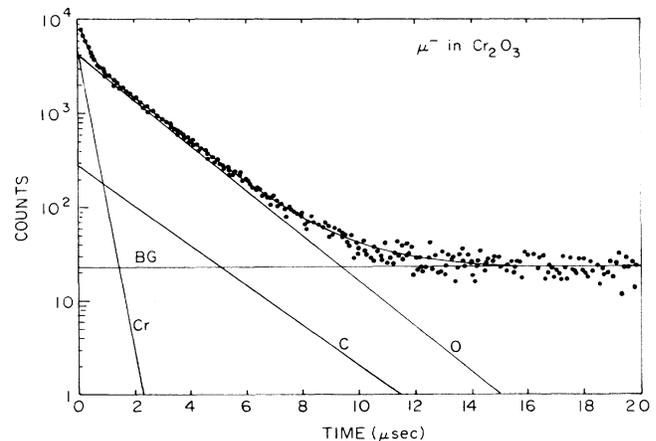


FIG. 3. Decay curve typical for an oxide target.

and then fixed. For heavy metal targets the carbon background from the scintillators is well separated and can be determined simultaneously. For the light elements and for oxide targets it was necessary to obtain the carbon background from independent runs and to fix it in the histogram being analyzed. Typically, 1–2 % of the muons stop in carbon and the correction to the lifetime was only 2 or 3 ns. For oxide targets it was also prudent to fix the oxygen lifetime at the value determined with the water target; otherwise, coupling occurred between the metal and oxygen lifetime.

III. DATA ANALYSIS

For most atoms the observed decay is a simple exponential. However, for nuclides with a spin J , there are two hyperfine states with the muon and nuclide spin either parallel or antiparallel. If the nuclide spin can be approximated as being due to a proton, then these two hyperfine states can have very different capture rates, because the weak interaction transition $\mu^-p \rightarrow \nu n$ is 600 times faster in the singlet state than the triplet state. Now the lower hyperfine state has $F = J - \frac{1}{2}$ for a positive nuclear magnetic moment, so if the nucleus has $J = l + \frac{1}{2}$ (such as ${}^7\text{Li}$, ${}^{11}\text{B}$, ${}^{19}\text{F}$, etc.), then the lower state has the proton and muon spin antiparallel which means the capture rate is higher (and vice versa).

To complicate matters further, there can be a transition between the hyperfine states via an $M1$ Auger transition.

For heavy elements this transition is so fast that the muon spends its whole life in the lower level only. For very light elements (hydrogen excluded because it is a special case), the transition is so slow that capture (or decay) of the muon takes place from a statistical mixture of the two hyperfine states. However, for a few cases, the best known being fluorine, the transition rate is comparable to the decay rate, so two capture rates can be observed.

The hyperfine transition rate can be detected most easily by detecting the neutrons, as was done in the preemptive work of Winston.²⁷ The transition can also be detected via the loss of polarization of the μ^- using μSR techniques.^{28,29} Normally, the effect cannot be detected via the electron decay of the muon, because this is dominated by the normal muon decay. However, our data on fluorine were of such high statistical precision that a simple decay did not fit the data satisfactorily. When detecting electrons, the decay can be approximated by

$$N(t) = A_z(1 - A_{he}e^{-\Lambda_h t})e^{-\Lambda^- t}, \quad (3)$$

where Λ_h is the hyperfine transition rate, Λ^\pm is the total decay rate of the upper (lower) level, A_z is the overall amplitude for the nuclide in question, and A_{he} is the hyperfine transition amplitude when one is detecting electrons, where

$$A_{he} = \frac{J+1}{2J+1} \frac{\Delta\Lambda}{\Lambda_h} \quad \text{with } \Delta\Lambda = \Lambda^- - \Lambda^+.$$

Table I presents the world data on the hyperfine effect

TABLE I. World data on the hyperfine effect.

| Nuclide | J^π | Magnetic moment | Primakoff (Ref. 32) | $\Delta/\langle\Lambda_c\rangle$ | | Λ_h (10^6 s^{-1}) |
|--------------------|-----------------|-----------------|---------------------------|----------------------------------|--------|--|
| | | | | Expt. (Ref.) | Calc. | |
| ${}^6\text{Li}$ | 1^+ | 0.82 | | | | <0.02 (28) |
| ${}^7\text{Li}$ | $\frac{3}{2}^-$ | 3.26 | 3.20 | | | <0.02 (28) |
| ${}^9\text{Be}$ | $\frac{3}{2}^-$ | -1.18 | 0 | | 0 | <0.05 (28) |
| ${}^{10}\text{B}$ | 3^+ | 1.80 | 0.98 | | 0.063 | 0.25 0.21 ± 0.05 (28) |
| ${}^{11}\text{B}$ | $\frac{3}{2}^-$ | 2.69 | 1.23 | | 0.068 | 0.25 0.33 ± 0.05 (28) 0.26 ± 0.06 (31) 0.25 ± 0.07 (32) |
| ${}^{13}\text{C}$ | $\frac{1}{2}^-$ | 0.70 | 0 [-0.34] ^a | | 0 | 0.053 0.020 ± 0.12 (29) |
| ${}^{14}\text{N}$ | 1^+ | 0.40 | [-0.53] ^a | | | ~ 0 0.076 ± 0.033 (29) |
| ${}^{19}\text{F}$ | $\frac{1}{2}^-$ | 2.63 | 0.74 | 0.77 ± 0.13 (23) | 0.015 | 5.8 5.8 ± 0.08 (27) 6.3 ± 0.18 (27) |
| ${}^{23}\text{Na}$ | $\frac{3}{2}^+$ | 2.22 | -0.22 | | -0.004 | 14 |
| ${}^{27}\text{Al}$ | $\frac{5}{2}^+$ | 3.64 | 0.28 | | 0.002 | 41 41 ± 9 (30) |
| ${}^{35}\text{Cl}$ | $\frac{3}{2}^+$ | 0.82 | -0.13 | | -0.015 | 8 |
| ${}^{37}\text{Cl}$ | $\frac{3}{2}^+$ | 0.68 | -0.13 | | -0.015 | 8 |

^aK. Koshigiri, H. Ohtsubo, and M. Morita; see Ref. 29.

in some selected nuclides. Our results from fitting the decay electron spectrum are given in Table II. We see that the fluorine results are in good agreement with Winston.²⁷ The only surprise is boron, for which no hyperfine effect is observed, yet with a limit about 30 times smaller than the predicted amplitude. There is also evidence from BOOM (the BOoster Meson Facility at KEK, Japan) (Ref. 31) that the difference between Λ^+ and Λ^- for ^{11}B is much smaller than expected.

Our results for the μ^- lifetimes are presented in Tables III and IV, together with previous data. To calculate the capture rate (Λ_c) one uses the relation

$$\Lambda_t = \Lambda_c + Q\Lambda_d,$$

where

$$\Lambda_t = 1/\tau_{\mu^-} \quad (4)$$

and

$$\Lambda_d = 1/\tau_{\mu^+},$$

where t denotes total, d denotes decay, and Q is the Huff factor⁷⁸ to take into account the fact that the normal muon decay rate is reduced because the binding of the μ^- reduces slightly the energy available in the decay. There is some doubt about the validity of the calculation, but some experiments are in agreement with Huff's estimate.⁷⁹ Fortunately, it does not have a major effect, but to be precise we have listed in Tables III and IV the values of the Huff factor that we used.

Because the capture rate for the light elements depends critically on the μ^+ lifetime, we have given the capture rate as calculated by the authors, who most often used their own value for the μ^+ lifetime, obtained with the same equipment. This has not always been the practice and some lists have "corrected" the μ^+ lifetime. We find that the capture rate calculated with the original μ^+ lifetime often agrees better with our value than a comparison between the lifetimes might indicate.

For the convenience of the reader we have attempted to make Tables III and IV as complete as possible, except that some very old (pre-1961) experiments⁸⁰⁻⁸¹ have been omitted. However, for hydrogen, mesomolecular effects are dominant,^{25,82-84} so the capture rate is meaningless without a comprehension of these effects, so we have given the most recent references only. Similarly a warning should be given vis à vis the heaviest elements (especially the actinides) because prompt fission induced dur-

ing the atomic cascade can complicate the measurement.^{25,58} The μ^- can become attached to a fragment, and have a longer lifetime component. For total capture rates it is therefore advisable to use the lifetimes obtained via muon-induced fission, although the estimated effect is to add no more than 2 ns to the apparent lifetime for electron detection.

On the whole, the agreement between our experiment and previous ones is quite satisfactory, taking into account all the difficulties; one should note especially the adequate agreement with the Saclay group^{6,7} for the light elements of $^6,^7\text{Li}$, Be, and C, because their measurements are the only precise measurements of recent origin. The difference between the measurements for nitrogen, however, is a little perplexing. This could be due to hyperfine effects, because for nitrogen, $J = l - \frac{1}{2}$, and the lowest hyperfine level has $F = J - \frac{1}{2}$, so the muon and proton spins are parallel, which is the configuration for the lower capture rate, i.e., the longer muon lifetime. Now the Saclay measurement did not take data until 3 μs after the arrival of the muon, so they would be measuring the capture rate in the lower level. The hyperfine transition rate was thought to be very slow, but a value of $\tau \sim 11 \mu\text{s}$ was observed recently at BOOM.²⁹ Morita *et al.* have suggested lifetimes of 1773 ns for the upper hyperfine level and 1941 ns for the lower level. This would be worth pursuing with neutron detectors which are much more sensitive to differences in the capture rates for the light elements.

IV. COMPARISON WITH THEORY

The traditional comparison has been with the Primakoff formula, viz.,

$$\Lambda_c(A, Z) = Z_{\text{eff}}^4 X_1 \left[1 - X_2 \left[\frac{A - Z}{2A} \right] \right], \quad (5)$$

where X_1 represents the muon capture rate in hydrogen, reduced by the neutrino phase space, and X_2 takes into account the Pauli exclusion principle for the nuclear environment. We use Z_{eff} as calculated by Ford and Wills⁷⁷ and the value is given in Tables III and IV. We find that for our data $X_1 = 170 \text{ s}^{-1}$ and $X_2 = 3.125$, which agrees exactly with earlier estimates. The results are displayed graphically in Fig. 4. (Note that nuclei with $Z \leq 7$ and odd proton nuclei for $8 \leq Z \leq 22$ are not included in the fit.) For heavy elements higher order Pauli corrections become necessary and an extension of the above formula was given by Goulard and Primakoff,⁸⁵ viz.,

$$\Lambda_c(A, Z) = Z_{\text{eff}}^4 G_1 \left[1 + G_2 \frac{A}{2Z} - G_3 \frac{A - 2Z}{2Z} - G_4 \left[\frac{A - Z}{2A} + \frac{A - 2Z}{8AZ} \right] \right]. \quad (6)$$

Fits to the data are given in Table V and we see that there is good agreement between the fits to previous results and to the TRIUMF data. The fit is also included in Fig. 4, which brings out into the open the obvious problem that there is a scatter well outside the errors.

If the deviation from the Goulard-Primakoff fit is plot-

TABLE II. Present measurements on hyperfine effect.

| Nuclide | A_{he} | Λ_h (10^6 s^{-1}) |
|-------------------|-------------------|---------------------------------------|
| ^9Be | 0.006 ± 0.002 | 0.05 (fixed) ^a |
| ^{10}B | 0.001 ± 0.002 | 0.21 (fixed) ^a |
| ^{11}B | 0.001 ± 0.003 | 0.33 (fixed) ^a |
| ^{13}C | 0.01 ± 0.01 | 0.2 ± 0.2 (fit) |
| ^{14}N | 0.008 ± 0.010 | 1.2 ± 1.5 (fit) |
| ^{19}F | 0.017 ± 0.010 | 8.8 ± 4.0 (fit) |
| ^{23}Na | 0.01 ± 0.02 | 14 (fixed) ^b |
| ^{nat}Cl | 0.01 ± 0.02 | 8 (fixed) ^b |

^aReference 28.

^bReference 27.

TABLE III. Compendium of total muon capture results for light nuclei. (Z_{eff} is taken from Ref. 77. When underlined it is an estimate.)

| Z (Z_{eff}) | Element | Mean life (ns) | Total capture rate (s^{-1}) | Huff factor | Refs. |
|--------------------------|-----------------|----------------------|---------------------------------|-------------|-------|
| Positive muon | | 2197.03 \pm 0.04 | | | 4,5 |
| 1 (1.0) | $^1\text{H}^b$ | 2194.903 \pm 0.066 | 420 \pm 20 | 1.00 | 34 |
| | $^1\text{H}^b$ | | 420 \pm 60 | 1.00 | 35 |
| | | 2194.53 \pm 0.11 | 470 \pm 29 | | 36 |
| 2 (1.98) | ^3He | | 2170 + 170 (−430) | 1.00 | 37 |
| | | | 2140 \pm 200 | | 38 |
| | ^4He | | 336 \pm 75 | | 39 |
| | | | 375 + 30 (−300) | | 37 |
| | | | 364 \pm 46 | | 60 |
| 3 (<u>2.94</u>) | ^6Li | 2173 \pm 5 | 6100 \pm 1400 | | 1 |
| | | 2175.3 \pm 0.4 | 4680 \pm 120 | 1.00 | 6 |
| | | 2177.0 \pm 2.0 | 4180 \pm 450 | | a |
| 3 | ^7Li | 2194 \pm 4 | 1800 \pm 1100 | | 1 |
| | | 2186.8 \pm 0.4 | 2260 \pm 120 | | 6 |
| | | 2188.3 \pm 2.0 | 1810 \pm 440 | | a |
| 4 (3.89) | Be | 2140 \pm 20 | 18 \pm 10 $\times 10^3$ | 1.00 | 40 |
| | | 2156 \pm 10 | 10 \pm 2 $\times 10^3$ | | 1 |
| | | 2169.0 \pm 1.0 | 5.9 \pm 0.2 $\times 10^3$ | | 7 |
| | | 2162.1 \pm 2.0 | 7.4 \pm 0.5 $\times 10^3$ | | a |
| 5 (<u>4.81</u>) | ^{10}B | 2082 \pm 6 | 26.5 \pm 1.5 $\times 10^3$ | 1.00 | 1 |
| | | 2070.7 \pm 3.0 | 27.8 \pm 0.7 $\times 10^3$ | | a |
| | ^{11}B | 2102 \pm 6 | 21.8 \pm 1.6 $\times 10^3$ | | 1 |
| | | 2096.1 \pm 3.0 | 21.9 \pm 0.7 $\times 10^3$ | | a |
| 6 (5.72) | C | 2020 \pm 20 | 44 \pm 10 $\times 10^3$ | 1.00 | 40 |
| | | | 36 \pm 4 $\times 10^3$ | | 53 |
| | | 2043 \pm 3 | 37.3 \pm 1.1 $\times 10^3$ | | 41 |
| | | 2041 \pm 5 | 36.1 \pm 1.0 $\times 10^3$ | | 42 |
| | | 2040 \pm 30 | 37 \pm 7 $\times 10^3$ | | 43 |
| | | 2025 \pm 4 | 39.7 \pm 1.3 $\times 10^3$ | | 1 |
| | | 2035 \pm 8 | 36.5 \pm 2.0 $\times 10^3$ | | 27 |
| | | 2060 \pm 30 | 30.3 \pm 7 $\times 10^3$ | | 44 |
| | | 2030.0 \pm 1.6 | 37.6 \pm 0.4 $\times 10^3$ | | 7 |
| | | 2040 \pm 10 | 35.2 \pm 2.0 $\times 10^3$ | | 73 |
| | | 2029 \pm 3 | 37.7 \pm 0.7 $\times 10^3$ | | 29 |
| | | 2026.3 \pm 1.5 | 38.8 \pm 0.5 $\times 10^3$ | | a |
| | ^{13}C | 2045 \pm 2 | 33.8 \pm 0.4 $\times 10^3$ | | 29 |
| | | 2029.1 \pm 3.0 | 37.6 \pm 0.7 $\times 10^3$ | | a |
| 7 (6.61) | N | 1860 \pm 20 | 86 \pm 11 $\times 10^3$ | 1.00 | 40 |
| | | 1927 \pm 13 | 65 \pm 4 $\times 10^3$ | | 1 |
| | | 1940.5 \pm 2.8 | 60.2 \pm 0.8 $\times 10^3$ | | 7 |
| | | 1910 \pm 3 | 68.4 \pm 0.8 $\times 10^3$ | | 29 |
| | | 1906.8 \pm 3.0 | 69.3 \pm 0.8 $\times 10^3$ | | a |
| 8 (7.49) | O | 1640 \pm 30 | 159 \pm 14 $\times 10^3$ | 0.998 | 40 |
| | | 1812 \pm 12 | 98 \pm 3 $\times 10^3$ | | 1 |
| | | 1810 \pm 20 | 98 \pm 5 $\times 10^3$ | | 44 |
| | | 1832 \pm 29 | 95 \pm 8 $\times 10^3$ | | 73 |
| | | 1795.4 \pm 2.0 | 102.6 \pm 0.6 $\times 10^3$ | | a |
| | ^{18}O | 1844.0 \pm 4.5 | 88.0 \pm 1.5 $\times 10^3$ | | a |
| 9 (8.32) | F | 1420 \pm 40 | 254 \pm 22 $\times 10^3$ | 0.998 | 40 |
| | | 1450 \pm 20 | 235 \pm 10 $\times 10^3$ | | 45 |
| | | 1458 \pm 13 | 231 \pm 6 $\times 10^3$ | | 27 |
| | | 1462.7 \pm 5.0 | 229 \pm 1 $\times 10^3$ | | a |

(these F data show the lifetime for the lower hf state; see Sec. IV D).

^aDenotes the results of this experiment.

^bFor hydrogen the capture rate depends on mesomolecular effects (Ref. 25). Thus we have given the most recent articles only.

TABLE IV. Compendium of total muon capture results for medium and heavy nuclei. (Z_{eff} is taken from Ref. 77. When it is underlined, it is an estimate. Entries in parentheses in column 4 are not given in the original reference.)

| Z (Z_{eff}) | Element | Mean life (ns) | Total capture rate ($10^6/s$) | Huff factor | Refs. | |
|--------------------------|---------|--------------------|------------------------------------|----------------|-------------------|----|
| 10 (<u>9.14</u>) | Ne | 1520 \pm 23 | 0.204 \pm 0.010 | 0.997 | 46 | |
| | | | 0.167 \pm 0.030 | | 47 | |
| | | | 0.30 \pm 0.02 | | 48 | |
| 11 (9.95) | Na | 1450 \pm 10 | 0.235 \pm 0.005 | 0.996 | 7 | |
| | | 1190 \pm 20 | 0.387 \pm 0.015 | | 40 | |
| | | 1204.0 \pm 2.0 | 0.3772 \pm 0.0014 | | a | |
| 12 (10.69) | Mg | 1040 \pm 20 | 0.507 \pm 0.020 | 0.995 | 40 | |
| | | 1071 \pm 2 | 0.480 \pm 0.002 | | 42 | |
| | | 1021 \pm 25 | 0.52 \pm 0.02 | | 49 | |
| | | 1067.2 \pm 2.0 | 0.4841 \pm 0.0018 | | a | |
| 13 (11.48) | Al | 880 \pm 10 | 0.691 \pm 0.020 | 0.993 | 40 | |
| | | 864 \pm 2 | 0.662 \pm 0.003 | | 42 | |
| | | 905 \pm 12 | 0.650 \pm 0.015 | | 45 | |
| | | 864.0 \pm 1.0 | 0.7054 \pm 0.0013 | | a | |
| 14 (12.22) | Si | 810 \pm 10 | 0.777 \pm 0.025 | 0.992 | 40 | |
| | | 767 \pm 2 | 0.850 \pm 0.003 | | 42 | |
| | | 758 \pm 20 | 0.86 \pm 0.04 | | 49 | |
| | | 756.0 \pm 1.0 | 0.8712 \pm 0.0018 | | a | |
| 15 (12.90) | P | 660 \pm 20 | 1.05 \pm 0.05 | 0.991 | 40 | |
| | | 635 \pm 2 | 1.121 \pm 0.005 | | 42 | |
| | | 611.2 \pm 1.0 | 1.185 \pm 0.003 | | a | |
| 16 (13.64) | S | 540 \pm 20 | 1.39 \pm 0.09 | 0.990 | 40 | |
| | | 567.4 \pm 8.4 | 1.31 \pm 0.03 | | 49 | |
| | | 559 \pm 3 | 1.34 \pm 0.01 | | 27 | |
| | | 554.7 \pm 1.0 | 1.352 \pm 0.003 | | a | |
| 17 (14.24) | Cl | 540 \pm 20 | 1.39 \pm 0.09 | 0.989 | 40 | |
| | | 560.8 \pm 2.0 | 1.333 \pm 0.006 | | a | |
| | | ³⁵ Cl | 444 \pm 10 | | 1.80 \pm 0.05 | 76 |
| | | ³⁷ Cl | 587 \pm 17 | | 1.25 \pm 0.05 | 76 |
| | | ^{nat} Cl | 479 \pm 17 | | 1.64 \pm 0.08 | 76 |
| 18 (<u>14.89</u>) | Ar | | 1.20 \pm 0.08 | | 48 | |
| | | 537 \pm 32 | 1.41 \pm 0.11 | | 0.988 | 59 |
| 19 (15.53) | K | 410 \pm 20 | 1.99 \pm 0.12 | 0.987 | 40 | |
| | | 435.0 \pm 1.0 | 1.849 \pm 0.005 | | a | |
| 20 (16.15) | Ca | 333 \pm 7 | 2.55 \pm 0.05 | 0.985 | 40 | |
| | | 345 \pm 3 | 2.444 \pm 0.023 | | 50 | |
| | | 335.9 \pm 0.9 | 2.529 \pm 0.008 | | 51 | |
| | | 365 \pm 8 | 2.29 \pm 0.05 | | 52 | |
| | | 332.7 \pm 1.5 | 2.557 \pm 0.014 | | a | |
| | | ^{43.8} Ca | 445 \pm 8 | | 1.793 \pm 0.040 | 50 |
| 21 (<u>16.77</u>) | Sc | 316.6 \pm 2.5 | 2.711 \pm 0.025 | 0.983 | a | |
| 22 (17.38) | Ti | 330 \pm 7 | 2.63 \pm 0.06 | 0.981 | 40 | |
| | | 327.3 \pm 4.5 | 2.60 \pm 0.04 | | 49 | |
| | | 329.3 \pm 1.3 | 2.590 \pm 0.012 | | a | |
| 23 (18.04) | V | 264 \pm 4 | 3.37 \pm 0.06 | 0.980 | 40 | |
| | | 271 \pm 5 | 3.24 \pm 0.07 | | 43 | |
| | | 282.6 \pm 3.2 | 3.09 \pm 0.05 | | 49 | |
| | | 284.5 \pm 2.0 | 3.069 \pm 0.025 | | a | |
| 24 (18.49) | Cr | 276 \pm 6 | 3.24 \pm 0.08 | 0.978 | 40 | |
| | | 264.5 \pm 3.2 | 3.33 \pm 0.06 | | 49 | |
| | | 255.3 \pm 2.0 | 3.472 \pm 0.031 | | a | |
| | | ⁵⁰ Cr | 233.7 \pm 2.7 | | 3.825 \pm 0.050 | 73 |
| | | ⁵² Cr | 256.0 \pm 3.0 | | 3.452 \pm 0.047 | 73 |
| | | ⁵³ Cr | 266.6 \pm 3.2 | | 3.297 \pm 0.045 | 73 |
| | | ⁵⁴ Cr | 284.8 \pm 3.3 | | 3.057 \pm 0.042 | 73 |
| | | ^{nat} Cr | 256.7 \pm 3.0 | | 3.444 \pm 0.047 | 73 |
| 25 (19.06) | Mn | 239 \pm 4 | 3.67 \pm 0.08 | 0.976 | 40 | |
| | | 225.5 \pm 2.3 | 3.98 \pm 0.05 | | 49 | |

TABLE IV. (Continued).

| Z (Z_{eff}) | Element | Mean life (ns) | Total capture rate ($10^6/s$) | Huff factor | Refs. | |
|------------------------|-------------------|-------------------|------------------------------------|----------------|------------|----|
| 26 (19.59) | Mn (con't) | 232.5±2.0 | 3.857 ±0.037 | 0.975 | a | |
| | Fe | 201 ±4 | 4.53 ±0.10 | | 40 | |
| | | 207 ±3 | 4.38 ±0.07 | | 43 | |
| | | 206.7±2.4 | 4.40 ±0.05 | | 49 | |
| 27 (20.13) | Co | 206.0±1.0 | 4.411 ±0.024 | 0.971 | a | |
| | | 188 ±3 | 4.89 ±0.09 | | 43 | |
| | | 184.0±1.7 | 4.96 ±0.05 | | 49 | |
| | | 185.8±1.0 | 4.940 ±0.029 | | a | |
| 28 (20.66) | Ni | 154 ±3 | 6.03 ±0.14 | 0.969 | 40 | |
| | | 158 ±3 | 5.89 ±0.12 | | 43 | |
| | | 159.4±3.1 | 5.83 ±0.13 | | 49 | |
| | | 156.9±1.0 | 5.932 ±0.041 | | a | |
| | ⁵⁸ Ni | 152.3±2.4 | 6.11 ±0.10 | | 73 | |
| | ⁶⁰ Ni | 166.2±2.6 | 5.56 ±0.10 | | 73 | |
| | ⁶² Ni | 193.4±3.5 | 4.72 ±0.10 | | 73 | |
| | ^{nat} Ni | 158.4±2.5 | 5.88 ±0.10 | | 73 | |
| | 29 (21.12) | Cu | 160 ±4 | 5.79 ±0.16 | 0.967 | 40 |
| | | | 169 ±6 | 5.47 ±0.20 | | 45 |
| 164.0±2.3 | | | 5.66 ±0.09 | 54 | | |
| 163.5±2.4 | | | 5.67 ±0.09 | 49 | | |
| 163.5±1.0 | | | 5.676 ±0.037 | a | | |
| ⁶³ Cu | | | 162.1±1.4 | 5.72 ±0.05 | | 49 |
| 30 (21.61) | Zn | 161 ±4 | 5.76 ±0.17 | 0.965 | 40 | |
| | | 169 ±4 | 5.5 ±0.1 | | 43 | |
| | | 161.2±1.1 | 5.76 ±0.05 | | 49 | |
| | | 159.4±1.0 | 5.834 ±0.039 | | a | |
| 31 (22.02) | Ga | 163.0±1.6 | 5.70 ±0.06 | 0.962 | 49 | |
| 32 (22.43) | Ge | 167.4±1.8 | 5.54 ±0.06 | 0.960 | 49 | |
| | | 166.5±1.0 | 5.569 ±0.036 | | a | |
| 33 (22.84) | As | 153.8±1.7 | 6.07 ±0.07 | 0.958 | 49 | |
| | | 153.9±2.4 | 6.06 ±0.12 | | 54 | |
| | | 152.9±1.0 | 6.104 ±0.043 | | a | |
| 34 (23.24) | Se | 163.0±1.2 | 5.70 ±0.05 | 0.955 | 49 | |
| | | 163.5±1.0 | 5.681 ±0.037 | | a | |
| 35 (23.65) | ⁷⁹ Br | 133.7±6.5 | 7.05 ±0.35 | 0.952 | 55 | |
| | ⁸¹ Br | 125.3±7.9 | 7.55 ±0.48 | | 55 | |
| | Br | 133.3±1.0 | 7.07 ±0.06 | | a | |
| 37 (24.47) | Rb | 136.5±2.7 | 6.89 ±0.14 | 0.948 | 49 | |
| 38 (24.85) | Sr | 130.1±2.3 | 7.25 ±0.14 | 0.945 | 49 | |
| | | 134.1±2.5 | 7.02 ±0.14 | | a | |
| | | ⁸⁸ Sr | 142.0±5.5 | | 6.61 ±0.27 | 49 |
| 39 (25.23) | Y | 120.2±1.4 | 7.89 ±0.11 | 0.942 | 54 | |
| 40 (25.61) | Zr | 110.8±0.8 | 8.59 ±0.07 | 0.940 | 49 | |
| | | 110.0±1.0 | 8.66 ±0.08 | | a | |
| 41 (25.99) | Nb | 92.3±1.1 | 10.40 ±0.14 | 0.939 | 54 | |
| | | 92.7±1.5 | 10.36 ±0.17 | | a | |
| 42 (26.37) | Mo | 105 ±2 | 9.09 ±0.18 | 0.936 | 40 | |
| | | 103.5±0.7 | 9.23 ±0.07 | | 49 | |
| | | 99.6±1.5 | 9.614 ±0.15 | | a | |
| 45 (27.32) | Rh | 95.8±0.6 | 10.01 ±0.07 | 0.929 | 49 | |
| 46 (27.63) | Pd | 96.0±0.6 | 10.00 ±0.07 | 0.927 | 49 | |
| 47 (27.95) | Ag | 85 ±3 | 11.25 ±0.50 | 0.925 | 40 | |
| | | 88.7±0.9 | 10.86 ±0.13 | | 54 | |
| | | 88.6±1.1 | 10.88 ±0.14 | | 49 | |
| | | 91.6±2.2 | 10.5 ±0.3 | | 76 | |
| | | 87.0±1.5 | 11.07 ±0.20 | | a | |
| | | 95 ±5 | 10.1 ±0.5 | | 40 | |
| 48 (28.20) | Cd | 90.5±0.8 | 10.63 ±0.11 | 0.921 | 54 | |

TABLE IV. (Continued).

| Z (Z_{eff}) | Element | Mean life (ns) | Total capture rate ($10^6/s$) | Huff factor | Refs. |
|------------------------|--------------------------------|-------------------|------------------------------------|----------------|-------|
| | Cd (con't) | 90.7±1.5 | 10.61 ±0.18 | | a |
| 49 (28.42) | In | 84.8±0.8 | 11.37 ±0.13 | 0.920 | 54 |
| | | 84.6±1.5 | 11.40 ±0.21 | | a |
| 50 (28.64) | Sn | 92 ±3 | 10.5 ±0.4 | 0.918 | 43 |
| | | 89.9±1.0 | 10.70 ±0.14 | | 54 |
| | | 92.1±1.5 | 10.44 ±0.18 | | a |
| 51 (28.79) | Sb | 91.7±1.1 | 10.49 ±0.14 | 0.916 | 54 |
| | | 94.1±1.7 | 10.21 ±0.20 | | a |
| 52 (29.03) | Te | 105.5±1.2 | 9.06 ±0.11 | 0.913 | 49 |
| | | 103.2±1.0 | 9.27 ±0.10 | | a |
| 53 (29.27) | I | 86.1±0.7 | 11.20 ±0.11 | 0.910 | 54 |
| | | 83.4±1.5 | 11.58 ±0.22 | | a |
| 55 (29.75) | Cs | 87.8±1.9 | 10.98 ±0.25 | 0.905 | 54 |
| 56 (29.99) | Ba | 94.5±0.7 | 10.18 ±0.10 | 0.902 | 54 |
| | | 96.6±1.5 | 9.94 ±0.16 | | a |
| 57 (30.22) | La | 89.9±0.7 | 10.71 ±0.10 | 0.901 | 54 |
| 58 (30.36) | Ce | 84.4±0.7 | 11.44 ±0.11 | 0.899 | 54 |
| | | 83.3±1.0 | 11.60 ±0.14 | | a |
| 59 (30.53) | Pr | 72.1±0.6 | 13.45 ±0.13 | 0.897 | 54 |
| 60 (30.69) | Nd | 78.5±0.8 | 12.32 ±0.14 | 0.895 | 54 |
| | | 77.5±2.0 | 12.50 ±0.33 | | a |
| 62 (31.01) | Sm | 79.2±1.0 | 12.22 ±0.17 | 0.890 | 54 |
| 64 (31.34) | Gd | 80.1±1.0 | 12.09 ±0.16 | 0.885 | 54 |
| | | 81.8±1.5 | 11.82 ±0.22 | | a |
| 65 (31.48) | Th | 76.2±0.7 | 12.73 ±0.13 | 0.882 | 54 |
| 66 (31.62) | Dy | 78.8±1.1 | 12.29 ±0.18 | 0.880 | a |
| 67 (31.76) | Ho | 74.9±0.6 | 12.95 ±0.13 | 0.877 | 54 |
| 68 (31.90) | Er | 74.4±1.5 | 13.04 ±0.27 | 0.875 | a |
| 72 (32.47) | Hf | 74.5±1.3 | 13.03 ±0.21 | 0.865 | 49 |
| 73 (32.61) | Ta | 75.5±0.6 | 12.86 ±0.13 | 0.862 | 54 |
| 74 (32.76) | W | 81 ±2 | 11.92 ±0.30 | 0.860 | 40 |
| | | 72 ±3 | 13.5 ±0.6 | | 43 |
| | | 74.3±1.2 | 13.07 ±0.21 | | 49 |
| | | 78.4±1.5 | 12.36 ±0.24 | | a |
| 79 (33.64) | Au | 72.6±0.5 | 13.39 ±0.11 | 0.850 | 54 |
| | | 74.3±1.5 | 13.07 ±0.28 | | a |
| 80 (33.81) | Hg | 76.2±1.5 | 12.74 ±0.26 | 0.848 | 49 |
| | | 76.2±1.5 | 12.74 ±0.26 | | a |
| 81 (34.21) | Tl | 75 ±4 | 12.90 ±0.75 | 0.846 | 40 |
| | | 70.3±0.9 | 13.83 ±0.20 | | 54 |
| | | 70.0±1.5 | 13.90 ±0.31 | | a |
| 82 (34.18) | Pb | 82 ±5 | 11.70 ±0.75 | 0.844 | 40 |
| | | 67 ±3 | 14.5 ±0.7 | | 43 |
| | | 74.9±0.4 | 12.98 ±0.10 | | 54 |
| | | 73.2±1.2 | 13.27 ±0.22 | | 49 |
| | | 75.4±1.0 | 13.45 ±0.18 | | a |
| | RPb ^b | 71.5±0.4 | 13.61 ±0.10 | | 54 |
| 83 (34.00) | Bi | 79 ±5 | 12.20 ±0.75 | 0.840 | 40 |
| | | 73.3±0.4 | 13.26 ±0.07 | | 54 |
| | | 74.2±1.0 | 13.10 ±0.18 | | a |
| 90 (34.73) | ²³² Th ^c | 80.4±2.0 | | 0.824 | 56e |
| | | 79.2±2.0 | | | 57e |
| | | 80.1±0.6 | | | 66n |
| | | 74.2±5.6 | (13.1 ±0.9) | | 61f |
| | | 87 ±4 | (11.1 ±0.6) | | 63f |
| | | 77.3±0.3 | (12.56 ±0.05) | | 67f |
| | | 84.0±4.5 | (11.5 ±0.6) | | 68f |
| | | 78.5±2.0 | (12.4 ±0.3) | | 71f |

TABLE IV. (Continued).

| Z (Z_{eff}) | Element | Mean life (ns) | Total capture rate ($10^6/s$) | Huff factor | Refs. | |
|--------------------------|---------------------|--------------------|------------------------------------|----------------|--------------|--------------|
| 92 (34.94) | $^{233}\text{U}^c$ | 61.7±3.8 | (15.8 ±0.9) | 0.820 | 62f | |
| | | 68.5±0.7 | (14.23 ±0.15) | | 71f | |
| | $^{235}\text{U}^c$ | 78 ±4 | | | 56e | |
| | | 75.4±1.9 | | | 57e | |
| | | 75.0±0.7 | | | 66n | |
| | | 71 ±2 | (13.7 ±0.4) | | 74K γ | |
| | | 65.3±2.8 | (14.9 ±0.6) | | 62f | |
| | | 66.5±4.2 | (14.7 ±1.0) | | 61f | |
| | | 75.6±2.3 | (12.9 ±0.4) | | 63f | |
| | | 72.9±0.9 | (13.3 ±0.2) | | 58f | |
| | | 72.8±0.6 | (13.36 ±0.12) | | 71f | |
| | | 71.6±0.6 | (13.58 ±0.12) | | 26f | |
| | | $^{236}\text{U}^c$ | 70 ±2 | | (13.9 ±0.4) | 74K γ |
| | | | $^{238}\text{U}^c$ | | 88 ±4 | |
| | | 81.5±2.0 | | | | 56e |
| | | 73.5±2.0 | | | | 57e |
| | | 84.6±1.5 | | | | a,e |
| | 78.3±1.0 | | | | 66n | |
| | 78.6±1.5 | | | | 69 γ | |
| | 79.1±0.5 | | | | 70 γ | |
| | 78 ±2 | (12.4 ±0.4) | | | 74K γ | |
| | 74.1±2.8 | (13.1 ±0.5) | | | 62f | |
| | 75.6±2.9 | (12.9 ±0.5) | | | 61f | |
| 76.0±1.0 | (12.8 ±0.2) | 63f | | | | |
| 77.1±0.2 | (12.60 ±0.04) | 67f | | | | |
| 77.9±0.5 | (12.46 ±0.09) | 58f | | | | |
| 77.7±0.6 | (12.50 ±0.10) | 71f | | | | |
| 78.0±2.0 | (12.4 ±0.4) | 72f | | | | |
| 77.2±0.4 | 12.57 ±0.07 | 26f | | | | |
| 93 (35.05) | $^{237}\text{Np}^c$ | 73.5±1.4 | | 0.818 | 66n | |
| | | 71.3±0.9 | (13.6 ±0.2) | | 58f | |
| | | 72 ±2 | (13.5 ±0.4) | | 65f | |
| 94 (35.16) | $^{239}\text{Pu}^c$ | 77.5±2.0 | | 0.816 | 56e | |
| | | 73.4±2.8 | | | 57e | |
| | | 74.5±0.5 | | | 66n | |
| | | 74 ±14 | (13.1 ±2.6) | | 64f | |
| | | 70 ±3 | (13.9 ±0.9) | | 65f | |
| | | 70.1±0.7 | (13.9 ±0.2) | | 58f | |
| | $^{242}\text{Pu}^c$ | 67 ±8 | (14.6 ±2.0) | | 75f | |
| | | 81.1±0.7 | | | 66n | |
| | | 75.4±0.9 | (12.9 ±0.2) | | 58f | |
| | | 79 ±5 | (12.3 ±0.8) | | 65f | |

^aDenotes the results of this experiment.

^bRPb denotes radiogenic lead (88% ^{206}Pb :9% ^{207}Pb :3% ^{208}Pb).

^cFor these nuclides, prompt fission can complicate the measurement. The letters after the reference denote the type of particle detected, viz., e, electrons; n, neutrons; γ , gammas, $K\gamma$, gammas in coincidence with K x rays; f, fission fragments, (f and $K\gamma$ are probably the most reliable for determining the total capture rate. See Refs. 26 and 58 for details.)

ted versus A , a systematic effect can be seen which could be related to shell effects; see Fig. 5. Two things are evident. First, the odd- Z nuclei have a systematically larger capture rate than neighboring even Z nuclei; secondly, the overall deviation varies with Z in a complex but not a random way. In some cases very large deviations occur; for example, niobium is 9% high and praseodymium is

5% high. It has been suggested that this could be due to the quenching of the Cabibbo angle caused by the high magnetic field experienced by the muon in the nuclear environment.⁸⁶ Further work for the actinides followed,⁸⁷ but Lee and Khanna have shown that the magnetic fields are not really high enough.⁸⁸ Also relevant is a recent experiment by Adelberger *et al.*⁸⁹ on the β decay of ^{24}Al ,

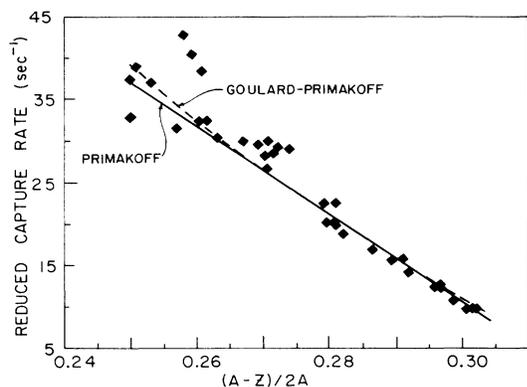


FIG. 4. The TRIUMF data are fitted to the Primakoff and Goulard-Primakoff formulae. The reduced capture rate is here defined as $\Lambda_c^{\text{expt}}/Z_{\text{eff}}^4$.

for which it was shown that there is no evidence for any vanishing of the Cabibbo angle. Now, for muon capture the Primakoff and Goulard-Primakoff formulae do not account correctly for isotopic effects; these formulae predict a larger spread between the isotopes than is observed experimentally in Ca, Cr, Ni, U, and Pu. (For Cu, Sr, and Br the experiments are not sufficiently precise; for Cl the experiment seems questionable.) Furthermore, in view of the overall pattern that even Z elements tend to have lower capture rates, what is more surprising than the Nb and Pr anomalies is that some even Z elements such as Th, U, and Pu lies significantly above the prediction. (Figure 5 is better for illustrating this point, as the Primakoff formula in Fig. 6 has been smoothed.) Because of all these uncertainties we prefer to take the more conservative position that nuclear structure effects are at the bottom of all these variations of the total muon capture rates.

Another way to illustrate these effects is given in Fig. 6. Here we plot the reduced capture rate $R_c Z/Z_{\text{eff}}^4$ versus the atomic number Z . The graph is adapted from the work of Kohyama and Fujii.¹² It is clear that there is a smooth fluctuation with Z , although some critical points are missing; in particular, it would be helpful to know the total muon capture rates in krypton and xenon. Now, it is true that the fluctuations in Fig. 6 are also related to the

TABLE V. Fitting results for Goulard-Primakoff formula [Eq. (6)].

| | TRIUMF data | Past results |
|-------------------------|-------------|--------------|
| Number of data | 30 | 58 |
| G_1 | 261 | 252 |
| G_2 | -0.040 | -0.038 |
| G_3 | -0.26 | -0.24 |
| G_4 | 3.24 | 3.23 |
| (Expt. - Fit)/Expt. (%) | 4.1 | 5.6 |

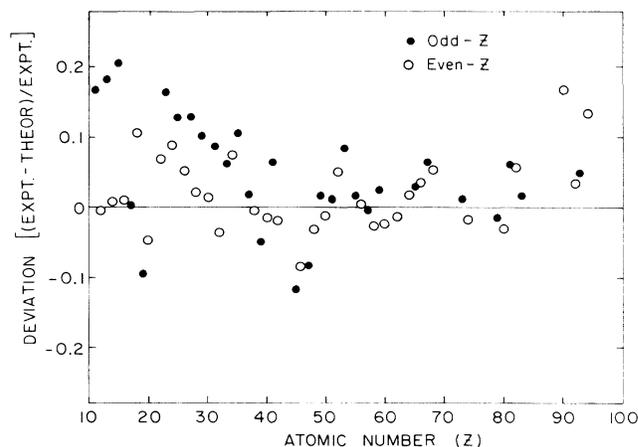


FIG. 5. Deviations of the experimental total capture rates from the Goulard-Primakoff best fit.

fluctuations in the neutron excess (which is factored out to some extent in the Primakoff plot). Thus we have also plotted the Primakoff fit in Fig. 6 to clarify this point. Figures 5 and 6 illustrate clearly that the extreme values of the capture rate that are observed in niobium and praeosdymium seem to be part of the general phenomenon, and there is no need to search for exotic explanations.

V. CONCLUSIONS

This experiment has provided some useful additions to our experimental knowledge of the lifetime of the negative

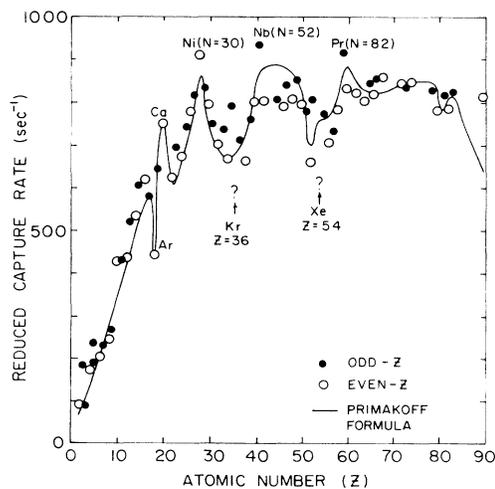


FIG. 6. Reduced total capture rates (i.e., $\Lambda_c^{\text{expt}}/Z_{\text{eff}}^4$) vs atomic number [adapted from Kohyama and Fujii (Ref. 12)]. The solid line represents the Primakoff formula, but it has been smoothed; therefore comparisons for individual elements might be erroneous.

muon in muonic atoms. A reasonably consistent and accurate body of information is now available. There are several unsettled problems, however: One is the hyperfine effect in light nuclei (especially boron and nitrogen), and another is that a better understanding is needed of the fluctuations in the capture rate as a function of both the atomic number and the neutron content of the nuclide.

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