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ABSTRACT

Negative muons stopped in a propane bubble chamber form mesic atoms with carbon nuclei. Subsequently they either decay by their usual mode or interact with the nucleus. Based on a sample of 2519 mesons, the probability for interaction is found to be (7.4±0.8)%, and the total absorption rate of muons in carbon becomes (0.36±0.04) $\times 10^5$ sec^{-1}. The result is found to be in satisfactory agreement with theory.

A MEASUREMENT OF THE TOTAL ABSORPTION RATE OF MUONS IN CARBON*

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I. INTRODUCTION

When a negative muon is brought to rest in matter, it is captured into Bohr orbits about a nucleus. Later it either decays through its usual mode into an electron and two neutrinos, or alternatively interacts. The rate at which the latter process can proceed is a function of the charge, Z, of the nucleus.[1,2]

Several authors have measured the interaction rates of muons with different nuclei.[3,4,5] The usual method has been to stop the mesons in a target of the required material, and then detect the emergent decay electrons with counters. From the number of muons entering the target and the number of decay electrons leaving, the proportion of muons interacting could be estimated. Such measurements have yielded accurate values for most nuclei investigated.

However, with light elements, the decay process is dominant and difficulties arising from background effects are encountered. For carbon, only about 10% of the mesons interact, and the capture rate has not been determined to much better than ± 25%. This is particularly unfortunate in that a great deal of interest has recently centered upon muon capture in carbon.

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The reaction which leads to the ground state of ^{12}B provides a test of the universal Fermi interaction theory,[6] and recent measurements of the partial rate for this process have depended to some extent upon the rather poorly known total absorption rate.[7] The determination of this latter quantity can, however, be improved by using a propane bubble chamber.

A negative muon, stopped in propane (C_3H_8), is captured into orbits about a carbon nucleus.[8] The presence or absence of an electron at the end of the meson's track gives a direct indication as to whether the muon decayed or interacted after stopping in what is effectively a carbon target. Counting the number of mesons that decay, N_d, and the number that interact, N_i, and assuming a value for the decay lifetime, τ_d, one can obtain the total absorption rate from the expression

$$\Lambda_i = \frac{N_i}{N_d \cdot \tau_d} \quad . \qquad (1)$$

II. METHOD

The photographs examined were taken with the 30-in. propane chamber operating in a magnetic field of 13 kgauss. No special exposure was made for this experiment; instead, film already existing of the 1.15 Bev/c K^--meson beam was used. The K mesons have a background consisting mainly of muons, some of which stop in the chamber and are suitable for our purpose. As can be inferred from the results presented later, this background is composed of approximately 90% muons and 10% pions.

While only comparatively few of the muons interact, all the stopped pions, of course, are captured. This makes it imperative that one should be able to correct adequately for the latter.

As a first step, the proportion of pions accepted into the sample is reduced by using the magnetic curvature of the tracks. In order to ensure a sufficient length of track for measurement, only particles having a visible range of greater than 25 cm in the chamber are considered. A template was prepared which shows the expected magnetic curvature of a muon track over this final length. Because of multiple scattering, about half the muons in practice have a curvature greater than this average value, the remainder having less. It is because of multiple scattering that some pion tracks simulate those of muons. A rigid criterion is adopted whereby only those tracks are accepted that have a greater curvature than that indicated by the template. This procedure, while rejecting many legitimate muons, makes pion acceptance improbable. The actual extent of the reduction in the pion contamination was determined in a subsidiary experiment. This consisted of taking tracks of positive pions, readily identifiable by their characteristic decay mode, and comparing them with a template for a positive muon. It was found that only 7 ± 2% of the pions had a greater curvature than that expected for the muon. As half the muons satisfy the criterion, the method of selection reduces the background by a factor of seven. Of the particles accepted into the sample, therefore, a little over 1% are pions.

The correction for these remaining pions is based upon the difference in the prong distributions of the capture stars. In contrast to pions, muons only comparatively rarely produce visible prongs. Morinaga and Fry have investigated the characteristics of stars arising from muon capture in the light elements of nuclear emulsion.[9] It was found that about 90% of the events had no visible secondaries. This figure, however, cannot be taken as applying to our work because of the greater efficiency for detecting short tracks in nuclear emulsion. The appropriate number of zero-pronged events is, consequently, expected to be higher. Nevertheless, the results of Morinaga and Fry are helpful. The emitted protons were found to have an energy spectrum which extended no higher than 15 Mev. In addition, the energies of the secondaries from the two or more pronged stars, were such that only rarely would more than a single prong have been resolvable had the stars occurred in a bubble chamber. It follows then that if stars are found emitting more than one prong or alternatively a single prong of energy greater than 15 Mev in our sample of supposed muons, these events can be discarded as examples of pion capture. However, not all pion stars are so readily recognized, because some give rise to low visible-energy releases.

In order to be able to estimate, from the observed energetic disintegrations, the number of small stars that are also present, a knowledge of the prong distributions of pion stars is required. In this connection, a subsidiary investigation was carried out on 141 pion-capture stars. The primaries for these events were identified through their having been created in Λ^{o} -hyperon decays. The results are shown in the first line of Table I, the single-pronged events being divided according to the energy of the prong, assuming it to be a proton. The final three columns provide a total of 62 events which have star characteristics that cannot be simulated by muon captures, and these compare with 79 events giving low visible-energy releases. The number of pions that give small stars in our sample of supposed muons will then simply be the number of mesons found to give energetic disintegrations, multiplied by the factor 1.3 ± 0.2 (i.e., 79/62).

A confirmatory check on this estimate is provided by the curvature selection already discussed. It has been shown that 7% of all pions satisfy the criterion. Thus, if a record is made of those pions rejected, one can infer from this the number that were accepted.

Summarizing the procedure, then, tracks of length greater than 25 cm are selected if they have a curvature greater than that which a muon would have in the absence of multiple scattering. It is observed whether the particle gives a decay electron or not, and the star characteristics of any interactions are noted. An additional record is made of those particles that produce stars but do not satisfy the curvature condition.

III. RESULTS

A total of 2544 stopped particles were accepted by the criterion, and, of these 2338 decayed and 206 interacted. The prong distribution of the capture stars is given in the second line of Table I.

Table I

Characteristics of capture stars

Primary particle	Number of prongs				
	0	1^a	1^b	2	3
Pions	58	21	45	14	3
Muons[c]	190	3	9	4	0

[a] Energy of the prong less than 15 Mev.

[b] Energy of the prong greater than 15 Mev.

[c] Uncorrected for pion contamination.

In addition to these events, there were 129 pions that gave energetic stars but were rejected by the muon-curvature criterion. On the basis of 7% of the pions satisfying the criterion, one would have expected about ten energetic stars within the sample. It is noted from the table that there are in fact 13 events in the final three columns. Following the arguments of the previous section, this number of energetic stars indicates a total pion contamination within the sample of 30 ± 5 events [i.e. $(1.3\pm0.2)(13\pm3.6) + 13$]. Subtracting them from the total, the number of interactions remaining is 176, and these are attributed to muon captures.

There are several other corrections to be considered:

(a) It is to be expected that there might be observational biases associated with events close to the edges of the chamber. If a decay were to occur very close to a wall or window, the electron could conceivably leave the chamber undetected. The event would then be erroneously classed as a zero-pronged interaction. On the other hand, in a similar location a particle might be mistakenly thought to have left the chamber without stopping. If so, it would have been overlooked during scanning. A study of the distribution of events throughout the chamber reveals that it is the latter effect that is important. Approximately five stars have apparently escaped detection in the regions of the chamber less than 0.5 cm from the upper and lower windows. Therefore, this number must be added to the total.

(b) There are several stray Compton electrons on each picture, and if any were to accidentally coincide with zero-pronged events, the muons would appear to have decayed. This effect was found to be negligible.

(c) Because of the continuous range of energies available to the electron from muon decay, some electrons might be of too small a range to be detected. A study of the expected energy spectrum shows this correction also to be insignificant.

(d) A process that leads to mistaking some muon captures for decays arises when the residual nucleus undergoes β- transition following the absorption of a muon. It is expected that about 18% of muon interactions produce boron-12 through the process:[6]

$$\mu^- + {}^{12}C \rightarrow {}^{12}B + \nu. \qquad (2)$$

The ^{12}B nucleus then beta-decays with a lifetime of 33.15±0.2 msec according to the reaction,[10]

$$^{12}B \rightarrow e^- + {^{12}C} + \bar{\nu} . \qquad (3)$$

If this reaction happened to occur quickly, the electron's track would be photographed. It would then be impossible to distinguish the event from a direct decay of a muon. In order to be able to estimate the correction for this effect, one needs to know the time during which the beta decay can occur and still produce an electron that will leave a visible track. The interval between the beam pulse and the light flash varies between 6 and 8 msec. This separation, however, only provides an upper limit to the time available, because an electron produced near the end of this delay will not have had sufficient time in which to form a track capable of being photographed. As it is difficult to devise a precise correction, we simply assume that all decays occurring in the first 4 msec are photographed. An adequate systematic error is then included in the final result to cover both the extreme cases of either none or alternatively all of the beta decays being recorded up to 8 msecs. From this effect four events should be transferred from muon decays to muon interactions.

(e) Finally, it must be remembered that if impurities consisting of heavy nuclei are present in the propane, they will seriously affect the measured capture rate. There was no reason to suspect that the chemically pure propane was contaminated in this way but, nevertheless, a sample of the liquid was subjected to mass spectrographic analysis at the completion of chamber operation. No impurities could be found; the analysis showed an upper limit of one in 10,000 for the number of nuclei of heavy elements present compared to those of carbon.

The finally corrected data yield a total of 2519 stopped muons, of which 185 interacted and 2334 decayed.

In order to derive the capture rate, a value for the decay lifetime of the muon has to be assumed. Based on the work of several authors,[11] the value chosen is 2.22×10^{-6} sec. There are several reasons why the lifetime of a bound muon should be different from that of the free meson.[12] These effects have been shown, however, to be negligible in the case of muons bound to carbon nuclei.[13]

Using relation (1), one finds the total absorption rate for muons in carbon to be

$$\Lambda_i = (0.36 \pm 0.04) \times 10^5 \text{ sec}^{-1}. \qquad (4)$$

The error arises in the following manner. From the number of muon interactions there is a statistical uncertainty of 7.5%. The errors in the correction for the pion contamination give a contribution amounting to 3%, while observational biases introduce a further 1%. These effects are statistically independent and yield a total of 8%. In addition there is a systematic error of about 2% associated with the correction for the beta decay of ^{12}B, and an uncertainty of 1% in the muon lifetime. The combination of all these effects yields the quoted error of 11%.

IV. DISCUSSION

The total absorption rate as measured in this experiment is somewhat lower than previous estimates. Using a propane chamber, Fields, McIlwain, and Fetkovich obtained a value of 0.45×10^{5} sec^{-1} based on 1000 stopped muons.[14] The counter technique employed by Sens[3] and by Bell and Hincks[4] yielded values of $(0.44\pm0.10)\times10^{5}$ sec^{-1} and $(0.55\pm0.15)\times10^{5}$ sec^{-1} respectively. A weighted mean of all the estimates gives

$$\Lambda_t = (0.40\pm0.03)\times10^{5}\ sec^{-1}. \qquad (5)$$

It remains to compare this result with a theoretical prediction. It is recalled that the simplest model, assuming a point nucleus, requires that the muon capture rate should have a Z^4 dependence. Wheeler took into account the finite size of the charge distribution and introduced an effective value of Z.[1] For carbon, Z_{eff} is 5.75. Primakoff extended the treatment to include the limitations imposed on the final states by the Pauli exclusion principle.[2] Finally, Flamand and Ford noted that the finite size of the nucleus modifies the muon wave function--an effect that reduces the muon density within the nucleus.[15] The theory of Primakoff as refined by Flamand and Ford, requires a total absorption rate for carbon of 0.41×10^{5} sec^{-1}. The agreement with experiment is seen to be very good, though it should be borne in mind that the theory actually predicts only the trend in the variation of the capture rate with Z; it does not necessarily give the exact value for each individual nucleus.

Lastly, it should be noted that the small change in the total absorption rate from the value previously adopted does not significantly effect the recent measurements of the partial rate for the reaction leading to the ground state of ^{12}B.[7]

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