Maryland. He also wishes to thank M. I. Dolin, E. Guth, K. B. Jacobson, M. Roberts, H. C. Schweinler, R. B. Setlow, T. A. Welton, and E. P. Wigner for valuable discussions. He is indebted to K. B. Jacobson for pointing out Ref. 9, and to R. O. Rahn for Ref. 12.

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[9] By cistron, I mean that portion of nucleic acid which codes for the synthesis of a single polypeptide (protein) chain. One codon corresponds roughly to a peptide molecular weight of 100. Most individual polypeptide chains, clearly identified as such, have molecular weights well under 50 000. See I. M. Klotz, Science 155, 697 (1967).

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# ENERGY SPECTRUM OF CHARGED PARTICLES EMITTED FOLLOWING MUON CAPTURE IN $Si^{28}$

Stanley E. Sobottka and Edward L. Wills
Department of Physics, University of Virginia, Charlottesville, Virginia*

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Results of a high-resolution study of the charged-particle energy spectrum resulting after $\mu^-$ capture in Si$^{28}$ are presented. The spectrum, attributed mainly to proton emission, exhibits a low-energy cutoff at 1.4 MeV and a maximum at about 2.5 MeV from which it decreases approximately exponentially with a decay constant of 4.6 MeV. A branching ratio of $0.15 \pm 0.02$ charged particle per capture was determined.

We have measured the energy spectrum and branching ratio for charged particle emission following muon capture in Si$^{28}$ with a Si(Li) target-detector system. We achieved an energy resolution of about 150 keV by measuring the pulse-height spectrum from the silicon detector. The pulse height was a measure of the total energy shared by the emitted particle and recoiling residual nucleus. The energy resolution was limited mainly by the pulse-height defect for heavy charged ions in silicon detectors.[1]

Previous observations have been limited to nuclear emulsion experiments[2-5] with substantially poorer energy resolution and statistical uncertainties. Morinaga and Fry[4] have found that, of muon captures in light emulsion nuclei, 9.5% result in proton emission and 3.4% in alpha emission. Proton emission from Ag nuclei has been interpreted to be a result of muon capture on $p$-$p$ pseudodeuterons at the nuclear surface by Singer[6] who estimated a branching ratio for this process. Capture on virtual pions exchanged by proton pairs was assumed by Bertero, Passatore, and Viano,[7] who calculated an energy distribution which had a peak at roughly the Coulomb barrier height. To the knowledge of the authors no detailed calculations of branching ratios or proton spectra have been made assuming an intermediate giant-resonance state excited by the muon-capture process.[8] However, Überall[9] has suggested that proton emission may indicate the presence of two-hole, two-particle states in the giant-dipole configuration. The data of the present experiment may help to distinguish between the above three mechanisms.

When negative muons stop in silicon, 35%

decay into an electron and two neutrinos. The remaining 65% are captured. If an intermediate state is assumed, the reaction is

$$\mu^- + \mathrm{Si}^{28} \to \mathrm{Al}^{28} + \nu + 100.5\ \mathrm{MeV}.$$

The excited $\mathrm{Al}^{28}$ nucleus can decay by the following modes:

$$\begin{aligned} \mathrm{Al}^{28} &\to \mathrm{Al}^{27} + n \quad (12.4\ \mathrm{MeV}), \\ &\to \mathrm{Mg}^{27} + p \quad (14.2\ \mathrm{MeV}), \\ &\to \mathrm{Na}^{24} + \alpha \quad (15.5\ \mathrm{MeV}), \\ &\to \mathrm{Mg}^{26} + d \quad (18.4\ \mathrm{MeV}). \end{aligned}$$

The energy listed with each final state is the ground-state energy with respect to the $\mathrm{Si}^{28}$ ground state. Neutron emission is expected to dominate because of the basic process of muon capture. For $\mathrm{Si}^{28}$ it is also energetically favored. Of the charged-particle emissions, proton emission is expected to dominate because it is energetically favored and is less inhibited by the Coulomb barrier. Because the $\mathrm{Mg}^{27}$ residual nucleus is long lived, the proton energy spectrum will not be smeared out by the kinematics of a disintegrating nucleus.

Our detector system (Fig. 1) consisted of two plastic scintillator detectors (1 and 3) and a lithium-drifted silicon detector (2). The Si(Li) detector, 3 mm thick and 3 $\mathrm{cm}^2$ in area, was operated at liquid-nitrogen temperature for minimum charge-collection time. Muons produced by the synchrocyclotron at the Space Radiation Effects Laboratory (National Aeronautics and Space Administration) were stopped in the Si(Li) detector (signature $12\bar{3}$). For each stopped muon a second pulse is observed if the muon decays or a charged particle is emitted after capture. Muon-decay electrons are mainly high energy and escape from the Si(Li) detector. By putting 1 and 3 into anticoincidence with 2, most of these could be eliminated. Hence the complete signature of a capture event was $12\bar{3}$ followed by $\bar{1}2\bar{3}$. Pulse heights of such events were analyzed if they occurred during a 4-μsec gate period which began 1 μsec after a $12\bar{3}$. The delay prevented the analyzed pulse from being distorted by the stopping-muon pulse. Real pulses which were preceded or followed too closely by accidental 12 or 23 coincidences were also rejected by the logic system. Due to the 770-nsec lifetime of negative muons in silicon,[10] only 24% of the stopped muons decayed or were captured during the gate period.

The raw data, covering an energy range from 350 keV to 26 MeV, are shown in Fig. 2. This energy scale, calibrated with a pulser and $\mathrm{Na}^{22}$ source, actually extended above 26 MeV but the data are not shown there since the system was nonlinear above this point. There was no change in the general trend of the spectrum at higher energies. The measured spectrum (55 715 events) represents almost 6% of the muon stops in the Si(Li) detector but contains a background contamination due to our decay-electron anticoincidence efficiency being only 83%.

The decay-electron contribution was determined by operating with a positive muon beam for which only decay is possible. This spectrum was then normalized to the negative spectrum by multiplying by the ratio of the numbers of negative to positive muon stops times the ratio of negative to positive muon-decay probabilities during the gate period. This contribution (14 300) events was 37% of the spectrum below 3 MeV and negligible above this energy. No other significant background was present. Since proton emission is expected to be the dominant charged-particle mode of de-excitation and the Si(Li) detector thickness of 3 mm corresponds to the range of 24-MeV protons,

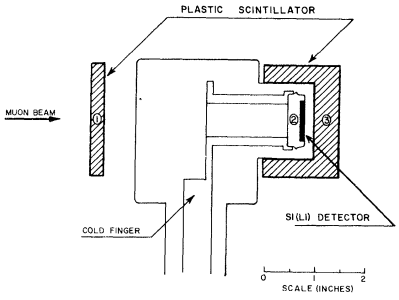

FIG. 1. Detector geometry.

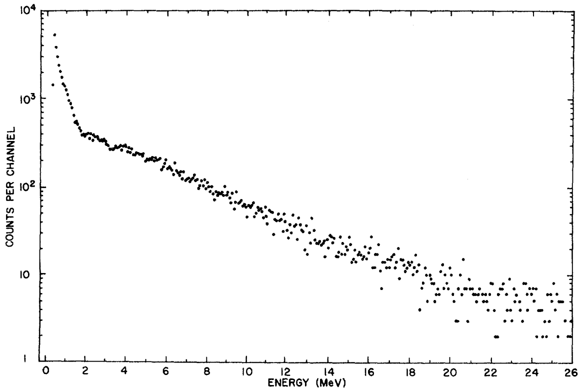

FIG. 2. Uncorrected data.

an appreciable percentage of the high-energy protons can escape, losing only a fraction of their energy. A second correction was made for this process in which the spectrum was assumed to be totally due to proton emission. Protons of energies above 26 MeV were not included in the correction because the estimated events above this energy represented only 2% of the total spectrum. The corrected spectrum, shown in Fig. 3, indicates that the applied escape correction was small and less than the statistical uncertainties for energies less than 21 MeV.

The corrected spectrum (Fig. 3) has a total spectral integral of 0.26 ± 0.05 event per capture. Note the valley occurring at about 1.4 MeV which separates the spectrum into two distinct parts, a low-energy spectrum and a high-energy spectrum. The statistical uncertainty in the valley depth is approximately ±50 counts per channel. We identify the low-energy spectrum as the upper end of the Al$^{27}$ recoil spectrum due to neutron emission. This identification is not inconsistent with the neutron spectrum measured by Sundelin.[11] The high-energy spectrum is due to the charged-particle reactions, primarily Mg$^{27}+p$. This spectrum (25 000 events) has a spectral integral of 0.15 ± 0.02 charged particle per capture including the portion above 26 MeV (approximately 2% of the events are between 26 and 32 MeV and 1% above 32 MeV) and has a decay constant of 4.6 MeV.

The spectrum reveals no structure which might be immediately identifiable as due to two-hole, two-particle states in the giant resonance[9] of Al$^{28}$. The peak of the spectrum occurs at 2.5 MeV, somewhat below the height of the Coulomb barrier (4.4 MeV) for Mg$^{27}+p$ but somewhat above the peak of the calculated neutron energy spectrum (1.3 MeV) for muon capture on deuterons.[12] More detailed calculations on the possible mechanisms for proton emission following muon capture are needed in order to identify the correct process.

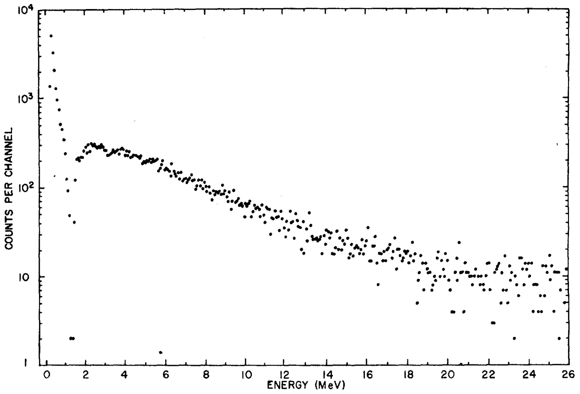

FIG. 3. Data after subtraction of muon-decay electron background and correction for escape of protons.

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