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 ^{6}Li of 2173 ± 5 ns and in ^{7}Li 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 synchrocylotrons 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 ^{6}Li (2175.3 ± 0.4 ns) and ^{7}Li (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 group[7] 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

$$\mu^- + \mathrm{p} \rightarrow \nu_\mu + \mathrm{n} \tag{1}$$

becomes more complicated in the nuclear environment; for example,

$$\mu^- + {}^{12}\mathrm{C} \rightarrow \nu_\mu + {}^{12}\mathrm{B}^* \ , \tag{2}$$

where ^{12}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. Bernabéu[11] proposed a model which avoids the uncertainty of the neutrino energy and Kohyama and Fujii[12] 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 effects[25] 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 thoroughly[26] and so we shall limit ourselves to simply reporting our results.

II. EXPERIMENTAL METHOD

The experiment was performed at the *M*20 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-

ward μ^- were used at about 87 MeV/c before the degrader with an incident flux up to 1000 s^{-1}. The experimental setup is shown in Fig. 1. The final collimator was 2.5 cm in diameter in a lead wall. Counter S3 was 5 cm in diameter and 0.7 mm thick; it was made as thin as possible to reduce the background from μ^- stopping in the counter itself. The veto counter S4 was $30\times45\times1.2$ cm^3. The cylindrical counter S5 had a diameter of 20 cm, while the four paddles S6—S9 measured $20\times20\times0.6$ cm^3; the whole setup had a solid angle of 60% of 4π with respect to the target.

The beam had a contamination of electrons with a few remnant pions. Counter S2 was made thick (1.2 cm) to record the pulse height of the muons (250—600 mV) and to reject electrons (30—150 mV) or double muons (>600 mV). Pions stop before the target. The residual contamination of electrons and pions was very small and caused no problems.

If there is a residual magnetic field where the muon stops, the muon magnetic moment will rotate and can give a false lifetime. A mu-metal shield was used to reduce the field from 1 G to less than 0.05 G. This implies a rotation of the muon spin by $<5°$ in 10 muon lifetimes or an apparent lifetime which is out by <7 ns. To counteract this problem, care was taken to center the target in the counter array. In tests with a μ^+ beam the left-right counters deviated from the average by 6.4 ± 4.4 ns and the top-bottom counters by 5.0 ± 4.4 ns, which is consistent with the field measurement. However, the average lifetime was always consistent with the world average. Remember also that the μ^+ beam is ~6 times more polarized than μ^- in a mesic atom, so, in the lifetime results presented here, the deviation of a particular telescope would be ~1 ns for light elements and less for heavy elements. Confirmation of these effects was made using a stopping π^+ beam which produces unpolarized μ^+ in the target. The deviations of the lifetimes were then 1.4 ± 4.4 and 3.0 ± 4.4 ns, respectively, which is consistent with zero.

Most targets were elemental and self-supporting, but a few powders and liquids were used, viz., ^{13}C, ^{18}O and ^{16}O agar, H_2O, LiF, CaF_2, PbF, CCl_4, Sc_2O_3, MnO_2, GeO_2, Br, I, BaO, NdO, W, and HgO. The light elements were contained in thin stainless steel containers and the heavier elements in plastic containers. All impurities were less than 1%, mostly much less.

The only difficult target was that for nitrogen. It was decided to use a liquid target in a stainless steel container with vacuum insulation. Two 0.1 mm entrance windows were used with rear thicknesses of 3 mm. For all the targets some muons can stop in the scintillator S3 or the wrapping of S4 and S5. As most muons stopping in hydrogen are immediately transferred to the carbon atoms in the plastic materials, this background exhibits the lifetime of carbon and is typically 1—2% of the stops. For heavy elements the carbon component is clearly separated. For

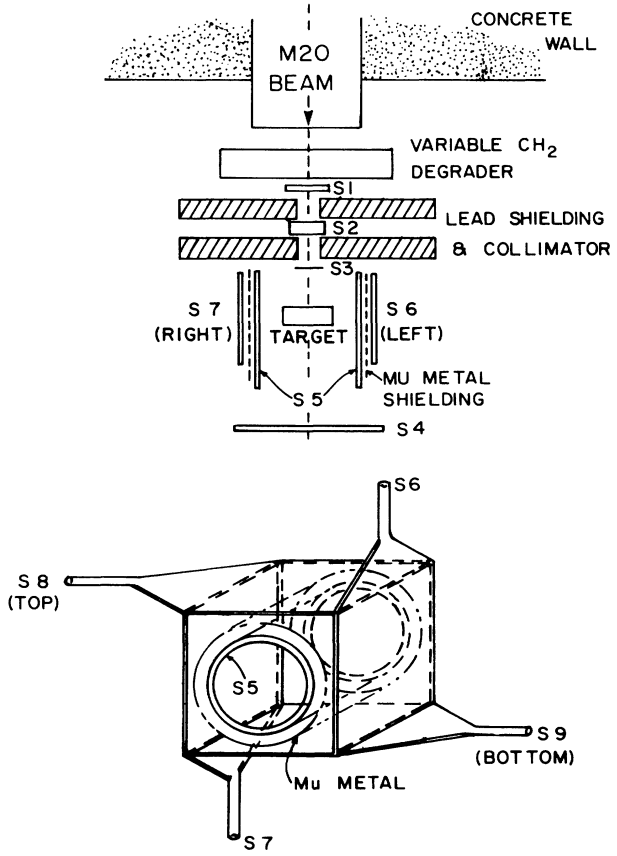

FIG. 1. Experimental setup.

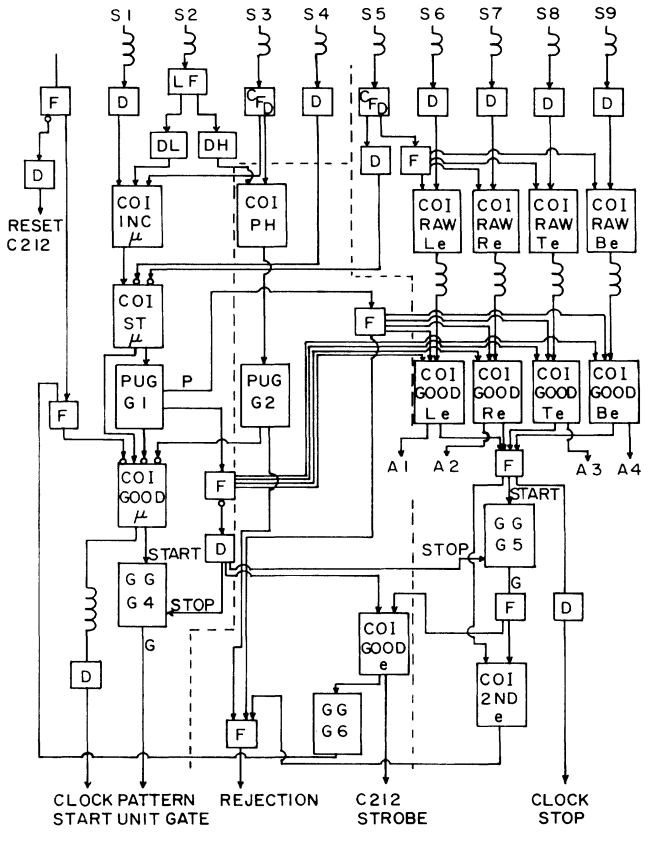

FIG. 2. Configuration of electronic equipment.

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 μSR (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 μs before and after was used for the light elements, 16 μs 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 4×10^3/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 $(1,2,3,\bar{4},\bar{5})$, 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)=$(1,2,3,\bar{4},\bar{5})$,

START (GOOD MUON) (no premuon rejection)=$(1,2,3,\bar{4},\bar{5},\overline{G1})$,

STOP (GOOD ELECTRON)=(5,6) or (5,7) or (5,8) or (5.9) .

Event rejected if

PREMUON=$(1,2,3,\bar{4},\bar{5})$ within 16 (32) μs before START ,

SECOND MUON=$(1,2,3,\bar{4},\bar{5})$ within 16 (32) μs after START ,

TWO COINCIDENT (or SLOW) MUONS=(2',3) with S2 pulse height >600 mV ,

SECOND ELECTRON=two STOPS within 16 (32) μs after START .

Gate created by

STOPPED MUON (pileup gate)=G1 (muon gate 16 or 32 μs) ,

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) μs 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

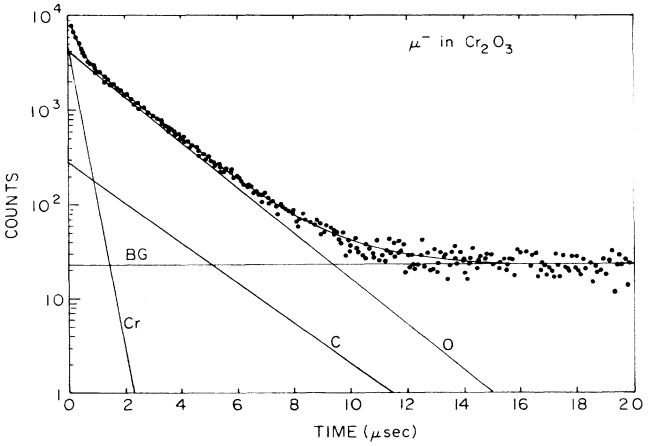

FIG. 3. Decay curve typical for an oxide target.

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}Li, ^{11}B, ^{19}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

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

where Λ_h is the hyperfine transition rate, $\Lambda^{\pm}$ 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	$\Delta/\langle\Lambda_c\rangle$ Primakoff (Ref. 32)	$\Delta/\langle\Lambda_c\rangle$ Expt. (Ref.)	A_{he}	Λ_h (10^6 s^{-1}) Calc.	Λ_h (10^6 s^{-1}) Expt. (Ref.)
^{6}Li	1^+	0.82					<0.02 (28)
^{7}Li	$\frac{3}{2}^-$	3.26	3.20				<0.02 (28)
^{9}Be	$\frac{3}{2}^-$	-1.18	0		0		<0.05 (28)
^{10}B	3^+	1.80	0.98		0.063	0.25	0.21±0.05 (28)
^{11}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}C	$\frac{1}{2}^-$	0.70	0 [−0.34][a]		0	0.053	0.020±0.12 (29)
^{14}N	1^+	0.40	[−0.53][a]			∼0	0.076±0.033 (29)
^{19}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}Na	$\frac{3}{2}^+$	2.22	−0.22		−0.004	14	
^{27}Al	$\frac{5}{2}^+$	3.64	0.28		0.002	41	41±9 (30)
^{35}Cl	$\frac{3}{2}^+$	0.82	−0.13		−0.015	8	
^{37}Cl	$\frac{3}{2}^+$	0.68	−0.13		−0.015	8	

[a]K. 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

$$\Lambda_t = 1/\tau_{\mu^-} \tag{4}$$

and

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

where t denotes total, d denotes decay, and Q is the Huff factor[78] 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) experiments[80–81] 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 during 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.

TABLE II. Present measurements on hyperfine effect.

Nuclide	A_{he}	Λ_h (10^6 s^{-1})
^{9}Be	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]

[a]Reference 28.
[b]Reference 27.

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}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 $\tau \sim 11$ μs 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.,

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

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 Wills[77] and the value is given in Tables III and IV. We find that for our data $X_1 = 170$ 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.,

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

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

[a]Denotes the results of this experiment.

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

TABLE IV. (*Continued*).

Z (Z_{eff})	Element	Mean life (ns)	Total capture rate (10^6/s)	Huff factor	Refs.
	Mn (con't)	232.5±2.0	3.857 ±0.037		a
26 (19.59)	Fe	201 ±4	4.53 ±0.10	0.975	40
		207 ±3	4.38 ±0.07		43
		206.7±2.4	4.40 ±0.05		49
		206.0±1.0	4.411 ±0.024		a
27 (20.13)	Co	188 ±3	4.89 ±0.09	0.971	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
48 (28.20)	Cd	95 ±5	10.1 ±0.5	0.921	40
		90.5±0.8	10.63 ±0.11		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)		61*f*
		87 ±4	(11.1 ±0.6)		63*f*
		77.3±0.3	(12.56 ±0.05)		67*f*
		84.0±4.5	(11.5 ±0.6)		68*f*
		78.5±2.0	(12.4 ±0.3)		71*f*

TABLE IV. (*Continued*).

Z (Z_{eff})	Element	Mean life (ns)	Total capture rate (10^6/s)	Huff factor	Refs.
92 (34.94)	$^{233}U^c$	61.7±3.8	(15.8 ±0.9)	0.820	62*f*
		68.5±0.7	(14.23 ±0.15)		71*f*
	$^{235}U^c$	78 ±4			56*e*
		75.4±1.9			57e
		75.0±0.7			66n
		71 ±2	(13.7 ±0.4)		74*Kγ*
		65.3±2.8	(14.9 ±0.6)		62*f*
		66.5±4.2	(14.7 ±1.0)		61*f*
		75.6±2.3	(12.9 ±0.4)		63*f*
		72.9±0.9	(13.3 ±0.2)		58*f*
		72.8±0.6	(13.36 ±0.12)		71*f*
		71.6±0.6	(13.58 ±0.12)		26*f*
	$^{236}U^c$	70 ±2	(13.9 ±0.4)		74*Kγ*
	$^{238}U^c$	88 ±4			40e
		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)		74*Kγ*
		74.1±2.8	(13.1 ±0.5)		62*f*
		75.6±2.9	(12.9 ±0.5)		61*f*
		76.0±1.0	(12.8 ±0.2)		63*f*
		77.1±0.2	(12.60 ±0.04)		67*f*
		77.9±0.5	(12.46 ±0.09)		58*f*
		77.7±0.6	(12.50 ±0.10)		71*f*
		78.0±2.0	(12.4 ±0.4)		72*f*
		77.2±0.4	12.57 ±0.07		26*f*
93 (35.05)	$^{237}Np^c$	73.5±1.4		0.818	66n
		71.3±0.9	(13.6 ±0.2)		58*f*
		72 ±2	(13.5 ±0.4)		65*f*
94 (35.16)	$^{239}Pu^c$	77.5±2.0		0.816	56e
		73.4±2.8			57e
		74.5±0.5			66n
		74 ±14	(13.1 ±2.6)		64*f*
		70 ±3	(13.9 ±0.9)		65*f*
		70.1±0.7	(13.9 ±0.2)		58*f*
		67 ±8	(14.6 ±2.0)		75*f*
	$^{242}Pu^c$	81.1±0.7			66n
		75.4±0.9	(12.9 ±0.2)		58*f*
		79 ±5	(12.3 ±0.8)		65*f*

[a]Denotes the results of this experiment.

[b]*R*Pb denotes radiogenic lead (88% ^{206}Pb:9% ^{207}Pb:3% ^{208}Pb).

[c]For 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,

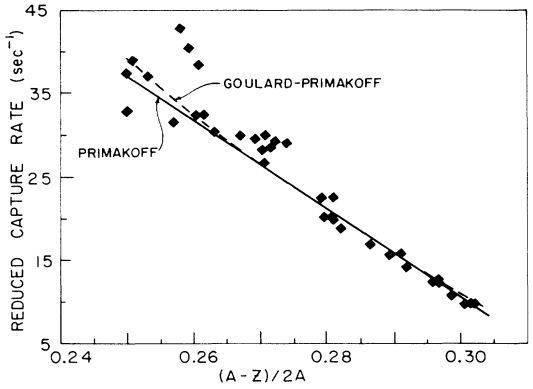

FIG. 4. The TRIUMF data are fitted to the Primakoff and Goulard-Primakoff formulae. The reduced capture rate is here defined as $\Lambda_c^{\text{expt}}/Z_{\text{eff}}^4$.

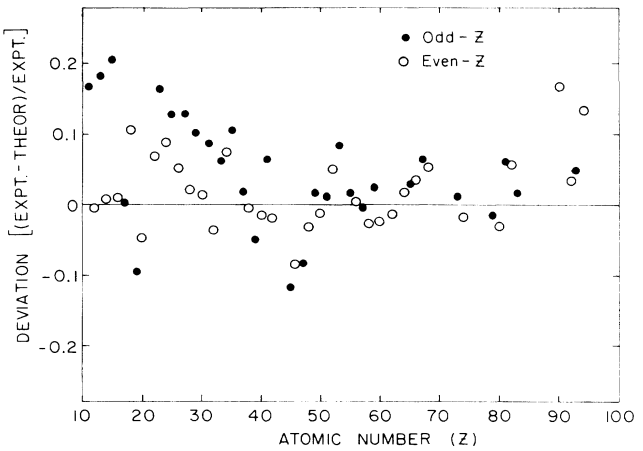

FIG. 5. Deviations of the experimental total capture rates from the Goulard-Primakoff best fit.

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 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 praesodymium seem to be part of the general phenomenon, and there is no need to search for exotic explanations.

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

V. CONCLUSIONS

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

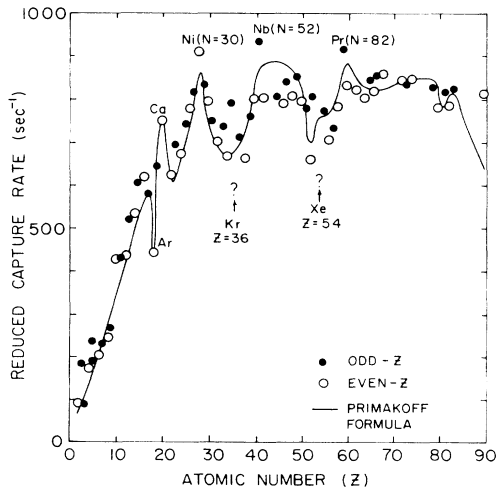

FIG. 6. Reduced total capture rates (i.e., $\Lambda_c^{\text{expt}} Z/Z_{\text{eff}}^4$) vs atomic number [adapted from Kohyama and Fujii (Ref. 12)]. The solid line represents the Primakoff formula, but it has been smoothed; therefore comparisons for individual elements might be erroneous.

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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