Search for a Conserved-Vector-Current Mechanism in the Emission of Protons from μ^- Stars in Emulsion*

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The energy spectrum of protons from 1289 single-prong μ^- stars in emulsion was studied, with special attention given to the energy region above 20 MeV. In this energy region, Bertero, Passatore, and Viano had predicted an enhanced proton emission as a result of muon interaction with pion currents in the nucleus according to the theory of conserved vector current (CVC). No evidence of the predicted 25-MeV peak in the CVC spectrum was found, nor was there any evidence of a high-energy tail to the spectrum which was predicted to extend up to 90 MeV. The results are quite consistent with Singer's earlier theory. If the CVC mechanism occurs here at all, it occurs at least a factor $(2.0\pm1.0)\times10^{-2}$ less frequently than predicted.

I. INTRODUCTION

THE earliest models[1] of the interaction of negative muons with nuclei assumed that the fundamental process was

$$\mu^-+p\rightarrow n+\nu_\mu,$$

resulting in a nuclear excitation of about 15–20 MeV, which gives rise to the evaporation of neutrons, protons, etc. Morinaga and Fry[2] studied the energy spectra both of protons and α particles emitted from single-prong μ^- stars in nuclear emulsion and got results which were consistent with the "evaporation model" prediction for the case of the emitted α particles.[3] However in the proton case, the energy spectrum of emitted particles was found to have an anomalous high-energy tail. Furthermore, the rate of proton emission was much greater than that expected from the evaporation model, although the α-particle rate was consistent with its predictions.

Singer[4] then showed that both of these difficulties could be resolved by assuming an additional process—namely, direct proton emission from the interaction of negative muons with proton pairs near the nuclear surface, through the reaction

$$\mu^-+(pp)\rightarrow n+p+\nu_\mu.$$

The kinematics of this interaction with a nucleon pair rather than a single nucleon results in the release of more energetic protons in this reaction ($E_{\max}\approx50$ MeV). The location of the reaction at the nuclear surface results in a relatively greater rate of proton emission due to the decreased probability of reflection from the potential barrier at the surface.

Recently Bertero, Passatore, and Viano[5] proposed still another direct-emission mechanism, one in which the muons interact with virtual pions exchanged by nucleons in the nucleus according to the theory of conserved vector current (CVC) (Fig. 1). These authors suggested that this mechanism could be distinguished from the other ones by an enhanced proton emission near 25 MeV, where the CVC spectrum peaks, and by an increase of the maximum energy of proton emission from 50 to 90 MeV. However, the proton spectrum observed by Morinaga and Fry[2] is not accurate for proton energies >15 MeV because of limited statistics and because long tracks were not followed into neighboring plates, necessitating large geometrical corrections for the few events in this high-energy region. More recent work by Kotelchuck[6] and by Vaĭsenberg *et al.*[7] dealt largely with multiprong muon stars and did not analyze the one-prong energy spectrum. The present work is an effort to detect the effect predicted by Bertero *et al.*,[5] thus giving direct evidence of the presence of the CVC mechanism in the interaction of muons with nuclei.

II. EXPERIMENTAL PROCEDURES

The emulsion plates which contained the muon stars were 3 in.×5 in.×600 μ Ilford G-5 pellicles. Placed together as a stack they had been exposed at the CERN synchrocyclotron to an analyzed beam of 2×10^7 μ^- of energy (52±8) MeV.[8]

The plates had previously been scanned by one of the authors (D.K.)[6] in the muon ending region 47–56 mm from the incoming edge of the pellicles. A large sample of stars was located and classified according to prong number. Scanner efficiency based on rescanning for one-prong stars was found to be 91%. Also, no scanning bias that depended on prong energy was found.

Plates in which the location of the one- and two-prong muon stars had already been determined were randomly selected and reexamined. Only those stars which were the result of the emission of a single charged particle

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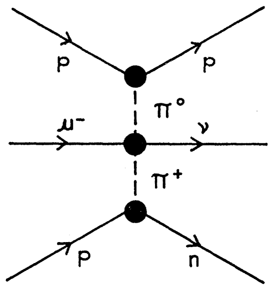

FIG. 1. Feynmann diagram of the CVC interaction.

after muon capture were of interest. This group includes one-prong stars and two-prong stars in which one of the prongs is very short and is interpreted as being due to a nuclear recoil. Near the end of their range, muons undergo many scatters which are often difficult to distinguish from an ending accompanied by a very short prong. To prevent such scatters from being counted as stars, only those with a prong greater than 8.7 μ were classified as one-prong stars. Two-prong stars, in which one prong length was greater than 8.7 μ and the other was 1.0–4.3 μ long, were classified as one-prong stars with recoil. These criteria are similar to those adopted by Kotelchuck,[6] and Morinaga and Fry.[2]

In each case of an event that was relocated and classified as a one-prong star or a one-prong star with recoil, the length of the prong was measured. The identification of stars and measurement of prong lengths was done under a total magnification of 330×. A grid had been carefully positioned and photographed on the bottom face of each pellicle. Using this grid and observing the position of a given track relative to other tracks in the neighborhood, tracks were followed from plate to plate.

The shortest distance from the scanning region to the surface of the stack was about 2 cm. To travel this distance a proton would need a kinetic energy of 80 MeV.[9] No track was observed to leave the emulsion stack, and thus no geometrical corrections to the data were necessary. Due to the great sensitivity of G-5 emulsion, it was not feasible to distinguish α-particle tracks from proton tracks; thus they were included in the data on the same basis as the proton tracks (see Sec. IIIA).

III. RESULTS

The ranges of 1289 tracks from single-prong stars and single-prong stars with recoil were measured. By use of the ratio of track endings to stars which was obtained previously,[6] the number of track endings which would be expected to produce this sample of stars was determined to be $(7.0\pm0.3)\times10^4$. Prong energies were derived from prong ranges by means of the range-energy formula for protons in G-5 emulsion (see Sec. IIIA),

$$E=0.281\times R^{0.568},$$

[9] D. M. Ritson, *Techniques of High Energy Physics* (Interscience Publishers, Inc., New York, 1961), p. 158.

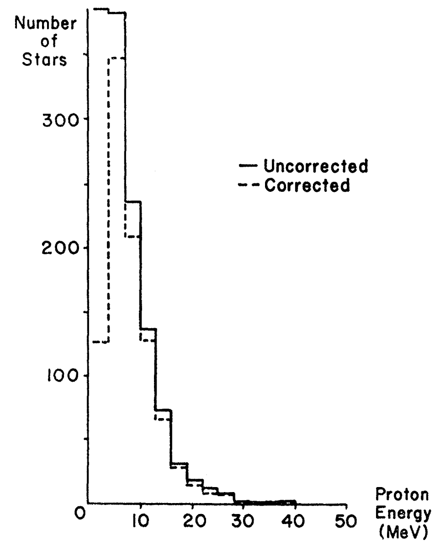

FIG. 2. Corrected and uncorrected energy spectra for tracks from single-prong stars. Corrections to the energy spectrum involved subtraction of stars in which α particles rather than protons were emitted and of stars formed from light nuclei in the emulsion. The correction for pion stars was negligible (see text). For the uncorrected curve, error limits (not shown) would reflect counting statistics only. Uncertainties in the corrections are discussed in the text.

where R=range in μ and E=kinetic energy in MeV. The uncorrected energy spectrum of the tracks from the 1289 single-prong stars is plotted in Fig. 2.

The theories with which the results of this experiment are to be compared only make predictions concerning proton emission following muon capture in heavy nuclei. The above experimental results thus had to be corrected to conform to these conditions. There were three types of contamination in the data—stars resulting from α-particle rather than proton emission, stars due to muon capture in the light elements of the emulsion, and stars due to nuclear capture of the small admixture of pions which was in the muon beam.

A. α-Particle Emission

As noted in Sec. II, it was not possible visually to discriminate between protons and α particles in the G-5 emulsion. However Morinaga and Fry,[2] using less sensitive C-2 emulsion, were able to distinguish the tracks of these two particles. They studied the energy spectra of these particles as well as their relative emission rates. One of their findings was that all α particles are emitted with energies less than 20 MeV.[10] However, an α-particle track of 20 MeV will have an apparent energy of 5 MeV if, as in this experiment, all tracks are treated as proton tracks. Thus, when the results

[10] Since the range of a 20-MeV g particle is about 180 μ, Morinaga and Fry needed to make only small geometrical corrections to their data for α particles compared to those made for protons. Hence their results for α particles are more dependable than those for protons at the high-energy range of the spectrum.

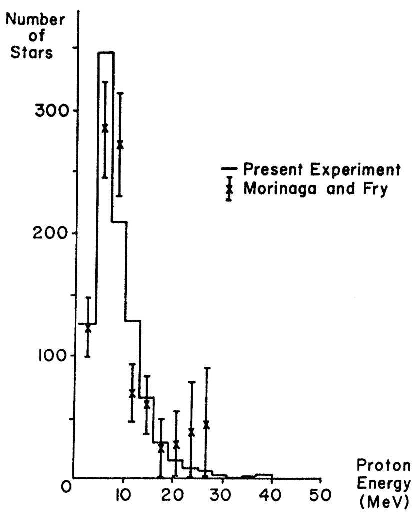

FIG. 3. Comparison of the corrected proton energy spectrum measured in the present experiment with that measured earlier by Morinaga and Fry. The earlier results are normalized to the size of the present star sample. The error limits shown on the Morinaga and Fry spectrum were calculated by the present authors from the data on the counting statistics and geometrical correction factors presented by Morinaga and Fry in their original paper (Ref. 2). The error limits for the present spectrum, which are not shown, would reflect counting statistics as well as small uncertainties in the corrections to the spectrum (see text).

or Morinaga and Fry were used to correct the present energy spectrum for α emission (Fig. 2), the correction contributed only to the two lowest-energy bins (1–4 and 4–7 MeV). Hence, even if somewhat imprecise, this correction should not interfere with observation of the effect studied by Bertero *et al.*,[5] which peaks in the 25-MeV region. The α-emission stars that had a short recoil (and thus had two prongs) were subtracted from our data along with all other such stars for reasons discussed below.

B. Stars from Light Elements

The light element in emulsion are primarily H, C, N, and O.[11] Since muon capture by hydrogen atoms will not produce a single-prong star in emulsion, all stars due to muon capture in light nuclei must be due to capture in C, N, or O. Since capture in light nuclei will often produce a short recoil track, whereas capture in heavy nuclei will not result in an observable nuclear recoil,[2] all stars with one prong plus recoil were classified as due to capture in light nuclei. These were subtracted from the original data.

Since not all stars from capture in light nuclei give visible recoils, it is necessary to estimate the fraction of light-nucleus events in the heavy-nucleus sample. In a recent study, Vaĭsenberg *et al.*,[7] using a criterion similar to the one used here,[12] found about 13% contamination of light-nucleus events in the heavy-nucleus sample.

However, in the energy region of interest (>20 MeV), the contamination should be much lower than this since at these proton energies *all* recoil tracks from light nuclei are at least 1 μ long, hence are likely to be seen under high-power magnification. Therefore, all stars with prong energies >20 MeV were examined under 1500× magnification. Only eight stars of energy >20 MeV were found to have a recoil. These stars were adjudged to be from light nuclei and were subtracted from the original data. Of these stars, only one had an energy >30 MeV (namely 33 MeV), so even if they were all left in the heavy-nucleus sample, they would not significantly have affected the conclusions from this experiment. Furthermore, since so few events were subtracted as a result of this examination, the 13% figure of Vaĭsenberg *et al.* remains the best estimate of light-nucleus contamination in the heavy-nucleus sample.

C. Pion Stars

The pion contamination in the muon-ending region of the plates had been determined previously.[6] Normalized to the number of muon endings studied in this experiment (17±5), one-prong stars due to pions are expected here over the entire energy spectrum. This represents only about 1% of the events examined. Multipronged pion stars were eliminated from this sample when the correction for stars from light nuclei was made.

A rough estimate of pion-star contamination between 20 and 30 MeV and above 30 MeV can also be made. Adelman[13] states that of the prongs emitted from *all* pion stars, (10.3±1.2)% correspond to protons of energy >20 MeV, and (6.0±0.8)% to protons of energy >30 MeV. Applying these results to the sample of one-prong pion stars here, only one pion star would be expected to give a proton of energy between 20 and 30 MeV, and another to give a proton of energy >30 MeV. Given the size of the star sample and the uncertainties in the other corrections, the correction for

[11] D. F. Powell, P. H. Fowler, and D. H. Perkins, *The Study of Elementary Particles by the Photographic Method* (Pergamon Press Inc., New York, 1959), p. 42.

[12] Vaĭsenberg, *et al.* [Ref. 7] classified a star as occurring off a heavy nucleus if the number of prongs was <4, and if all prong lengths were >30 μ. However, their tabulated results gased on these criteria indicate that 96% of the stars adjudged to be from heavy nuclei had only one prong. Therefore, had all multipronged events been assigned to the light nuclei (i.e., had the criteria for assigning a star to be a heavy nucleus been that it have only one prong and its length be >30 μ), then the fraction of light-nucleus events in the heavy-nucleus sample would have been essentially unchanged. In the present experiment, the criteria for assignment of a star to a heavy nucleus is that it have one prong and the prong's length be >8.7 μ. This differs from the modified criteria of Vaisenbert *et al.* only in the length condition and results in a slightly greater contamination of the heavy-nucleus sample here. However, the added contamination is found in the lowest-energy bin, and we are interested here only in proton energies >20 MeV. Thus, the 13% contamination figure of Vaĭsenberg *et al.* is appropriate for comparison with the present experiment.

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pion-star contamination is negligible throughout the proton energy range.

The energy spectrum of one-prong muon stars, corrected for α-particle emission as well as for stars from light nuclei, is shown in Fig. 2.

IV. DISCUSSION AND CONCLUSIONS

The proton energy spectrum of Morinaga and Fry[2] for one-prong stars originating in heavy nuclei is given in Fig. 3. This spectrum, normalized to the size of the ending sample used in this experiment, is compared with the one found in this study. The portion of the spectrum above 20 MeV is measured more accurately here, but in general the two spectra are in good agreement. In particular, their peaks occur at roughly the same energy, and thus both agree with Singer's prediction.[4] The rate of star production is also consistent in the two experiments as noted in an earlier paper[6] and agree again with the theory. Hence the results of the present experiment are in agreement with Singer's theoretical predictions.

However, this is not the case for the mechanism of Bertero *et al.*[5] These authors made their calculations for two different Fermi-gas models—one in which the effective nucleon mass $M^*=M$, and one in which $M^*=\frac{1}{2}M$, where M is the rest mass of a free nucleon. The two predicted spectra for that part of the spectrum due to the CVC mechanism are given in Fig. 4. Bertero *et al.*[5] give the star yield based on the CVC mechanism as a fraction of the number of endings which undergo nuclear interactions with heavy nuclei. The number of these endings expected is determined by multiplying the number of endings in this sample by the fraction of endings which undergo nuclear interaction with heavy nuclei as determined by Morinaga and Fry.[2] Both spectra are calculated for capture by Ag nuclei. However, the results for Br are not expected to be much different from this since the percentage of stars due to the CVC mechanism is about the same for Ca, Ag, and Pb.[5]

As indicated in Fig. 4, high-energy protons are not found in this experiment in anywhere near the quantity predicted. Consider first the energy region above 30 MeV. Only (4±2) stars—error limits in this section reflect counting statistics only—were found in this energy region, whereas 245 and 205 stars were predicted for the $M^*=M$ and $M^*=\frac{1}{2}M$ models respectively. Thus the number of observed stars above 30 MeV is a factor of $(1.6\pm0.8)\times10^{-2}$ less than predicted for $M^*=M$, and $(2.0\pm1.0)\times10^{-2}$ less than that for $M^*=\frac{1}{2}M$. It should be noted that Bertero *et al.*[5] state that they may have overestimated the predicted percentage of stars by a factor of 2 or 3 because they neglected transmission losses in the nucleus. However, this correction still would not make theory and experiment consistent here. The only uncertainty in the experimental results in this energy region, besides that due to statistics, is the possibility of a small (≤13%) contamination of light-nucleus events in the heavy-nucleus sample.

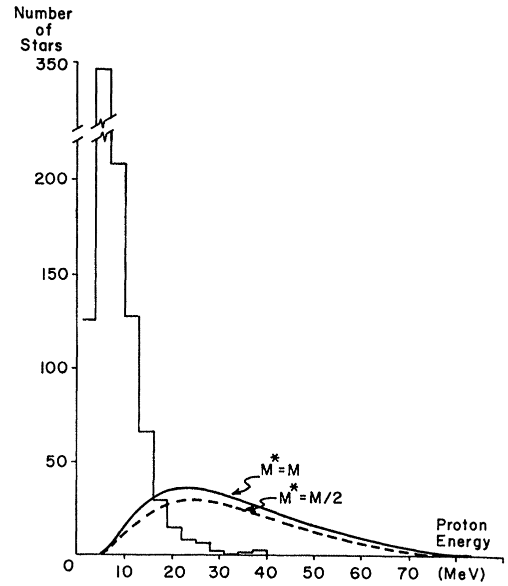

FIG. 4. Comparison of experimental results with theoretical predictions of Bertero *et al.* The histogram represents the experimental proton spectrum, corrected for α-particle emission and stars off light nuclei. (Pion star production was negligible.) The solid curve represents just that part of the proton spectrum predicted by the mechanism of Bertero *et al.* for $M^*=M$. The dotted curve is the same as the solid one except that $M^*=\frac{1}{2}M$.

In addition to a small number of stars above 30 MeV, there is no evidence of the predicted peak in the CVC spectrum near 25 MeV. Yet Bertero *et al.*[5] state that the position of the peak is reliable, even if the shape of the tail of their spectrum is somewhat uncertain. The observed number of one-prong stars between 20 and 30 MeV is (26±5.6). Since 140 stars for $M^*=M$ and 65 for $M^*=\frac{1}{2}M$ are predicted in this energy region, the observed results are smaller than predictions by factors of $(1.9\pm0.4)\times10^{-1}$ and $(4.0\pm0.8)\times10^{-1}$, respectively. These factors represent upper limits only, since the Singer mechanism as well as the CVC mechanism predicts stars in this energy region.

Finally the complete absence of stars above 40 MeV is quite at odds with the prediction of 125 stars above 40 MeV predicted for $M^*=M$ or 111 for $M^*=\frac{1}{2}M$.

TABLE I. Comparison of the theoretical predictions of Bertero *et al.* with the results of this experiment.

Kinetic energy of emitted protons (MeV)	Number of stars predicted $M^*=M$	$M^*=\frac{1}{2}M$	Number of stars observed
>20	385	270	30
>30	245	205	4
>40	125	111	0

It should be noted that Singer's mechanism predicts a maximum proton energy of 50 MeV and the CVC mechanism a maximum of 90 MeV. Thus, the presence of any muon stars with proton energies between 50 and 90 MeV would give clear evidence that at least some interactions were taking place through the CVC mechanism. No such stars were found. All of the above results comparing the number of stars predicted and observed are given in Table I.

In conclusion, this experiment finds no supporting evidence for the CVC mechanism proposed by Bertero *et al.*[5] The experimental results are quite consistent with the predictions of Singer.[4] If the mechanism of Berteor *et al.*, is present at all, it occurs at least a factor $(2.0\pm 1.0)\times 10^{-2}$ less often than predicted.

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Masses and Decay of Al^{24}, P^{28}, Cl^{32}, Sc^{40}, and Their $T_z=0$ Analog States*

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The β spectra and γ transitions in the decay of Al^{24}, P^{28}, Cl^{32}, and Sc^{40}, produced by the (p,n) reaction in the UCLA sector-focused cyclotron, have been measured with a wedge-gap magnetic spectrometer and a 3-cm³ lithium-drifted germanium detector. An on-line SDS-925 computer was used to separate, by half-life analysis, the activity of interest from longer-lived contaminants. The half-lives were measured to an accuracy of 0.5% and decay schemes are proposed. The ground-state masses are determined to 25–40 keV. In all cases, observation of a superallowed β transition unambiguously determines the $T=1$, $T_z=O$ analog state. The excitation energies of these analog states are measured to an accuracy of 3 keV. Mass relationships are used to predict from these data the excitation energy of the first $T=2$, $T_z=O$ analog states.

I. INTRODUCTION

THE decay properties of the positron emitters of the $2s$-$1d$ shell have gained considerable interest in the past years. On one hand, the theoretical interpretation of the low-lying states of the stable isotopes of this region of the light nuclei has been the subject of numerous papers. Calculations of energy spectra have been done using the SU_3 classification of nuclear states,[1–3] Hartree-Fock methods,[4,5] and the intermediate-coupling shell model.[6,7] The success of these computations requires as a next step a comparison of the theoretical transition rates with experimental values. For this purpose, accurate experimental branching ratios of the positron spectra emitted by the proton-rich parent of such nuclei, as well as of the subsequent γ transitions, are needed.

On the other hand, an accurate determination of the ground-state masses of β^+ unstable nuclei and of the isobaric analog states of their daughters is needed to make a bridge between the experimental observation of highly excited analog states in such reactions as (p,n) (p,d) (p,t) and their theoretical prediction. Recent isobaric mass formulae or mass relationships[8,9] are able to predict the position of isobaric analog states to a high degree of accuracy. To stay ahead of these theoretical predictions, or to provide useful data for their improvement, it has now become necessary to determine the energy of isobaric levels to a few kilo electron volts.

The present work describes the measurement of the β and γ spectra from Al^{24}, P^{28}, Cl^{32}, and Sc^{40}. The use of a large wedge-gap magnetic spectrometer permitted the measurement of the ground-state masses to an accuracy of 25–50 keV. The momentum resolution of the instrument allowed an accurate unfolding of the β spectra

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