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$$K(q)=\frac{3}{2}\left(\frac{M_d}{U}\right)^2\left(\frac{mM_d-p_1\cdot d_2}{2mM_d}\right)^2\frac{mM_d-n\cdot d_2}{2mM_d}\,\frac{mM-n\cdot d_1}{2mM_d},$$

where p_1, d_1, and d_2 are the proton, initial- and final-deuteron center-of-mass 4-momenta, respectively; U= total energy in the c.m. system; m = proton mass; M_d = deuteron mass; $n=d_2-p_1$.

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Relative Capture Rates for Slow π^-, K^-, Σ^- in a Neon-Hydrogen Mixture

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We find the relative hydrogen capture rates for π^-, K^-, and Σ^- in a 24 mole percent mixture of neon in hydrogen to be $(17\pm5)\%$, $(26\pm5)\%$, and $(48\pm6)\%$, respectively. A possible mechanism for these differences is presented.

INTRODUCTION

The details of the atomic processes which precede the nuclear capture of slow, heavy, negative particles have long been of interest. If the fundamental physical properties of nuclei and/or elementary particles are to be investigated using these absorptions, it is necessary to know the atomic state from which nuclear absorption occurs. When the stopping material is an elemental mixture, the first priority is clearly the delineation of the fraction of absorptions occurring on each element. The earliest estimate of this fraction was given by Fermi and Teller[1] in their so-called Z law which states that the relative capture probability of negative mesons by the atoms of chemical compounds is proportional to NZ, where Z is the atomic number and N is the number of atoms in the compound. While the general tenor of the experimental data[2] has been confirmatory of this prediction, many deviations are known. In particular, the class of hydrogenous mixtures and compounds, for which the concept of a degenerate electron gas is a poor approximation, requires a different approach since a mesonic hydrogen atom forms a small system relative to atomic dimensions, and is capable of readily diffusing throughout the stopping medium. Because of the lower energy states available for heavy mesonic atoms, the meson can undergo transfer from the proton to a heavier atom. Early experiments[3] with negative muons indicated that all muons interact with neon when the neon concentration in liquid hydrogen is as small as 30 ppm. The problem is more interesting for strongly interacting particles where the interaction rate between the negative particle and proton may be sufficiently rapid so that the mesonic atom disintegrates prior to the transfer of the meson from the proton to a more massive system.

Relative capture data for heavy, negative, strongly interacting particles stopping in liquid hydrogenous mixtures is somewhat sparse. However, recently, Pawlewicz *et al.*[4] have measured the fraction of antiprotons annihilating at rest on hydrogen in a propane bubble chamber. They have concluded that antiprotons are ten times more likely than pions to be absorbed by hydrogen. Assuming the initial fraction of hydrogen captures for $\bar{p}$ and π^- to be the same, this implies that the transfer probability from hydrogen to carbon is much greater for π^- than for $\bar{p}$. The purpose of the present work is to present our data for a similar problem, namely, the relative hydrogen capture rate for π^-, K^-, and Σ^- in a neon-hydrogen mixture. Our data were obtained from an exposure of the BNL-Columbia 30-in. hydrogen bubble chamber filled with a 24 mole percent admixture of neon in hydrogen (1 neon atom to 6.3 hydrogen atoms). Since the principal goal of the experiment was to study stopping K^- interactions, our π^- and Σ^- data have been obtained by utilizing the reaction products of K^- interactions.

EXPERIMENTAL RESULTS

Capture of π^- by Hydrogen

When K^- mesons are absorbed by nuclei, one of the principal final-state products is a Λ hyperon, which in approximately $\frac{2}{3}$ of the cases decays into a proton and a π^-. Since the π^- is easily identified, slow, and therefore likely to interact in the chamber, Λ decay has been used as the source of π^-'s in this experiment. Because the low-energy inelastic pion-nucleon cross section is not large, it is expected that few (<5%) of these pions will interact in flight. We have excluded from our sample only those events where the pion left the fiducial volume, decayed, or where it patently interacted in flight. A histogram (not shown) of the residual range of the π^- at the point of interaction gave no evidence for any substantial number of in-flight events. With these criteria, our sample contained 4906 stopping-π^- interactions.

The fraction of π^- captures by hydrogen was determined by measuring the electron-positron pair energy spectrum from the π^- events, from which the γ-ray spectrum was deduced. The kinematics of $\pi^- p$ interactions are well defined – the expected γ-ray spectrum consisting of monoergic γ rays at 130 MeV and a flat spectrum of γ rays centered at 70 MeV with a full width of ≈30 MeV. Each event was double scanned for the presence of an energetic electron-positron pair ($E_+ + E_- > 30$ MeV). The measured energy spectrum for 132 of the observed pairs is shown in Fig. 1. We were unable to measure the energy of twelve additional pairs although they gave all indications of emanating from a pion stoppage. Figure 2 shows the resulting energy

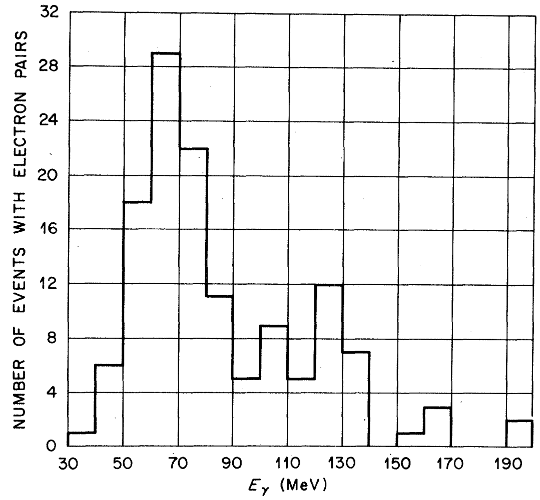

FIG. 1. Measured energy spectrum for electron-positron pairs observed in this experiment.

spectrum of the γ rays after correction for the finite volume of the bubble chamber and the energy dependence of the conversion length. γ rays of this energy (>30 MeV) can originate from π^- capture by hydrogen ($\pi^- p \to \gamma n$, $\pi^- p \to \pi^0 n \to \gamma\gamma n$) or from radiative pion capture by neon. This latter process[5] has been estimated to account for about 1% of the pion captures by light nuclei. Thus about 40 of the higher-energy γ rays in the sample have this origin. The remaining high-energy γ rays (>100 MeV) should be due to hydrogen capture ($\pi^- p \to \gamma n$), while those with energy between 30 and 100 MeV presumably represent π^0 decay. The ratio of charge exchange to radiative $\pi^- p$ interactions (Panofsky ratio) deduced from our data is 1.75 ± 0.3, which is consistent with recent determinations of this quantity.[6] After accounting for

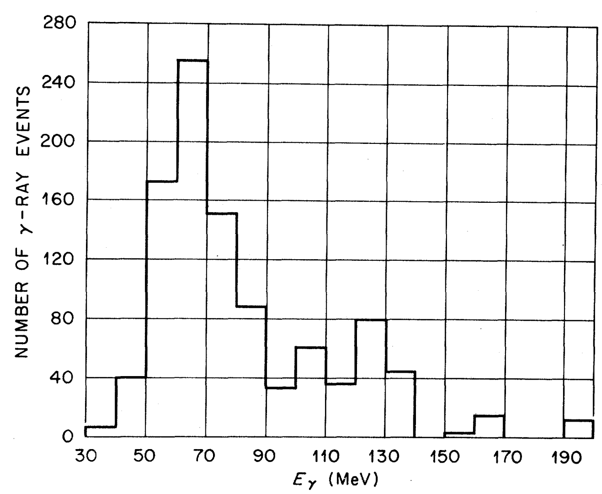

FIG. 2. γ-ray spectrum (corrected for detection efficiency).

the radiative neon captures, our spectrum corresponds to 583 hydrogen captures. The efficiency of the double scan was estimated to be 90%. However, the spatial distribution of the observed electron-positron pairs indicated that $(22 \pm 5)\%$ of the more steeply dipping pairs were lost. Inclusion of these corrections implies that $(17 \pm 5)\%$ of the stopping pions were captured by hydrogen in our mixture. (The error has been increased because of the unprocessed events.)

Capture of K^- and Σ^- by Hydrogen

Although our data concerning the relative hydrogen capture rates have previously been published,[7,8] we include a brief resumé for completeness and also because expanded statistics for the K^- data have modified the published value. Stopping K^- mesons were selected on the basis of the projected radius of curvature on the scanning table. A histogram of the residual range of these selected K^- tracks[7] showed that a large percentage of the events were overstopped. After removal of the remaining in-flight K^- decays by using the number of observed τ decays and their known branching ratio, our sample contained 2193 events presumed to be "at rest" captures by either neon or hydrogen. Separation of hydrogen from neon interactions was effected by means of the $K^-p \to \Sigma^\pm \pi^\mp$ reaction which yields a collinear $\Sigma^\pm$ and $\pi^\mp$ with unique-momentum pions. Application of the known $(K^-p)_{\text{rest}}$ branching ratios[9] yielded 544 hydrogen captures in 2193 events or a hydrogen capture probability of $(26 \pm 3)\%$. As a check of our results, the angular distribution of all $\Sigma\pi$ pairs in our sample was compared with a similar distribution obtained for light nuclei from emulsion studies by Lovell and Schorochoff.[10] A comparison of the two angular distributions indicates that our data have an excess of events near $\cos\theta_{\Sigma\pi} = -1$ (due to the presence of hydrogen captures in our sample) which corresponds to a hydrogen capture rate of $(26 \pm 5)\%$.

The Σ^- used in this experiment come from the stopping K^--hydrogen interactions, where the reaction products are a collinear $\Sigma^-\pi^+$ pair, each of unique momentum, 173 MeV/c. By further requiring the momenta of these collinear Σ^- and π^+ to be within 1 standard deviation of this value, our sample contained 639 Σ^- events. Examination of the Λ spectrum associated with these Σ^- endings[8] together with the known branching ratios for $\Sigma^-p \to \Sigma^0 n$ and $\Sigma^-p \to \Lambda^0 n$ as well as for Λ decay leads to the conclusion that $(48 \pm 6)\%$ of the at-rest Σ^- captures occur on hydrogen.

DISCUSSION

Summarizing our data, we find the percentages of negative stopping particles which undergo hydrogen capture in a 24 mole percent neon mixture to be

$$P_\pi = (17 \pm 5)\%\,, \quad P_K = (26 \pm 5)\%\,, \quad P_\Sigma = (48 \pm 6)\%\,.$$

The failure of these numbers to agree either with each other or with the Fermi-Teller Z law which predicts $P = 39\%$ for all particles suggests that either there exists a mass dependence of the initial capture rates or that possibly atomic or nuclear effects are involved. Since no satisfactory theory of the initial capture process exists, we consider the latter. Because of Stark mixing of the various atomic levels, strongly interacting particles are captured predominantly from atomic S states in liquid hydrogen. Since the relative strengths[11] of the low-energy S-wave interactions, in increasing order of strength, are πp, Kp, and Σp, it is plausible that the longest-lived specie would be π^-p while Σ^-p would have the shortest lifetime. Since the probability of the meson's being transferred from hydrogen to neon is directly proportional to the lifetime of the mesonic hydrogen atom, we would expect the π^- to be transferred the most and Σ^- the least, which is consistent with our observations.

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