Gamma-rays from Muon Capture in $^{14}$N

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Abstract

Many new $\gamma$-rays have been observed, following muon capture on $^{14}$N. One had been reported before, and the low yield is confirmed, indicating that the nuclear structure of $^{14}$N is still not understood. Gamma-rays from $^{13}$C resulting from the reaction $^{14}$N($\mu^-,\nu n$)$^{13}$C compare favourably with states observed in the reaction $^{14}$N($\gamma,p$)$^{13}$C. More precise energies are also given for the 7017 and 6730 keV $\gamma$-rays in $^{14}$C.

Key words: muon capture, $^{14}$N, gamma-rays

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1 Introduction

Muon capture had been shown to be an excellent reaction for studying isovector magnetic transitions in light elements. The weak interaction aspects of the reaction are well understood, at the level of a few percent; this is far better than the nuclear structure uncertainties, which can be a factor of 2, or even greater. A recent survey was carried out by Gorringe et al.[1,2] for the targets of $^{23}$Na, $^{24}$Mg, $^{28}$Si, $^{31}$P, and $^{32}$S. They showed that the muon capture transition rates are similar to those observed in the (n,p) reaction, but cannot be reproduced very well by calculations based on the OXBASH code [3] for nuclear structure in the 2s-1d shell. Brown and Wildenthal [4] obtained the universal SD interaction, used in this code, by fitting 440 energy levels in the 2s-1d shell.

For 1p shell nuclei the situation is better on the whole. Muon capture on $^{12}$C has been reproduced by the recent calculations of Hayes and Towner [5] and Volpe et al.[6], and $^{16}$O seems to be reasonably understood too, as indicated by the work of Haxton and Johnson[7] and Warburton et al.[8]. However these are recent calculations using quite complex descriptions of the A=12 and A=16 nuclei. The case of $^{14}$N remains one of the more puzzling examples amongst light nuclei. The experiment of Giffon et al.[9] is the most recent experiment of muon capture on $^{14}$N, and they observed only one $\gamma$-ray, viz the one at 7017 keV, which is the ground state transition from the 7019 keV level (the difference in energy is because the recoil energy is quite significant for such a high energy gamma and a light nucleus). Now Giffon et al.[9] obtained a capture rate to this level of $4640 \pm 700$ s$^{-1}$ which is equivalent to a yield of $(7.0 \pm 1.2)\%$ per muon capture. Earlier measurements of this capture rate were slightly higher but of lower accuracy, and will be discussed later. We take the total muon capture rate to be $(66 \pm 5) \times 10^3$ s$^{-1}$, taking an average of three inconsistent measurements [10].

There are three calculations of the capture rate to the 7019 keV level; Mukhopadhyay [11] obtained a value of 20,000 s$^{-1}$ (i.e. a yield of 30 % !!). He used the Cohen-Kurath model for 1 p shell nuclei, and harmonic oscillator radial wave functions. Mukhopadhyay realized that the calculated rate was unrealistic and so estimated that the $(2s-1d)^2$ excitations in the 7019 keV level could reduce the rate to $\approx 9700$ s$^{-1}$, which is better but still somewhat high. A later calculation by Desgrolard et al. [12] confirmed that in the Cohen-Kurath model, the capture rate is $\approx 23,000$ s$^{-1}$, and the addition of exchange currents reduces the rate by only 20 % which is far from sufficient [13]. Thus it is clear that for $^{14}$N, these calculations are in serious disagreement with experiment even though there is no major problem with other nuclei (apart from $^{11}$B which is
also an ongoing problem [14]). These calculations were for the allowed transitions, i.e. the $1^+$ transitions which, from the $1^+$ ground state of $^{14}\text{N}$, excite the $^{14}\text{C}$ ground state ($0^+$), the 6589 keV level ($0^+$) and the 7019 keV level ($2^+$), under discussion. Two other unbound levels are also fed, a $2^+$ at 8.3 MeV and a $1^+$ at 11.3 MeV with a calculated rate of $\approx 1.3 \times 10^3$ (yield of $\approx 2\%$).

Many other reactions excite these same levels; for example $(d,^2\text{He})$, $(\pi^-,\gamma)$, and $(n,p)$. The best comparison is probably the $(d,^2\text{He})$ reaction, but unfortunately no data exists. The $(\pi^-,\gamma)$ reaction has been studied with an energy resolution of 720 keV [15] and clear structure is observed at 7.0, 8.3, 10.7, 15.4, and 20 MeV excitation energy. Only the first peak is bound and thus all the possible transitions to the 6 excited bound states are not resolved. The $(\pi^-,\gamma)$ reaction has been reviewed in general by Gmitro et al. [16] and the reaction $^{14}\text{N}(\pi^-,\gamma)$ in particular has been analyzed by Kissener et al. [17,18]. Now the $(\pi^-,\gamma)$ reaction proceeds mainly from the 2p atomic state and only a small fraction from the 1s state, depending on the mass; for $^{14}\text{N} R_p/R_n = 5:1$. Because the 2p state adds a $1^-$ to the initial state $J^\pi$ conditions, $2^+$ and $3^+$ transitions are more prominent. Thus a direct comparison between the $(\pi^-,\gamma)$ and $(\mu^-,\nu)$ reactions is hazardous, but if a calculation has addressed both reactions, one can have more confidence in that approach. Similarly the $(n,p)$ reaction can be used for another valuable comparison. The reaction $^{14}\text{N}(n,p)^{14}\text{C}$ has been studied at 59 MeV by Needham et al. [19] and at 280 MeV by a group at TRIUMF [20], both with an energy resolution of about 1 MeV. Together these experiments give an excellent and consistent picture of the situation. The TRIUMF data at $0^\circ$ show levels at 7.0 MeV ($2^+, 46\%$); 8.3 MeV ($2^+, 36\%$); 10.4 MeV ($2^+, 8\%$); and 11.3 MeV ($1^+, 10\%$). The $J^\pi$ of each level is given, as is the contribution to the $0^\circ$ strength (roughly $B(\text{GT})$). Note that the group also has complementary and consistent data on the $(p,n)$ and $(p,p')$ reactions. The Needham et al. results are compatible, with figures illustrating data at 16$^\circ$, 18$^\circ$, and 48$^\circ$, which show levels excited at 7.0, 8.3, 11.3, 15.4 MeV and a double peaked giant resonance at about 20.4 MeV. The angles of 16$^\circ$ and 18$^\circ$ correspond best to a momentum transfer of the $(\mu^-,\nu)$ reaction, although 59 MeV is a little low in bombarding energy. The main conclusion from all these reactions is that the $1^+$ transition strength is much more distributed than that calculated in the Cohen-Kurath model.

We thus come to the final calculation of the $^{14}\text{N}(\mu^-,\nu)^{14}\text{C}$ reaction, that by Kissener et al. [21]. They were analyzing both the $(\mu^-,\nu)$ and the $(\pi^-,\gamma)$ reactions, and hence were more aware of the pitfalls. In particular they knew that $(e,e')$ scattering had shown that the $1^+$ strength to $2^+$ levels was split about equally between the bound level at 7019 keV, and an unbound one at 8.3 MeV. In the Cohen-Kurath model, the bound level takes almost all the strength. However Kissener et al. split the strength, apparently phenomeno-
logically, and not by introducing 2p-2h excitations in their calculation. This calculation resulted in a yield of 11% to each of these levels, and explains at least one factor of 2. The other important feature of their calculation is that they address all the possible transitions, including high energy excitations in $^{14}\text{C}$ which decay via neutron emission to levels in $^{13}\text{C}$ and $^{12}\text{C}$. Although the results of the calculations do not correspond in every detail to the observations in the present experiment, at least a good overall picture is given. Thus for example Kissener et al. show that the $^{14}\text{C}$ ground state is only weakly fed in direct transitions by the $(\mu^- , \nu)$ reaction, and this is related to the slow beta decay rate of $^{14}\text{C}$. Kissener et al. also find that the sum of transitions to bound levels of $^{14}\text{C}$ is 15%; for higher energy excitations in $^{14}\text{C}$, they estimate that the yield is 42% to bound levels of $^{13}\text{C}$, and 40% to bound levels of $^{12}\text{C}$. The rest is made up of charged particle emission ($\approx 3\%$), which is probably a low value ($\approx 15\%$ is more common). Note that Kissener et al. calculated the total muon capture rate to be $109 \times 10^3 \text{ s}^{-1}$ compared to the experimental value of $(66 \pm 5) \times 10^3 \text{ s}^{-1}$, but by presenting their results as yields per capture, they circumvent that problem.

For the reaction $^{14}\text{N}(\mu^- , \nu n)^{13}\text{C}$, one can envisage two reaction modes. One is a direct knock-out term, similar to the pole-term seen in the $(\pi^- , \gamma)$ reaction. The levels observed in $^{13}\text{C}$ would thus correspond to levels excited in reactions such as $(d,^3\text{He}), (p,2p)$ or $(e,e'p)$. The spectroscopic factors for these reactions are very similar. An alternative description of muon capture would be in terms of an excitation of a spin-dipole giant resonance (mainly $2^-$ and some $1^-$), followed by a de-excitation similar to the $(\gamma,p)$ reaction. Of course the $(\gamma,p)$ reaction goes via the E1 giant dipole resonance, which is at a similar but not identical energy. The comparison between the knock-out and excitation models has been discussed in some detail in a recent review of muon capture [22]. There is not a lot of difference between the observable effects, but as long ago as the muon capture work of Miller et al. [23] in 1972 on $^{28}\text{Si}$, it was shown that the $(\gamma,p)$ reaction is a better analogue. Of course there will be some knock-out component, especially when a high energy neutron is produced in muon capture, but this represents only 10% to 20% of neutron production. The data for the reaction $^{14}\text{N}(\gamma,p)$ are limited, but we shall make a fruitful comparison.

One unresolved problem in muonic nitrogen is the hyperfine effect. For nuclei with spin, the $1s$ state in a muonic atom is split into two hyperfine levels, which can be a few eV to $\approx 1$ keV apart in energy. The M1 transition is too slow to be important, but Telegdi and Winston and co-workers at Chicago [24,25] showed that Auger emission can speed up the transition rate to time scales of $\approx \mu$s in light elements, and $\approx \text{ns}$ in heavy elements. The best example is $^{19}\text{F}$ which was studied by the Chicago group and has been confirmed several
times since [26]. The case of $^{14}$N is quite perplexing because a depolarization was observed in $\mu^-$-SR by Ishida et al.[27]. Although some of the effect was attributed to external electromagnetic fields, the residual was ascribed to a hyperfine transition rate of $(0.076 \pm 0.033) \ \mu s^{-1}$, i.e. $\tau \approx 13 \ \mu s$. Now Winston[25] calculated the muonic hyperfine rate, via a simple atomic model of electron ejection, and his model fits every known example, especially $^{19}$F. For $^{14}$N the prediction is that there should be no effect, because the separation of the hyperfine energy levels is 7.4 eV, whereas in the carbon atom, the least bound electron is bound by 11.3 eV, i.e. the ionization potential. (the $\mu^-$ is well within the inner electrons, so the muonic $^{14}$N system appears to be a $^{14}$C nucleus to the atomic electrons). If the pseudo $^{14}$C atom has formed a “C”N bond, the ionization potential is 14.3 eV, which makes Auger emission even less likely. Thus it is possible that Ishida et al.[27] observed other depolarization mechanisms. We note that Wiaux [14], using a muon capture technique for $^{11}$B, observed a slower hyperfine transition rate than that observed in a $\mu^-$-SR experiment. We have searched for hyperfine effects in $^{14}$N, but because the supposed time constant is long, it is difficult to detect, and our observations are inconclusive. Thus we shall assume that our capture rates are for a statistical mixture of the two hyperfine states. However even if there were a slow hyperfine transition, the effect on our results would be smaller than the errors.

Thus muon capture in $^{14}$N exhibits many interesting effects. Our experiment was proposed in order to obtain some more relevant observations. One great advantage of $^{14}$N is that there are only a few bound levels in $^{14}$C, $^{13}$C, and $^{12}$C. Thus we are able to make a complete analysis of all possible transitions for these nuclei.

2 Experimental Method

The experimental technique is well established, and has been described in several previous publications [1,2]. Details can be found in the thesis of Stocki[26]. We shall limit ourselves to the more important features.

The experiment was performed on the M9B channel at the TRIUMF cyclotron. The beam line includes a 6 m, 1.2 T superconducting solenoid in which 90 MeV/c pions can decay. The resulting backward muons are then selected by a bending magnet and pass through a collimator into the experimental area. The collimator was made out of lead bricks, but faced with 13 mm of polyethylene to minimize background neutrons and $\gamma$-rays. The beam rate was about $2 \times 10^5 \ \text{s}^{-1}$, with a pion contamination of $< 0.2 \ %$ and an electron contamination of $\approx 20 \ %$. Three plastic scintillators defined a muon
stop, the defining counter being 51 mm in diameter.

The target was liquid nitrogen contained in a styrofoam box, internal dimensions 215 mm (beam direction) \(\times\) 195 mm \(\times\) 550 mm. The length in the beam direction was more than sufficient to stop the muons, so the veto counter behind the target was effectively redundant. A mu-metal shield was immersed in the liquid nitrogen to reduce the ambient magnetic field from 1.5 gauss to 0.1 gauss. This minimized spin precession effects.

To detect the \(\gamma\)-rays from muon capture, two high purity germanium detectors (HPGe) were placed opposite each other at 90° to the beam direction. Both detectors were n-type detectors to minimize radiation damage. The largest was Ge1, a 44% detector, with an in-beam energy resolution of 2.53 keV at 1.3 MeV and a timing resolution of 6 ns. The other, Ge2, was a 21% detector, with an in-beam energy resolution of 2.19 keV at 1.3 MeV, and a timing resolution of 7 ns. Their front windows were 27.5 cm and 33.1 cm away from the centre of the target, respectively. In front of each was a plastic scintillator to tag electron events. Each HPGe was surrounded by a Compton suppressor, composed of a segmented NaI(Tl) annulus. In this experiment the suppressors were implemented in software mode, so single and double escape peaks were in fact observed, so we were able to take advantage of that feature.

The electronics consisted of spectroscopic amplifiers and timing filter amplifiers, followed by constant fraction discriminators (CFD). An event was defined by a pulse in a germanium detector, and then tags from the electron counters, and pulse height information from the Compton Suppressors were also recorded. Events from a delayed muon stop were then sent to a router for 10.8 \(\mu\)s. This device can accept up to 4 pulses and route them to four distinct TDCs. Thus one can identify events with only one candidate muon, from those with two, three, or even four muon stops in the previous 10.8 \(\mu\)s. Typically 15% of events have two muon stops, which made selection of events problematic, for determination of lifetimes. Two methods were used; one selecting events with only one muon stop, the other accepting all events. Accepting the first muon, whether or not it was followed by another muon, created a clearly distorted time spectrum.

The energy calibration of the detectors was carried out by a variety of techniques. Offline \(^{152}\)Eu and RdTh sources were useful. The \(\gamma\)-ray energies were known to a better than 10 eV which is far more accurate than is needed. Of course the beam on conditions are somewhat different, and calibrations at a much higher energy were required. The spectra were divided into 3 regions.
(low, medium, and high energy) and it was found that, in each region, linear fits for the energy calibration were quite adequate. The beam-on calibrations that were used are listed in Table 1. Note that the \((n,\gamma)\) lines are room background and not due to the liquid nitrogen target, but they are narrow lines and therefore are convenient for calibration purposes, especially as the energies are known to 0.1 keV in a region with few calibration lines. Also noticeable is the \(\gamma\)-ray from \(^{16}\text{N}\) \(\beta\)-decay, coming from the irradiated cooling water in the nearby quadrupoles. It has an energy of 6,129,140(30) eV\(^{36}\) whereas several compilations seem to use the erroneous excitation energy of \(E_x = 6,129,893(40)\) eV and a \(\gamma\)-ray energy of 6,128,630(40) eV \(^{37,38}\). We note that we have used the single and double escape peaks with energy differences of 511.00 and 1022.00 keV respectively. This is unreliable and the actual difference can be 0.1 to 0.3 keV less, depending on the detector \(^{35-39}\). Because our lines are Doppler broadened, such small calibration errors were not studied. Higher precision work would need to take this effect into account.

The efficiency of the germanium detectors was determined offline with calibrated sources, and online using muonic X-rays. An excellent target for this purpose is gold, and the emission probabilities are given in Table 2. The 2p-1s intensities were taken from Hartmann \textit{et al.}\(^{40}\) and the others from a Muon Cascade Program \(^{41}\). The efficiency curve for Ge2 is presented in Figure 1. The individual values were fitted to a curve of the form:

\[ Efficiency = a_1E^{a_2} + a_3e^{-a_4E} + a_5e^{-a_6E} + a_7e^{-a_8E} \]

(1)

where \(E\) is the photon energy and \(a_i\) are parameters for the fit. This gives an adequate fit over the whole energy region.

### 3 Data Analysis

Because there are a limited number of \(\gamma\)-rays which can be produced in muon capture in \(^{14}\text{N}\), it was not too difficult to identify the various lines, using the known transitions. However, many other transitions were also observed including: muonic X-rays in C, N, Fe, and Ni; \((n,n')\) lines from N, Al, Fe, Ge, and Pb; \(\beta\)-decay lines from \(^{16}\text{N}, \text{\text{22}Na}, \text{\text{41}Ar}, \text{\text{60}Co}\), and as mentioned before \((n,\gamma)\) capture \(\gamma\)-rays from H, N, Al, Cl, Fe, Ge, and In. Over 150 lines were identified, most with confidence. This was done to ensure that we had not missed a candidate line from muon capture. The reason that so many background lines occur is twofold. First in \(^{14}\text{N}\) only 12.7(8)\% of muons capture, the rest decay. Secondly, because of the longer muon lifetime, the \(\gamma\)-ray gate has to be kept open for \(\approx 10 \mu s\), whereas for an element like Ca a gate of only 1.7
$\mu$s is needed. This makes the $^{14}$N spectra about 50 times more vulnerable to background lines than those for Ca.

Another difficulty in $^{14}$N is that the muon capture lines are Doppler broadened as they are often emitted while the $^{14}$C recoils after the neutrino emission. This broadening is box shaped and amounts to 14 keV per MeV $\gamma$-ray energy, i.e. about 100 keV for a 7 MeV $\gamma$-ray. A few energy levels in $^{14}$C and $^{13}$C are long lived with respect to the slowing down time ($\approx$ 1 ps), and then the $\gamma$-rays are narrow peaks. In $^{13}$C the 3684 keV line is Doppler broadened by the neutrino emission and then again by neutrons of various energies. Empirically we found a triangular shape fitted the observed line.

The box shaped spectra were fitted to the formula:

$$y(x) = \frac{N}{2} \left[ \text{erf} \left( \frac{E(1+\beta)-x}{\sqrt{2}S} \right) - \text{erf} \left( \frac{E(1-\beta)-x}{\sqrt{2}S} \right) \right] + Ax + B$$  

(2)

where E is the centroid of the peak, $\beta$ is the recoil velocity divided by the speed of light ($\approx$ 0.0075), S is the parameter accounting for the HPGe energy resolution, N is the overall amplitude, and A and B are background terms.

A typical fit to the full energy peak of the 7017 keV peak is shown in Figure 2. This line is fortunately free from background $\gamma$-rays and the yield is easy to determine (note that there should be a very weak line from Cl(n,$\gamma$) as predicted by the Cl(n,$\gamma$) branching ratios, the effect of this line is subtracted out of the 7017 keV $\gamma$-ray yield). The 6092 keV peak is much more complicated and two fits to this peak are illustrated in Figure 3. It is immediately clear that a spectrum with good statistics is required to fit such a complex structure. We observe two background lines superimposed on the $^{14}$C 6092 keV $\gamma$ -ray, the $^{35}$Cl(n,$\gamma$) at 6110.88 keV and the $^{16}$N $\beta$ decay line at 6129.14 keV, both fortunately are narrow peaks. At the centre of the structure is an interesting peak, due to $\gamma$-rays from the same $^{14}$C level at 6092 keV, but narrow because they come from cascades from higher, longer lived levels. The single escape peak is illustrated in Figure 4, and another background line is apparent, the 5592.2 keV line from $^{127}$I(n, $\gamma$) as well as the single escape peaks from all the other effects of Figure 3.

In Figure 5 is illustrated a fit to the $^{13}$C peak at 3685 keV. It is composed of a Doppler broadened component, and a central peak, again coming from a cascade from the long lived level at 3854 keV. The separation of these two components is more uncertain, as the shape of the Doppler broadened component
is purely a phenomenological assessment.

4 Results

From the various fits to the three $^{14}$C $\gamma$-rays (not all illustrated) we obtain the energies observed in this experiment, listed in Table 3. The $\gamma$-ray energies are corrected for the recoil correction (1.89, 1.74, 1.42 respectively) to obtain the energy of the excited state. This is compared with the compilation of Ajzenberg-Selove [29], and a study of the $^{13}$C(d,p)$^{14}$C reaction by Piskor and Schäferlingova [42]. Although this study was noted by Ajzenberg-Selove under Reaction 16, it was not integrated into her table of level energies which is the same as the 1986 compilation. Our results for the 6092 and 6730 keV levels agree, but the 7019 keV is inconsistent. We note again that no correction has been made for the escape peaks being slightly less than the 511 keV difference; our other errors are much larger.

As there is concern about the hyperfine transition, we fitted the time dependence of several $\gamma$-rays. The 3684 keV line in $^{13}$C has a high yield, but a complicated shape because of the cascading, see Figure 5. However hyperfine asymmetry effects have been seen in such cases, so a study of the time dependence was attempted. The yields of this $\gamma$-ray and of electron events were selected. Each time spectrum was then fitted to obtain a flat background, which was then subtracted off. Finally the ratio of these two subtracted spectra is illustrated in Figure 6. Even though about 7000 $\gamma$-ray events were obtained, it is clear that the study is inconclusive. The results are compatible with no hyperfine transition with $R(\gamma/e) = 4 \times 10^{-4}$, but could also be fitted with a significant asymmetry. Of course there is no guarantee that a particular transition, especially one from a ($\mu^-, \nu n$) reaction, will have a large asymmetry. It is clear that better statistics are needed, and also results from more lines. For the rest of the analysis we shall assume no hyperfine transition, and a statistical population of the hyperfine levels.

The yields of many lines have been studied by using the fitting techniques described above, using gaussian, box, or triangular fitting functions, where appropriate. In the cases where a limit was set the possible Doppler broadening of lines was taken into account, where appropriate. Windows were set on the expected position, and the nearby background was subtracted. No attempt was made to fit possible shapes as these are variable and uncertain. However that technique has the potential of setting slightly lower limits. In Table 4 we list the limits on various lines obtained using Ge1; also included are the lifetimes of the original levels [29,43,44]. Only 3 of these lines have positive
identification. The 4438 keV line in $^{12}$C can be caused by background from target induced neutrons in the plastic scintillators. We made a time study to eliminate background neutrons, but did not have enough information to estimate the contribution from target produced neutrons. Similarly $^{10}$B could have come from capture on beam scintillators. Note that we have no positive identification of $(\mu^-,\nu p)$ nor $(\mu^-,\nu\alpha)$ reactions (i.e. $^{13}$B or $^{10}$Be) with quite useful limits.

In Table 5 we present the results for the $^{13}$C and $^{14}$C $\gamma$-rays. Some of the $^{13}$C results are an average of Ge1 and Ge2, but those for $^{14}$C are for Ge1 only as the acceptance for Ge2 was too low to be useful. The fitting for the 3685 keV $\gamma$-ray finds that $(15.9 \pm 1.0)$% of the $\gamma$-ray yield is fed from the 3854 keV level via a 169 keV cascade (B.R. = 36.3%). This $\gamma$-ray was below threshold, but from the yield of the 3854 keV ground state transition, using the known branching ratio (62.5%), one can deduce that $(19 \pm 8 \%)$ of the 3685 keV yield is from the cascade, in agreement with the fitting procedure.

Equally well the $^{14}$C 6092 keV $\gamma$-ray has a complex structure. From the full energy peak we find that $(8.6 \pm 5.3)$ % of the yield is from cascade feeding; from the single escape peak the value is $(15 \pm 12 \%)$. Furthermore there is no evidence for a second Doppler broadened peak on the principal peak, which we use as evidence against feeding from the 7341 keV level. Equally well, the ground state transition for this 7341 keV level (B.R. = 16.7 \%) is not observed. Thus, for the 6092 keV $\gamma$-ray we assume any contribution from the 7341 level to be zero, and average the two central gaussian yields to obtain that a weighted average of $(10 \pm 6 \%)$ of the 6092 keV yield is cascading. Thus the direct feeding of the 6094 keV level is $(1.2 \pm 0.6\%)$ and the cascading $(0.12 \pm 0.08\%)$ per capture. Now we know the 6732 keV level is populated ($\tau = 66$ ps) and would contribute $(0.05 \pm 0.02\%)$ per muon capture to the 6092 keV $\gamma$-ray. This leaves $(0.07 \pm 0.08\%)$ which could be feeding from the 6589 keV level which has a branching ratio of 98.9\% for a cascade via 495.35 keV $\gamma$-ray. This $\gamma$-ray is not observed, but the limit is only $<0.049\%$ per muon capture. Thus our results are compatible with a feeding of $\approx 0.04\%$ which is expected in several calculations.

From these fitting procedures, and using other known branching ratios we obtain the direct feeding of all the levels. Table 6 presents the limits for complex reactions; Table 7 presents the results for $^{13}$C and $^{14}$C. Apart from the 7019 keV level in $^{14}$C, these are all new results. The sum of the yields to bound $^{14}$C levels is $(6.0 \pm 1.6\%)$ which agrees well with the $(\pi^-,\gamma)$ result of $(6.22 \pm 0.40\%)$ [15].
Our absolute yield for the 7019 keV level is lower than all previous results. Most have not been published and we have to rely on conference proceedings, reports, and the review of Mukhopadhyay [45]. These results, our own, and a recommended average are presented in Table 8. Note that we have used the rates from other experiments to calculate the yields; in an experiment it is done the other way but we do not have the original yields. As we had significant difficulty with our absolute normalization, we take the agreement to be satisfactory. Earlier unpublished results could have significant contributions from background lines and we know that Bellotti et al. had a serious contamination of unknown origin, see page 131 of Mukhopadhyay[44] (we do not observe any line at 6315 keV ). None of these results had the statistical accuracy, nor the energy resolution of our own data. Thus we combine our results with only the Saclay result to obtain a recommended yield of \((6.6 \pm 0.9)\)%, i.e. a rate of \((4390 \pm 580) \text{s}^{-1}\).

All the results for \(^{13}\text{C}\) and \(^{14}\text{C}\) are combined in Table 9, and compared with a variety of reactions, and theoretical calculations. The \(^{13}\text{C}\) level feeding is compared with the results for the reaction \(^{14}\text{N}(\gamma,p)\) [49,50]. We take the integrated cross section up to 29 MeV; the ground state and 7550 keV transitions are given by Gellie et al. [49], and the 3089, 3685, and 3854 keV levels are taken from Thompson et al.[50] who studied the \(\gamma\)-rays emitted during irradiation by 29 MeV bremsstrahlung. The \((d,^3\text{He})\) reaction has been studied by Hinterberger et al.[51] and the spectroscopic factor \(C^2S\) was found to be 0.8, 0.3, and 1.4 for the ground state, 3685, and 7550 keV states respectively; the feeding of the 3089 keV level is small ( \(C^2S \approx 0.05\) ) and the feeding of the 3854 keV level is not even detected. Thus the \((\gamma,p)\) reaction is a better analogue because the 3089 and 3854 keV levels are clearly detected in muon capture. Kissener et al.[21] predicted that the pattern of capture be close to the spectroscopic factors, with none feeding the 3089 and 3854 keV levels, in contradiction to experiment.

For \(^{14}\text{C}\), we compare with the calculation of Kissener et al.[21] for the \((\mu,\nu)\) reaction. Remember that the split between the 7019 keV level and the 8318 keV level is phenomenological. The calculation of Mukhopadhyay [11] was for only allowed transitions, i.e. \(1^+\) transitions to \(0^+, 1^+, 2^+\) states. The 28\% feeding of the 7019 keV was confirmed by Desgrolard et al.[12] for the Cohen-Kurath model. Mukhopadhyay estimated that the (2p-2h) contributions would roughly halve the transition rate; the other half would go to another \(2^+\) state and we have used this estimate in Table 9. Note that Mukhopadhyay gives transition rates, so we converted to yield using a total capture rate of \((66 \pm 5) \times 10^3 \text{s}^{-1}\). However Kissener et al. found a total capture rate of \(109 \times 10^3 \text{s}^{-1}\) and converted to yield themselves, so this difference probably explains why the sums for the yields of Mukhopadhyay are higher than those of Kissener et
It is clear, however, that even using the Saclay yield of \((7.0 \pm 1.0)\%\), the Kissener calculation is still overestimating the yield for the 7012 keV level. A major problem thus remains.

We also list in Table 9 the experimental results of Perroud \textit{et al.}\cite{15} for the \((\pi^-,\gamma)\) reaction at rest. As their resolution was only 720 keV all the bound levels are in one unresolved peak with a yield of 6.2(4)\% of all radiative capture. We also give the calculated yields of Kissener \textit{et al.}\cite{18} for the \((\pi^-,\gamma)\) reaction. These values have been estimated from the height of the bars in a figure, so are approximate. We can see that the calculation fits the experimental yields quite well, and both compare quite favourably with the \((\mu^-,\nu)\) reaction, even though only 17\% of the \((\pi^-,\gamma)\) captures are from the 1s state.

We can now estimate the overall situation for muon capture in \(^{14}\)N, using empirical information. If we renormalize our results up by 50\% to approach the Saclay yields, we suggest about 9(2)\% of muon captures give bound states in \(^{14}\)C and 14(3)\% produce bound excited states in \(^{13}\)C. The \((\gamma,p)\) reaction then implies about 32(8)\% direct feeding of the \(^{13}\)C ground state and 27(8)\% direct feeding of the \(^{12}\)C ground state via the 7.55 level in \(^{13}\)C. If we add 4\% feeding of the first excited state in \(^{12}\)C and 13\% for charged particles, we obtain a sum of 99(10)\%, which is reasonable. Note that this empirical approach is fairly similar to the theoretical estimate of Kissener \textit{et al.} viz. 15\% to bound levels of \(^{12}\)C, 42\% to bound levels of \(^{13}\)C and 40\% to bound levels of \(^{12}\)C with only 3\% charged particle emission.

5 Conclusions

We have provided a lot of new information about muon capture in \(^{14}\)N. The direct transitions to \(^{14}\)C are clearly detected with major feeding going to only three of the 7 bound levels. These three levels, at 6094, 6732, and 7019 keV have similar yields, yet the calculation of Kissener \textit{et al.} predicts that the 7019 keV should dominate. (Note that our relative yields are more dependable than the absolute values). It thus seems that the nuclear structure of the \(A = 14\) system is quite complex and 2p-2h excitations in the wave function make radical changes to the yields. Calculations along the lines of work in \(^{12}\)C \cite{5,6} and \(^{16}\)O \cite{7,8} would be really helpful.

Three \(\gamma\)-rays from \(^{13}\)C are observed and their pattern follows the \((\gamma,p)\) reaction yields better than the knock out reactions and their spectroscopic factors.
Even the \((\gamma,p)\) reaction is not a perfect analogue, and it would be interesting to have data on the integrated yield for lower energy bremsstrahlung \((\approx 24\ MeV\ or\ so)\).

Other \(\gamma\)-rays have been searched for but no convincing evidence found. The only line clearly detected was from the 4439\ keV state in \(^{12}\text{C}\), and it is certainly excited in muon capture, but it is also strongly excited by background mechanisms, so no useful estimate could be made (one would need extensive runs with carbon and boron targets to separate the various effects).

No \(\gamma\)-rays were observed from the reaction \(^{14}\text{N}(\mu^-,\nu p)^{13}\text{B}\) which is surprising. We obtained a limit of \(< 0.17\%\) for the first excited state at 3483\ keV. In other light nuclei this reaction has been clearly detected; for example Miller et al.\[23\] found that the reaction \(^{24}\text{Mg}(\mu^-,\nu p)^{23}\text{Ne}\) gives a yield of 0.20(5)\% for the 980\ keV \(\gamma\)-ray and 0.5(1)\% for the 1770\ keV line; similarly they observed for \(^{28}\text{Si}(\mu^-,\nu p)^{27}\text{Mg}\) a yield of 1.9(2)\% for the 984\ keV line. Our only comment is that the high energy of the first excited state in \(^{13}\text{B}\) may affect the yield adversely. Equally well Kissener et al. estimate a low yield for this reaction, but there is obviously some uncertainty in their estimate.

In heavy nuclei the reaction \((\mu^-,\nu pn)\) is stronger than the \((\mu^-,\nu p)\) reaction \[52\]. In \(^{40}\text{Ca}\) these reactions have equal \(\gamma\)-ray yields of about 6\% each \[53\]. Miller observed a yield of 4.4(6)\% in \(^{24}\text{Mg}\) and 10(1)\% in \(^{28}\text{Si}\). It is thus surprising that our limit for the first excited state of \(^{12}\text{B}\) at 953\ keV is \(< 0.27\%\).

The mass \(A=14\) system has retained its enigmatic status. In particular there is more than sufficient evidence that the Cohen-Kurath model is inadequate and that the nuclear structure is quite complex. A comprehensive theoretical study using modern computational technology would be most welcome.

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Fig. 1. The $\gamma$-ray acceptances for HPGe detector 2.

Fig. 2. The 7017 keV Doppler fit.
Fig. 3. Fits to the 6092 keV $\gamma$-ray. (top) with a sloping background (bottom) with a flat background i.e. $A=0$ in equation 2.
Fig. 4. The Doppler fit of the 6092 keV, single escape peak.

Fig. 5. The Doppler fit of the 3685 keV peak.
Fig. 6. The ratio of the 3684 keV $\gamma$-ray to the electron time spectra.
Table 1
Energies of γ-rays and muonic X-rays used as calibration for the HPGe detector

| Source                          | Energy (keV)        |
|---------------------------------|---------------------|
| Medium Energy                   |                     |
| Background from $^{14}$N(n,n'γ) | 5104.89 (10)        |
| $^{13}$C line from muon capture | 3853.194 (19)       |
| $^{228}$Th                      | 2614.533 (13)       |
| $\mu^{-}$ Au X-ray 3d$_{5/2}$ → 2p$_{3/2}$ | 2341.21(45)      |
| $\mu^{-}$ Au X-ray 2p$_{1/2}$ → 1s$_{1/2}$ | 5590.7(5)*         |
| $\mu^{-}$ I X-ray 2p$_{1/2}$ → 1s$_{1/2}$ | 3667.361 (35)   |
| $\mu^{-}$ I X-ray 2p$_{3/2}$ → 1s$_{1/2}$ | 3723.742(35)    |
| High Energy                     |                     |
| $^{56}$Fe(n,γ) [33–35]         | 7645.58 (10)        |
| $^{56}$Fe(n,γ) [33–35]         | 7631.18(10)         |
| Single escape of $^{56}$Fe(n,γ) | 7134.58(10)       |
| Single escape of $^{56}$Fe(n,γ) | 7120.18(10)       |
| Double escape of $^{56}$Fe(n,γ) | 6623.58(10)       |
| $^{14}$N(n,n'γ) [28]           | 5104.89(10)         |
| $\mu^{-}$ Au X-ray 2p$_{1/2}$ → 1s$_{1/2}$ | 5590.7(5)*        |

*These energies were taken from Figure 6 of [31].

Table 2
The muonic x-ray transition probabilities.

| Energy (keV) | Element | Transition | Probability     |
|--------------|---------|------------|-----------------|
| 102.4        | N       | 2p → 1s   | 0.70 ± 0.07     |
| 400.14       | Au      | 5g$_{9/2}$ → 4f$_{7/2}$ | 0.39 ± 0.06 |
| 405.654[30]  | Au      | 5g$_{7/2}$ → 4f$_{5/2}$ | 0.30 ± 0.06 |
| 869.98[30]   | Au      | 4f$_{7/2}$ → 3d$_{5/2}$ | 0.44 ± 0.04 |
| 899.14[30]   | Au      | 4f$_{5/2}$ → 3d$_{3/2}$ | 0.31 ± 0.04 |
| 2343.44[30]  | Au      | 3d$_{5/2}$ → 2p$_{3/2}$ | 0.52 ± 0.08 |
| 2474.22[30]  | Au      | 3d$_{3/2}$ → 2p$_{1/2}$ | 0.29 ± 0.08 |
| 5590.7[31]*  | Au      | 2p$_{1/2}$ → 1s$_{1/2}$ | 0.333 ± 0.019 |
| 5762.6[31]*  | Au      | 2p$_{3/2}$ → 1s$_{1/2}$ | 0.559 ± 0.032 |

*These energies were taken from Figure 6 of [31].
Table 3

$^{14}\text{C}$ $\gamma$-ray full energies (FE), single escape (SE) energies, and excited state energies in keV. Previous work is taken from the compilation by Ajzenberg-Selove [29] and the $^{13}\text{C}(d, p)^{14}\text{C}$ work of Piskor and Schäferlingova [42].

| Peak Type | Energy Type | Energy | Excitation Energy | Previous $^{13}\text{C}(d, p)^{14}\text{C}$ work [29] | $E_x$ [42] |
|-----------|-------------|--------|-------------------|---------------------------------|-------------|
| FE        | Full Energy | 7016.63(49) | Same              | 7012.0(42)                      | 7011.4(8)   |
| SE        | Single Escape | 6505.6(15) | 7016.6(15)        |                                 |             |
| Average   |             | 7016.6(13) | 7018.5(13)        | 7012.0(42)                      | 7011.4(8)   |
| FE        | Full Energy | 6729.68(18) | Same              | 6728.2(13)                      | 6731.58(11) |
| SE        | Single Escape | 6220.1(4) | 6731.1(4)         |                                 |             |
| Average   |             | 6729.9(10) | 6731.6(10)        | 6728.2(13)                      | 6731.58(11) |
| FE model 1 | Full Energy | 6092.4(13) | Same              | 6093.1(14)                      | 6094.05(11) |
| FE model 2 | Full Energy | 6092.2(11) | Same              | 6093.1(14)                      | 6094.05(11) |
| FE model 3 | Full Energy | 6088.2(22) | Same              | 6093.8(2)                       | 6094.05(11) |
| Average   |             | 6091.76(93) | Same              | 6093.1(14)                      | 6094.05(11) |
| SE        | Single Escape | 5580.4(17) | 6091.4(17)        |                                 |             |
| Average   |             | 6091.7(14) | 6093.1(14)        | 6093.8(2)                       | 6094.05(11) |
The γ-ray yield results for $^{12}$C and $^{10}$B and limits for $^{10}$Be, $^{12}$B, and $^{13}$B. Lifetimes of the initial levels are taken from Ajzenberg-Selove.[29,43,44]

| Gamma Energy | Yield/captured $\mu^-$ in (%) | Nuclide | Lifetime [29,43,44] |
|--------------|-------------------------------|---------|---------------------|
| 718.3 *      | 0.12 ± 0.04                   | $^{10}$B | 1020(5) fs          |
| 1021.7       | 0.13 ± 0.07                   | $^{10}$B | 7(3) fs             |
| 4438.03 *    | $1 \pm \frac{3}{1}$          | $^{12}$C | 61(4) fs            |
| 219.4        | < 0.047                       | $^{10}$Be | 1.1(3) ps           |
| 2591         | < 0.15                        | $^{10}$Be | < 80 fs             |
|              |                               |         | 180 ± 17 fs         |
| 2811         | < 0.16                        | $^{10}$Be | 1.1(3) ps           |
| 2895         | < 0.086                       | $^{10}$Be | ?                   |
| 3367.4 *     | Hidden by $^{12}$C double escape | $^{10}$Be | 180 ± 17 fs         |
| 5957         | < 0.034                       | $^{10}$Be | < 80 fs             |
| 720.5        | Hidden by $^{10}$B            | $^{12}$B | < 50 fs             |
| 947.11       | < 0.057                       | $^{12}$B | < 70 fs             |
| 953.10 *     | < 0.27                        | $^{12}$B | 260(40) fs          |
| 1667.7       | < 0.04                        | $^{12}$B | < 70 fs             |
| 1673.7       | < 0.06                        | $^{12}$B | < 50 fs             |
| 2722.7       | < 0.01                        | $^{12}$B | ?                   |
| 418          | Hidden by $^{127}$I(n,n'γ)    | $^{13}$B | 62 (50) fs          |
| 596          | Hidden by $^{127}$I(n,n'γ)    | $^{13}$B | 62 (50) fs          |
| 3483 *       | < 0.17                        | $^{13}$B | ?                   |
| 3713         | < 0.044                       | $^{13}$B | < 380 fs            |
| 4131         | < 0.62                        | $^{13}$B | 62(50) fs           |

* First excited state
Table 5
The γ-ray yield results for $^{14}$C and $^{13}$C. The errors in the yield quoted below are only the relative errors and do not include a 23% absolute normalization error. The lifetimes are taken from Ajzenberg-Selove [29].

| Gamma Energy (keV) | Yield/captured $\mu^-$ in (%) | Lifetime [29] |
|--------------------|-------------------------------|---------------|
| **$^{14}$C**       |                               |               |
| 495                | < 0.048                       | 4.3(6) ps     |
| 613                | < 0.12                        | 160(60) fs    |
| 634                | < 0.14                        | 96(11) ps     |
| 809                | < 0.50                        | 36(4) fs      |
| 918                | < 0.29 (probably ≈ 0.05)      | 13(2) fs      |
| 1248               | Hidden by Ge(n,γ)             | 160(60) fs    |
| 6092 *             | 1.3 ± 0.3                     | < 10 fs       |
| 6730               | 1.3 ± 0.2                     | 96(11) ps     |
| 7017               | 3.4 ± 0.6                     | 13(2) fs      |
| 7339               | < 0.068                       | 160(60) fs    |
| **$^{13}$C**       |                               |               |
| 169                | Below threshold               | 12.4(2) ps    |
| 595                | Hidden by $^{127}$I(n,n')     | 1.59(13) fs   |
| 764                | < 0.20                        | 12.4(2) fs    |
| 3089               | 1.5 ± 0.3                     | 1.55(15) fs   |
| 3685 *             | 5.5 ± 0.2**                   | 1.59(13) fs   |
| 3854               | 1.9 ± 0.2**                   | 12.4(2) ps    |

* This is the entire peak (Doppler plus Gaussian components).

** These yields were averaged values from the two detectors.
Table 6
The nuclear level yield results for $^{12}$C and $^{10}$B and limits for $^{10}$Be, $^{12}$B, and $^{13}$B.

| Level energy (keV) | $\gamma$-ray used | Yield/captured $\mu^-$ in (%) | Reaction | Nuclide |
|--------------------|---------------------|-------------------------------|----------|---------|
| 718.35 $^*$        | 718.3               | -0.01 ± 0.25                  | $(\mu^-,\nu p3n)$ | $^{10}$B |
| 1740.15            | 1021.7              | < 0.13 ± 0.07                 | $(\mu^-,\nu p3n)$ | $^{10}$B |
| 4438.91 $^*$       | 4438.03             | $1 \pm \frac{3}{1}$          | $(\mu^-,\nu 2n)$  | $^{12}$C |
| 5958.39            | 5956.5              | < 0.034                       | $(\mu^-,\nu \alpha)$ | $^{10}$Be |
| 6179.3             | 219.4               | < 0.20                        | $(\mu^-,\nu \alpha)$ | $^{10}$Be |
|                    | 2811                | < 0.21                        | $(\mu^-,\nu \alpha)$ | $^{10}$Be |
| 953.14 $^*$        | 953.10              | < 0.27                        | $(\mu^-,\nu pn)$  | $^{12}$B |
| 2620.8             | 947.11              | < 0.41                        | $(\mu^-,\nu pn)$  | $^{12}$B |
| 2723               | 2722.7              | < 0.01                        | $(\mu^-,\nu pn)$  | $^{12}$B |
| 3483 $^*$           | 3483                | < 0.17                        | $(\mu^-,\nu p)$   | $^{13}$B |
| 3713               | 3713                | < 0.044                       | $(\mu^-,\nu p)$   | $^{13}$B |
| 4131               | 4131                | < 0.91                        | $(\mu^-,\nu p)$   | $^{13}$B |

* First excited state
Table 7
The nuclear level yield results for $^{14}$C and $^{13}$C. Note that the $\gamma$-ray energies in $^{13}$C and $^{14}$C are lower than the level excitation energies because of the nuclear recoil.

| Level energy (keV) | $\gamma$-ray used | Yield/captured $\mu^-$ in (%) |
|-------------------|-------------------|-------------------------------|
| $^{14}$C           |                   |                               |
| 7341              | 613               | < 0.35                        |
| 7339              |                   | < 0.42                        |
| 7019              | 918               | < 20                          |
| 7017              |                   | 3.4 ± 1.4                     |
| 6903              | 809               | < 0.50                        |
| 6589              | 495               | < 0.049                       |
| 6732              | 634               | < 3.9                         |
| 6730              |                   | 1.40 ± 0.49 ± 0.12            |
| 6094              | 6092              | 1.2 ± 0.6 ± 0.79              |
| $^{13}$C          |                   |                               |
| 3853              | 3853              | 3.0 ± 0.8                     |
| 3684              | 3684              | 4.4 ± 1.3                     |
| 3089              | 3089              | 1.4 ± 0.7                     |

Table 8
Measurements of partial muon capture rates in $^{14}$N to the 7019 keV level. Note the uncertainty on the total capture rate of $(66 \pm 5) \times 10^3$ s$^{-1}$ contributes significantly to errors.

| Experiment         | Partial capture rate (s$^{-1}$) | Yield/captured $\mu^-$ in (%) |
|--------------------|----------------------------------|-------------------------------|
| Present            | 2240 ± 920                      | 3.4 ± 1.4                     |
| Saclay [9]         | 4640 ± 700                      | 7.0 ± 1.0                     |
| Dubna [46]         | 10000 ± 3000                    | 15 ± 5                        |
| Louvain [50]       | 8000                            | 12                            |
| PSI (SIN) [48]     | 6000 ± 1500                     | 9.1 ± 2.3                     |
| Recommended value  | 4390 ± 580                      | 6.6 ± 0.9                     |
Table 9
Comparison of γ-ray yields from muon capture in $^{14}$N with other reactions. The direct feeding for each excited state is given, taking into account the γ-ray branching ratios and cascade feeding. (All bound states of $^{13}$C and $^{14}$C are listed plus a few major unbound ones). Also given are the integrated yields for the (γ,p) reaction up to 29 MeV [49,50], the ($\pi^-,\gamma$) yields of Perroud et al.[15], the ($\mu^-,\nu$) calculation of Kissener et al.[21] (all transitions), the calculation of Mukhopadhyay [11] (allowed transitions only, i.e. $1^+$), and the ($\pi^-,\gamma$) calculation of Kissener et al.[18] (all transitions). [Note unbound energies do not always agree!]

| Nuclide | Excited State | (μ,ν) direct (keV) J$^\pi$ | feeding (%) | (μ,ν) calc (%) [21] | (μ,ν) calc (%) [11] | (γ,p) $\int \sigma .dE$ (MeV·mb) |
|---------|---------------|----------------------------|-------------|---------------------|---------------------|---------------------------------|
| $^{13}$C | g.s. $\frac{1}{2}^-$ | ? | 26 | 20 |
|         | 3089 $\frac{3}{2}^+$ | 1.4(7) | - | small |
|         | 3685 $\frac{5}{2}^-$ | 4.4(13) | 16 | 7(2) |
|         | 3854 $\frac{5}{2}^+$ | 3.0(8) | - | 1.7(7) |
|         | 7550 $\frac{5}{2}^-$ | unbound | 18 | 17 |
|         | ($\pi^-,\gamma$) exp [15] | | | | |
|         | ($\pi^-,\gamma$) calc. [18] | | | | |
| $^{14}$C | g.s. $0^+$ | ? | 0.4 | 0.25(11) | 0.25 |
|         | 6094 $1^-$ | $1.2 \pm \frac{0.6}{1.0}$ | 1.1 | |
|         | 6589 $0^+$ | $< 0.05$ | 0.3 | |
|         | 6732 $3^-$ | 1.4(5) | 2.7 | |
|         | 6903 $0^-$ | $< 0.5$ | | |
|         | 7019 $2^+$ | 3.4(14) | 11 | 15 |
|         | 7341 $2^-$ | $< 0.4$ | | 0.8 |
|         | 8318 ($2^+$) | unbound | 11 | 15 | 3.4(3) | 3.1 |
|         | 11306 ($1^+$) | unbound | 2 | 2.3(4) | 1.3 |