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K^+ Total Cross Sections as a Test for Nucleon "Swelling"

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A measurement of the K^+ total cross sections on carbon and deuterium and their ratios from 450 to 740 MeV/c has been carried out at the Brookhaven Alternating Gradient Synchrotron. The observed ratios depart significantly from those expected from conventional nuclear physics calculations. The data are compared with models of nucleon "swelling," which ascribe the effect to quark deconfinement or, alternatively, to vector-meson exchange with density-dependent masses.

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The low-momentum K^+ holds a very special position as the weakest of any available strongly interacting probes. It has a mean free path in the nucleus larger than 6 fm. Thus the K^+ is capable of probing the entire volume of the nucleus.[1] Single scattering of the K^+ with a nucleon in the nucleus dominates scattering, and only small and calculable higher-order corrections are needed. These properties make the K^+ the ideal hadronic probe of nuclear-medium effects, and a useful complement to leptonic or electromagnetic probes. The nucleon is a dynamical entity and its internal structure can, in principle, be altered by its surrounding nuclear environment. This work reports an experiment in which the K^+ is used to compare the nucleon in the nucleus with a free nucleon.

Siegel, Kaufmann, and Gibbs,[2] recognizing the special properties of the K^+ probe and its analogy to the leptonic probes of the European Muon Collaboration (EMC) effect, argued that if the nucleons in the nucleus "swell" (partial deconfinement), the effect could be detected by measuring the ratio of the K^+ total cross section on carbon to that on deuterium. At low momenta (<800 MeV/c) the K^+N interaction is dominated by the S_{11} channel. The authors predicted that a 10% increase in nucleon size carries with it a (5–10)% increase in $\delta_{S_{11}}$. Such an increase would be consistent with that of the quark-confinement scale predicted by Close *et al.*[3] Siegel, Kaufmann, and Gibbs calculated the above-mentioned ratio in an optical model and concluded that an increase of 10% in the S_{11} K^+N phase shift would result in ratios significantly higher than the upper limits of the calculation with free K^+N phase shifts and conventional medium corrections which do not include nucleon "swelling."

Brown, Dover, Siegel, and Weise[4] took another view of the swelling effect and pointed out that in meson-exchange models of the K^+N interaction, ρ and ω exchanges play a dominant role. The vector-meson mass is density dependent which in turn implies a density-dependent K^+N scattering amplitude. The elastic scattering and reaction cross sections were then calculated in an optical potential derived from the scattering amplitude. They also calculated the ratio of total cross sections of K^+C to K^+d, with the result that a reasonable density parameter produced an increase in the ratio similar to the predictions of Siegel, Kaufmann, and Gibbs. Weise[5] has compared these alternative models and discussed their interpretation in terms of nucleon swelling. In this paper, the term nucleon swelling is meant to encompass either the quark-based or meson-exchange viewpoint. This total-cross-section measurement cannot distinguish between these alternative explanations.

K^+p and K^+d scattering have been studied extensively but prior to this experiment the only K^+-nucleus data available were total-cross-section measurements on C at momenta above 714 MeV/c,[6] and differential elastic cross sections on C and Ca at 800 MeV/*c*.[7] The lowest-momentum total-cross-section datum measured by Bugg *et al.*[6] seems to deviate from the conventional calculations but the momentum is too high and uncertainties too large to establish a significant deviation. The elastic-scattering measurements by Marlow *et al.*[7] contain an overall 17% normalization uncertainty that prevents any definite conclusion.

In the present work total K^+ cross sections on carbon and deuterium were obtained by placing targets of graphite and deuterated polyethylene (CD_2) in kaon beams available from the Brookhaven Alternating Gradient Synchrotron (AGS). The experiment was done in two parts: the first in the C2 branch of the Low Energy Separated Beam I (LESB-I) and the second in the C6 branch of LESB-II. Data were obtained at 453, 507, 559, 641, 703, and 740 MeV/*c* (kaon momenta at the center of the target).

Figure 1 is a schematic diagram of the experimental apparatus. The concept of "total cross section" for charged particles involves the subtraction of the divergent Coulomb and nuclear-Coulomb interference terms which dominate the cross section as the scattering angle approaches zero. The method used here consisted of measuring particles scattered into an array of nine 6-mm-thick scintillation disks which subtended a set of increasing solid angles ranging from 40 to 470 msr.

Particle identification was provided by a tunable differential Čerenkov counter using radiator cells containing liquids with refractive indices suitable for kaons ranging from 500 to 760 MeV/*c*, corresponding to 450–740 MeV/*c* at the target center. Using the Čerenkov counter, combined with the time of flight, resulted in a discrimination factor for kaons against pions of better than 10^5. Beam intensities on target ranged from 500 K^+/spill at 500 MeV/*c* to 10^4 spill at 760 MeV/*c* with a 1.2-sec spill every 3.0 sec. Lead shielding was provided as shown to maintain rates in the transmission scintillators below 2×10^5/sec. A thin 5-cm-diam scintillator was located just upstream of the target position to limit the incident beam size to less than the smallest (6 cm) target diameter. A target-changing mechanism was employed to cycle the carbon, polyethylene, and open holder positions at roughly 5-min intervals. The target thicknesses, about 3.6 g/cm^2, were matched to produce nearly equal kaon energy losses. The hydrogen weight fraction in the CD_2 target was measured to be $(2.6\pm0.5)\%$ by detecting the 2.224-MeV γ rays from the $^1H(n,\gamma)^2H$ reaction with a neutron beam at the Brookhaven High Flux Beam Reactor.

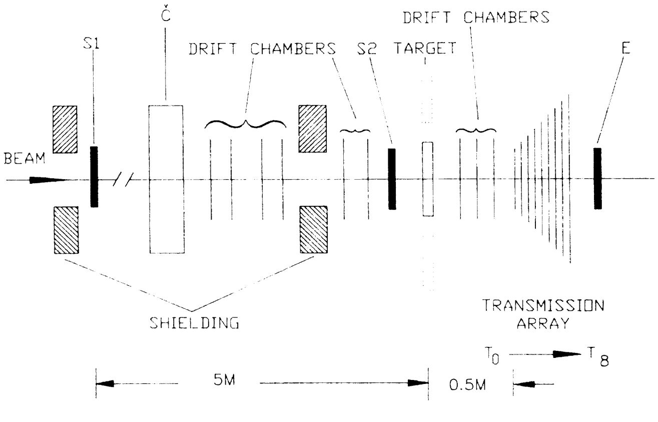

FIG. 1. A schematic drawing, not to scale, of the experimental apparatus. *S*1 and *S*2 represent beam-defining scintillators, and *Č* the tunable Čerenkov counter. The *E* counter served to monitor the beam and define transmission array efficiency. Drift chambers allowed determination of particle trajectories and were essential for the evaluation of systematic corrections.

Logical OR circuitry among the scintillator disks provided a set of scaler readings S_i, which represent the cumulative sum of all particles scattered into the solid angles Ω_i. The same was done without the target in place. The partial cross sections are given by the relation

$$\sigma(\Omega_i)=\frac{1}{nt}\ln\left[\frac{S_i^0/B^0}{S_i/B}\right],$$

where nt is the number of scatterers/cm^2, B is the number of incident K^+, and the superscripts on S_i^0 and B^0 refer to the empty-target measurement. Certain systematic errors were unavoidably present in the experiment and their evaluation was facilitated by the drift chambers, which provided coordinates for a selected fraction ($\simeq 2.5\%$) of the events. The track descriptors, as well as the scaler readings, were written to magnetic tape for subsequent analysis.

An extrapolation to zero scattering angle is made after correction for the Coulomb and nuclear elastic-scattering amplitudes. We follow the description of Kaufmann and Gibbs[8] and use their computed corrections. These authors show that, while the corrections are somewhat model dependent, the extrapolation to zero scattering angle results in a total cross section which is virtually model independent. The deuterium cross section is obtained by extrapolation to zero solid angle of the difference $\sigma_d=\frac{1}{2}(\sigma_{CD_2}-\sigma_C)$.

The analysis of statistical errors for the cross section follows the prescription of Amaldi *et al.*[9] Typically about $(2\text{–}3)\times10^7$ events are analyzed for each target at each momentum, with a consequent cross-section precision of (0.5–1.0)%. The deuterium total cross sections obtained in this experiment are in good agreement with the data of Carroll *et al.*[10] Figure 2 is illustrative of the analysis procedure for 641 MeV/*c*. Shown in the figure are the linear extrapolations to zero scattering angle after the corrections for Coulomb and nuclear scattering.[8] At 641 MeV/*c*, the procedure was tested by altering the distance between the target and the counter array. The results were consistent with those obtained at

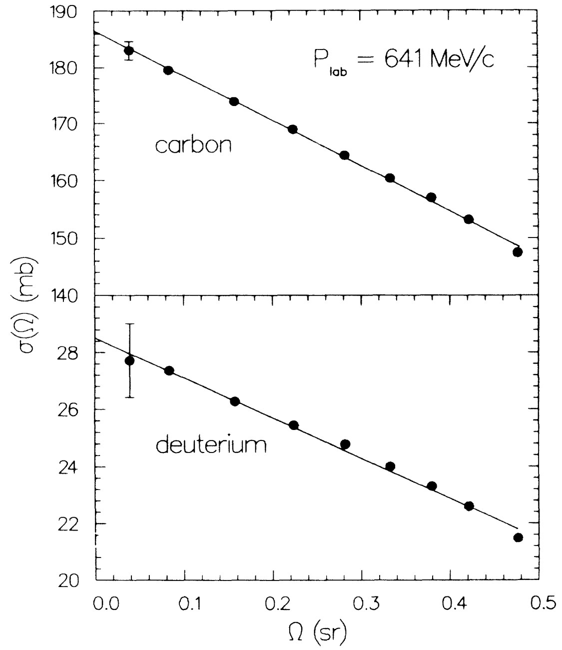

FIG. 2. An example of the extrapolation technique used to determine the total cross sections. The curves are linear least-squares fits. A representative ± 1 standard deviation error bar is indicated.

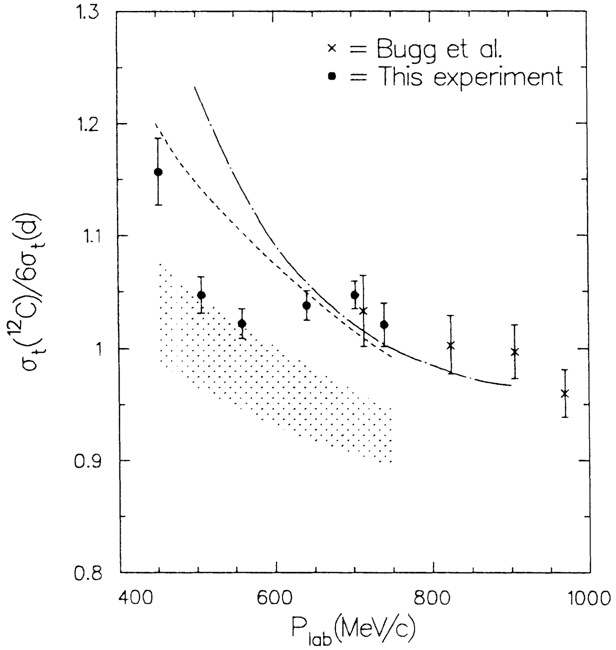

FIG. 3. The results of the present experiment in the form of the ratio $\sigma_C/6\sigma_d$. The earlier data of Bugg *et al.* (Ref. 6) at higher momenta are also shown. The shaded band corresponds to the range of ratios allowed by varying the parameters in a "conventional" calculation, as defined in Ref. 2; the dashed curve indicates the effect of a 10% increase in the S_{11} K^+N phase shift applied to the upper boundary of the band. The dot-dashed curve shows the prediction of Ref. 4. The data have not been corrected for inscattering from lead collimators. This correction tends to raise the ratio slightly and accentuate the disagreement with the conventional calculations.

the nominal distance. The influence of the beam shape and divergence were evaluated with a Monte Carlo simulation. The effects of both the beam phase space and the target isotopic impurity are small and corrigible.

The two systematic corrections which are the most important in this experiment involved kaon decays and inscattering from the lead collimator depicted in Fig. 1. The effect of kaon decays downstream of the target is momentum dependent and causes an apparent increase in the cross section, since the presence of the target introduces a momentum loss in the exiting beam and a consequent increase in decay rate. Decays of the entering K^+ beam following the Čerenkov counter which were not rejected by time of flight also lead to a correction. This effect is of the order of a few percent and is readily calculable. The inscattering correction is due to those kaons [about (2-3)% of the beam] which have interacted in the lead shielding upstream of the target leading to reaction products which reach the target and the transmission array. The inscattering was apparent from the particle tracks reconstructed from the data on tape. This correction is small, about 2%, but not well determined because of the limited statistics of the tracked events. However, the inscattering correction is observed to increase the ratio. This is plausible in view of the fact that an admixture of inelastically produced hadronic products would tend to lower the ratio; hence the correction would raise it. Figure 3 shows the data not corrected for inscattering. The earlier data of Bugg *et al.*[6] are also shown.

As we discussed in the introduction, within the classical picture of unchanged nucleons in the nucleus, the K^+ interaction with the nucleus can be constructed from the K^+N interaction with great reliability. State-of-the-art calculations are presented as the shaded area in Fig. 3. The data are in significant disagreement with the conventional calculations, where by "conventional" we mean calculations which include all effects considered by Ref. 2 except that of nucleon swelling. The dashed curve shows the predicted ratio based on a 10% increase in the S_{11} phase shift, consistent with the parameters chosen by Close *et al.*[3] to explain the EMC effect. The dot-dashed curve is taken from the prediction of Brown *et al.*[4] Figure 3 shows that the experimental data points between 450 and 800 MeV/c indicate significantly larger cross-section ratios than are predicted by the calculations using the conventional phase shifts, as defined above. It is also evident that the measurements do not reproduce well the momentum dependence suggested either by the models of Ref. 2 or 4. Experimental studies which extend the measurements to several additional nuclei are now in progress.

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