Muons capture on light isotopes in Double Chooz

M Strait1, *
(For the Double Chooz Collaboration)

1 The Enrico Fermi Institute, The University of Chicago, Chicago, Illinois 60637, USA
(Dated: August 9, 2016)

Using the Double Chooz reactor neutrino detector, we have measured the products of $\mu^-$ capture on $^{12}$C, $^{13}$C, $^{14}$N and $^{16}$O. Over a period of 490 days, we collected $2.3 \times 10^6$ stopping cosmic $\mu^-$, of which $1.8 \times 10^5$ captured on these nuclei in the inner detector. The resulting isotopes were tagged using prompt neutron emission (when applicable), the subsequent beta decays, and, in some cases, $\beta$-delayed neutrons. Production of these $\beta n$ isotopes, primarily $^9$Li, which are $\beta$-background components, was found at a significance of 5.5σ. The probability of $^6$Li production per capture on $^{12}$C is $(2.4 \pm 0.9 \text{ (stat)} \pm 0.1 \text{ (syst)}) \times 10^{-3}$. We have made the most precise measurement of the rate of $^{12}$C($\mu^-,\nu)^{11}$B to date, $6.57^{+0.35}_{-0.21} \times 10^3 \text{ s}^{-1}$, or $(17.35^{+0.35}_{-0.35})\%$ of nuclear captures. By tagging excited states emitting gammas, the ground state transition rate to $^{12}$B is found to be $5.68^{+0.14}_{-0.21} \times 10^3 \text{ s}^{-1}$.

PACS numbers: 25.30.Mr, 27.20.+n, 14.60.Pq

A stopped $\mu^-$ is rapidly captured by an atom. From here, a muon can either decay or undergo nuclear capture. This process is the muon analog to the electron capture decay that proton-rich isotopes undergo. However, muon capture is always energetically favorable. The large mass of the muon makes available a wide variety of final states. In addition to converting a proton to a neutron, nucleons can be ejected from the nucleus [1]. Measurements of the probabilities of these various states are useful for reactor neutrino experiments because they form backgrounds to the inverse beta decay reaction. Our measurements also provide input for understanding nuclear structure and can be used to validate models of neutrino cross sections [2].

We use 489.5 days of far detector data. The detector has been described in detail elsewhere [3]. In brief, it consists of four concentric liquid zones and an outer veto of plastic scintillator. It is under a hill with 300 m.w.e. overburden. The muon rate through the liquid volumes is 40 Hz, of which about 0.3% stop in the inner detector scintillator.

Double Chooz can be used to monitor several signals associated with muon capture: (1) the muon track (2) $\gamma$ from nuclear de-excitation of the daughter nucleus $\mu^-$ stops at the stop position (3) capture of neutrons from nuclear de-excitation of the daughter nucleus $\mu^-$ stops at the stop position (4) $\beta$ or $\beta n$ decay of daughter nucleus, 10 ms - 10 s capture of neutron from $\beta n$ decay.

The most common isotope in Double Chooz is $^{12}$C, but $^{13}$C, $^{14}$N, and $^{16}$-18O are also present in relevant quantities. (There is also hydrogen, but it never captures $\mu^-$ in compounds.) Daughters can therefore include any isotope produced by removing zero or more nucleons from $^{18}$N.

* E-mail address: strait@hep.uchicago.edu. Now at the University of Minnesota: strait@physics.umn.edu.

FIG. 1. $^{12}$B data and fits used to find probabilities.

TABLE I. $^{12,13}$B results. $N_{\mu^-}$ is the error from $\mu^-$ counting, $P_{\text{cap}}$ is the error from the total capture rate.

| Reaction | Prob. | Total | Stat. | $N_{\mu^-}$ | $^{12}$B eff. | $P_{\text{cap}}$ |
|----------|-------|-------|-------|------------|--------------|---------------|
| $^{12}$C$\rightarrow^{12}$B | $17.35^{+0.35}_{-0.35}$ | $-0.21$ | $\pm 0.13$ | $\pm 0.13$ | $\pm 0.21$ |
| $^{13}$C$\rightarrow^{13}$B | $51.6 \pm 5.6$ | $\pm 5.0 \pm 0.4$ | $\pm 2.6$ |
| $^{13}$C$\rightarrow^{13}$B | $< 40$ | 90% CL |

I. $^{12}$B

Previous experiments have measured $^{12}$B production by stopping muons in carbon, but none have been able to separate production by $^{12}$C and $^{13}$C [1, 4]. We can distinguish between these by observing the neutron when the parent is $^{13}$C. Production of $^{13}$B forms a background.

A stringent selection of stopping muons is used to prevent contamination by through-going muons. Selected events and fits are shown in Fig. 1 and Table I. The most recent measurement of any of these...
processes comes from Ref. [4], in which the probability per atomic capture for $^{12}\text{C}$ is, after correcting a calculation mistake [5], $(1.51 \pm 0.07)\%$.

II. $\beta n$ ISOTOPES

Double Chooz is optimized to detect $\nu_e$ via inverse beta decay, $p(\nu_e, e^+)n$. A delayed coincidence is formed between the positron and the capture of the neutron. A major background is $^9\text{Li}$ formed by muons; its $\beta n$ decay is nearly indistinguishable from inverse beta decay. The existing $\nu_e$ selection is used to select $\beta n$ decays, both for events with captures on gadolinium and hydrogen [3, 6]. An excess is found near stopping muons in time and space. Fifteen events are selected within 300 mm and 400 ms of stopping muons. Time distributions are shown in Fig. 2a(b) for any number of neutrons (one neutron) following the muon. The flat background, due almost entirely to reactor neutrinos, arises from accidental coincidences.

With no neutron requirement, the time distribution is fit using an unbinned maximum likelihood [7] under the hypothesis that there are several $\beta n$ isotopes (half-lives given): $^{11}\text{Li}$ (8.75 ms), $^{13}\text{B}$ (17.3 ms), $^8\text{He}$ (119 ms), $^7\text{Li}$ (178 ms), $^{16}\text{C}$ (747 ms), and $^{17}\text{N}$ (4.18 s). The fit is done in three bins of reactor power to take advantage of the lower background during zero- and one-reactor periods.

![FIG. 2. Observation of $\beta n$ events. (a) With no neutron requirement. (b) Requiring exactly one neutron.](image)

There is a $5.5\sigma$ preference for a $\beta n$ signal. The significance of $^9\text{Li}$ and $^8\text{He}$, specifically, is $2.7\sigma$. According to neuron features. Those with a neutron are compatible with the expected rate of $^{18}\text{O}(\mu^-, \nu)\text{Li}$. The amount of $^9\text{Li}$ in the two samples is incompatible with the hypothesis of $^{12}\text{C}(\mu^-, \nu_\alpha)\text{Li}$ at 2.7$\sigma$, indicating that $^{13}\text{C}(\mu^-, \nu_\alpha)\text{Li}$ most likely is responsible.

![FIG. 3. Sample $^{12}\text{B}_7$ spectrum. Selected events, estimated backgrounds, and the overall fit are shown.](image)

| Reaction            | Probability/capture |
|---------------------|---------------------|
| $^{12}\text{C}(\mu^-, \nu_\alpha)\text{He}$ | <0.43%              |
| $^{12}\text{C}(\mu^-, \nu_\alpha)\text{He}$ | <0.47%              |
| $^{12}\text{C}(\mu^-, \nu_\alpha)\text{He}$ | 7 x 10^{-4}        |
| $^{12}\text{C}(\mu^-, \nu_\alpha)\text{He}$ | <8 x 10^{-4}       |
| $^{12}\text{C}(\mu^-, \nu_\alpha)\text{Be}$ | 3.2 x 10^{-5}      |
| $^{12}\text{C}(\mu^-, \nu_\alpha)\text{Li}$ | (0.64 ± 0.04(stat) ± 0.02(syst))% |
| $^{12}\text{C}(\mu^-, \nu_\alpha)\text{Be}$ | <20%                |
| $^{12}\text{C}(\mu^-, \nu_\alpha)\text{Li}$ | (17.35 ± 0.3(stat) ± 0.27(syst))% |
| $^{12}\text{C}(\mu^-, \nu_\alpha)\text{Li}$ | <7 x 10^{-4}       |
| $^{12}\text{C}(\mu^-, \nu_\alpha)\text{Li}$ | 2.4 x 10^{-4}      |
| $^{12}\text{C}(\mu^-, \nu_\alpha)\text{Li}$ | (2.4 ± 0.9(stat) ± 0.05(syst))% |
| $^{12}\text{C}(\mu^-, \nu_\alpha)\text{Li}$ | <7%                 |
| $^{12}\text{C}(\mu^-, \nu_\alpha)\text{Li}$ | 20%                 |
| $^{12}\text{C}(\mu^-, \nu_\alpha)\text{Li}$ | (51.6 ± 5.0(stat) ± 2.6(syst))% |
| $^{12}\text{C}(\mu^-, \nu_\alpha)\text{Li}$ | <40%                |
| $^{12}\text{C}(\mu^-, \nu_\alpha)\text{Li}$ | <3.6%               |
| $^{12}\text{C}(\mu^-, \nu_\alpha)\text{Li}$ | <0.16%              |
| $^{13}\text{C}(\mu^-, \nu_\alpha)\text{Li}$ | <9 x 10^{-4}       |
| $^{13}\text{C}(\mu^-, \nu_\alpha)\text{Li}$ | <0%                 |
| $^{13}\text{C}(\mu^-, \nu_\alpha)\text{Li}$ | <8 x 10^{-4}       |

TABLE II. Probabilities per nuclear muon capture. Limits are at 90% CL. The $^9\text{Li}$ results assume no $^8\text{He}$, and $^{13}\text{C}(\mu^-, \nu_\alpha)\text{Li}$ assumes no $^{12}\text{C}$ contribution.
TABLE III. Transition rates to each bound $^{12}$B level.

| Daughter Rate ($10^3$ s$^{-1}$) |
|---------------------------------|
| $^{12}$B(total) 6.57$^{+0.07}_{-0.06}$(stat) ± 0.07(syst) |
| $^{12}$B(g.s.) 5.68$^{+0.13}_{-0.12}$(stat) ± 0.06(syst) |
| $^{12}$B*(953) 0.31$^{+0.09}_{-0.07}$(stat) ± 0.01(syst) |
| $^{12}$B*(1674) 0.06$^{+0.04}_{-0.03}$(stat) ± 0.003(syst) |
| $^{12}$B*(2621) 0.47$^{+0.06}_{-0.05}$(stat) ± 0.01(syst) |

Many other isotopes were also searched for. A summary of results is shown in Table II.

III. EXCLUSIVE STATES OF $^{12}$B

When $^{12}$B is formed in an excited state, we observe gammas from its de-excitation, as shown in Fig. 3. This allows measurements of the rate of transition to excited states and, by subtraction, of the ground state. Because Double Chooz has good gamma containment, each state is identified unambiguously, despite the “unbelievably capricious” [1] arrangement of levels that has plagued earlier measurements. Results for $^{12}$B are shown in Table III and are compared to previous work in Fig. 4.

IV. SUMMARY

The probabilities of muon capture reactions on carbon, nitrogen and oxygen have been measured. The reactions $^{12}$C($\mu^-$, $\nu$)$^{12}$B$^*\nu$ have been observed before; more precise results are reported. Others have been observed, or had limits set, for the first time.

[1] D. F. Measday, Phys. Rept. 354, 243 (2001).
[2] F. Krmpotić, A. Samana, and A. Mariano, Phys. Rev. C 71, 044319 (2005).
[3] Y. Abe et al. (Double Chooz), JHEP 10, 086 (2014), arXiv:1406.7763 [hep-ex].
[4] E. J. Maier, R. M. Edelstein, and R. T. Siegel, Phys. Rev. 133, B663 (1964).
[5] Y. Abe et al. (Double Chooz), Phys. Rev. C93, 054608 (2016), arXiv:1512.07562 [nucl-ex].
[6] Y. Abe et al. (Double Chooz), JHEP 1, 163 (2016), arXiv:1510.08937 [hep-ex].
[7] R. Barlow, Nucl. Inst. Meth. Phys. Res. A 297, 496 (1990).
[8] M. Fukui, T. Sato, H. Ohtsubo, M. Morita, and K. Koshigiri, Prog. Theor. Phys. 70, 827 (1983).
[9] M. Fukui, T. Sato, H. Ohtsubo, M. Morita, and K. Koshigiri, Prog. Theor. Phys. 78, 343 (1987).
[10] A. C. Hayes and I. S. Towner, Phys. Rev. C61, 044603 (2000), arXiv:nucl-th/9907049 [nucl-th].
[11] A. R. Samana, D. Saude, and F. Krmpotić, AIP Conference Proceedings 1663, 120003 (2015).
[12] G. H. Miller, M. Eckhause, F. R. Kane, P. Martin, and R. E. Welsh, Phys. Lett. B41, 50 (1972).
[13] L. P. Roesch et al., Phys. Lett. B107, 31 (1981).
[14] M. Giffon et al., Phys. Rev. C24, 241 (1981).