The emission of particles after atomic muon capture was studied extensively during the early 70’s. In particular, proton and neutron spectra were measured in order to determine whether nuclear emission was due to a direct or a thermalized process. It was found that protons emitted after atomic muon capture decreased from a probability of 15% in light nuclei (C, N, O) to essentially 0% for heavy systems such as $^{120}$Sn, and that only 10% of this emission could be ascribed to statistical processes. On the other hand a significant thermal spectrum of neutrons in addition to a direct component was found. Unfortunately these studies were not always self consistent so that information of relevance to MECO is ambiguous.
I. PREVIOUS EXPERIMENTAL RESULTS

There are several summaries of experimental results\[1–3\] which discuss the observation and theoretical interpretation of the emission spectrum of protons, deuterons, and alphas after atomic muon capture. Unfortunately the literature is not always self consistent. It appears that charged particle emission can be as large as 15% in Carbon and Oxygen nuclei, decreasing to a few % in emulsion nuclei (Ag/Br) and to essentially 0% in heavier systems such as \(^{120}\text{Sn}\). Just how the spectrum divides into the various particle types is not known, although one study indicates that the emission of alphas appears to be more consistent with a thermalized distribution than protons. The pyroton spectrum is found to have a high energy tail, and is more consistent with the direct process of muon capture on a quasi-deuteron.

High energy proton, deuterium, and tritium emission\[4\] from \(^{28}\text{Si}, ^{32}\text{S}, ^{40}\text{Ca}, \) and \(^{64}\text{Cu}\) is summarized in Figure 1. In this figure the partial spectrum integral is given for protons and deuterons. Here \(W\) is the probability of particle emission per muon capture. These data were taken by counters so that the actual spectra have a low energy cut-off, about 14 MeV for protons. Thus one sees that the partial spectrum integral, reflecting high energy proton emission, peaks at \(Z=20\). Unfortunately the proton spectrum below 14 MeV is not known, and the contribution from lower energy emissions to this integral is underdetermined.

The total charged particle spectrum has also been measured in a Si(Li) detector\[5\], and is shown in Figure 2. This spectrum is corrected for electrons from muon decays and proton emissions from this detector. Obviously it has a high-energy cut-off at 25 MeV. The charged particle spectrum from the Si target obtained in Ref.[4] matches these data in the region of overlap. The spectrum shape shows a continual exponential decrease in differential emission probability from below the Coulomb barrier, out to some 50 MeV. The low energy rise in the spectrum below the break at about 1.4 MeV is associated with \(^{27}\text{Al}\) recoils, and is consistent with thermal neutron emission in the reaction;

\[
\mu + ^{28}\text{Si} \rightarrow ^{27}\text{Al} + n + \nu_\mu.
\]

The exponential decay constant of the spectrum tail is about 3.1 MeV, and the spectrum peaks at 2.5 MeV, somewhat below the Coulomb barrier of 4.6 MeV. The total spectrum integral gives a probability for charged particle emission of 15% per \(\mu\) capture. Note that the spectrum integral from the Si data of Ref.[4] for energies above 18 MeV is only about 1%,
FIG. 1. The Spectrum Integral for Charged Particle Emission after Muon Capture above Various Energy Thresholds as a Function of Z. from Ref.[4]

indicating that most of the charged particles emitted from this nucleus have energies less than 18 MeV. This reflects an experimental problem when attempting to observe charged particle emission with counters external to the target.

Several experiments used radiochemical techniques to determine the probability of charged particle emission. This can give the full spectrum integral for particle emission if a unique reaction leaving a radioactive daughter can be identified. An example is shown in [2] where the charged particle yield per stopped muon for several nuclei is shown for the reactions \((\mu;p,2n)\), \((\mu;pn)\), and \((\mu;p)\). One can compare the sum of the yield from these reactions for Mn, about 2%, to the data of Ref.[4], also about 2% for the sum of proton and deuteron emission, but for particle energies above 15 MeV. To compare these yields, the data may both be normalized to the yield per \(\mu\)-capture. Assuming that the counter data is correct, it appears that the radiochemical yield must be low unless the spectrum for Mn below 15 MeV falls very rapidly to zero, unlike the data for Si.

There are also radiochemical measurements for Si [6], however these data only observe the \((\mu;p)\) reaction. They indicate that 5% of the \(\mu\)-captures lead to proton emission. If these
data and those of Ref.[5] are correct, then there must be significant, simultaneous neutron and proton emission. Indeed this does appear to be the case in the radiochemical data of Ref.[4], but these data were for heavier targets. Still the radiochemical data seems to give much too low a yield.

In summary, it appears despite some uncertainties, that charged particle emission from light nuclei can be as high as 15% (consistent in several experiments). The energy spectrum rises to a peak near the Coulomb barrier (1-4MeV) and then decays exponentially up to high energies, ≥ 50 MeV. Proton emission with simultaneous neutron emission predominates, but other charged particles are also emitted in measurable quantities.
FIG. 3. Radiochemical Analysis of the Charged particle Yield after Muon Capture as a Function of the Coulomb Barrier. from Ref.[6]

II. IMPACT ON MECO

Meco captures stopping muons in an $^{27}$Al target. The signal of interest is due to an electron, emitted with approximately 100 MeV/c momentum. Thus if the detector is tuned for this momentum range, protons of kinetic energy above 5.3 MeV may cause significant background. I assume below that the Si spectrum of Figure 3 represents the charged particle spectrum from $^{27}$Al, and normalize the spectrum integral to obtain 15% charged particle emission after a $\mu$ capture. If one then assumes that the proton/deuteron ratio is the same for this integral as was measured in Ref.[4] for energies above 18 MeV (probably not a good assumption), then about 65% of this spectrum are protons and 35% deuterons. One notes that deuterons, may also create substantial background, but because of their higher magnetic rigidity, the field of the detector selects those particles from a higher energy window.

Previously the proton spectrum I generated for Meco was obtained from a spectrum shape fit to the exponential proton tail and normalized by the radiochemical experiments. It now
appears that this must underestimate the number of low energy protons. Thus I now fit the Si spectrum of Ref.[5] with a function of the form;

\[ W(T) = A_1(1 - T_{th}/T)^\alpha e^{-T/T_1}, \quad E \geq 8\text{MeV}; \quad (1) \]
\[ = A_2 e^{-T/T_2}, \quad 8\text{MeV} \leq T \leq 20\text{MeV}; \quad (2) \]
\[ = A_3 e^{-T/T_3}, \quad T \geq 20\text{MeV}. \quad (3) \]

where \( T \) is the kinetic energy and the fitted parameters are; \( A_1 = 0.092405, 5.4374^{-3}, 5.1785^{-4} \) MeV\(^{-1} \), \( T_{th}=1.4 \) Mev, \( \alpha=1.3279 \), and \( T_i = 3.1, 5.1, 10.0 \) MeV. The shape of this spectrum is shown in Figure 4. It has a low energy cut-off at 1.4 Mev, just below the Coulomb barrier at 4.6 MeV.

III. CONCLUSIONS

A more careful study of the number of charged particles emitted after atomic muon capture indicates that previous estimates of this spectrum were underestimated. Therefore a new spectrum generator was created which better represents the measured charged spectrum
from Si. This spectrum is normalized to other data which indicate that the yield of protons is 10%, and the yield of deuterons is 5% per stopped muon.

Finally, one notes that a target heavier than Al could significantly decrease the number of emitted charged particles, although the time for muon capture in a heavier nucleus decreases, reducing the sensitivity to muon conversion.

[1] H. Uberall, Springer Tracks in Modern Physics, 71(1974)1.

[2] P. Singer, Springer Tracks in Modern Physics, 71(1974)39.

[3] N. C. Mukhopadhyay, Physics Reports, 30(1977)1.

[4] Y. G. Budyashov, et. al., Soviet Physics JETP, 33(1971)11.

[5] S. Sobottka and E. L. Wills, Phys. Rev. Lett., 20(1968)596.

[6] L. Vil’gel’mova, et. al., Soviet J. Nucl. Phys., 13(1971)310.