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K_L-Nucleus Total Cross Sections between 30 and 150 GeV: Quantitative Evidence for Inelastic Screening

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We have obtained high-statistics, virtually systematics-free K_L-nucleus total-cross-section data for C, Al, Cu, Sn, and Pb from 30 to 150 GeV. These cross sections have an $A^{0.84\pm0.01}$ dependence over most of the momentum range, in agreement with the Glauber-Franco model. Their magnitudes are, however, not compatible with that model alone: The discrepancies are clearly resolved once one allows for inelastic screening within the nucleus. The data strongly support the theory of this latter effect as given by Karmanov and Kondratyuk.

We present here high-precision data on the momentum dependence of the K_L-nucleus total cross section for a variety of nuclei (C, Al, Cu, Sn, and Pb) in the energy range 30–150 GeV. Such data provide a stringent test of models of high-energy hadron-nucleus interactions, in particular of the quantitative theory[1] of the mechanism of "inelastic screening."[2] This mechanism results from the ability of an incident hadron to dissociate at one point within the target nucleus and to "recombine" subsequently at another. This, in analogy to elastic screening, effectively increases the hadron's mean free path within the nucleus and thus lowers the actual total cross section with respect to the one predicted naively. Evidence for this mechanism has already been provided[3] by analogous studies of neutron-nucleus total cross sections. The inelastic screening term is larger for kaons; results of Murthy *et al.*[3] and Biel *et al.*[4] are somewhat inconsistent with each other as to the magnitude of the effect for neutrons.

Our data were obtained at Fermi National Accelerator Laboratory in a "good-geometry" transmission experiment. In an ideal experiment of this kind, the total cross section is given by the elementary relation $\sigma = (1/LN)\ln N_0/N_T$, where N_0 (N_T) is the incident (transmitted) flux, and L and N are the length and number density of the absorber. N_0 and N_T should be determined with identical detection efficiency. If a single beam is used, N_0 and N_T cannot be determined without the use of an independent secondary monitor, and the latter can easily become a source of systematic errors. For this reason we resorted to a *double-beam technique*: Our beam line carried *two* sharply separated, closely spaced neutral beams of essentially equal fluxes. During any given accelerator pulse, one of these beams contained the absorber, while the other was unattenuated. N_0 and N_T were determined simultaneously via the number of $K_{\mu 3}$ decays in a single decay region far downstream of the absorber. The roles of the two beams were alternated on a pulse-by-pulse basis by repositioning the absorber automatically. As every accelerator pulse contained both attenuated and unattenuated K_L's, sources of systematic error such as intensity or reconstruction efficiency fluctuations were of negligible consequence.

Figure 1 shows the beam line ($M4$ at Fermilab) schematically. The double beam was defined by a steel collimator at 368 ft from the production target. This primary collimator had two holes of 0.5×0.5 in.^{2}, vertically separated by a slab of 0.125 in. These holes defined two beams with nominal production angles of 7.19 and 7.32 mrad. To improve the definition of the two beams, they were further collimated and swept at two stations between the primary collimator and the decay region where the $K_{\mu 3}$ events were detected. In that region the beams were 2.3×2.3 in.^{2} in size and separated by about 0.6 in. The various absorbers were mounted immediately downstream of the primary collimator on a rotating frame so that any one of them could be positioned precisely in either beam. The same device served to alternate the roles of the two beams every pulse.

The $K_{\mu 3}$ decays were detected in a 30-ft-long evacuated region, defined by a thin scintillator in anticoincidence upstream and a multiwire proportional chamber (MWPC) fast hodoscope downstream in coincidence with a two-particle signature required in the spectrometer following the decay region. This spectrometer was closely similar to the one used earlier by us,[5] except for the following changes: (a) all pairs of spark chambers were replaced by MWPC's; (b) a He bag was placed within the analyzing magnet. We recall that a hodoscope behind 10 ft of steel was provided for muon identification.

Each beam had under typical running conditions (3×10^{12} 400-GeV protons on target/pulse) a flux of about 2.5×10^5 K_L's and 1.5×10^6 neutrons per pulse, yielding a total trigger rate of two-particle events with a hit in the muon hodoscope of about 300 per pulse. The full pattern recognition of these events was performed on line in the interval (8 to 12 sec) between pulses (over 70% of the triggers reconstructing), while the kinematics was computed with a detailed field map off line. For each absorber except carbon over 10^6 re-

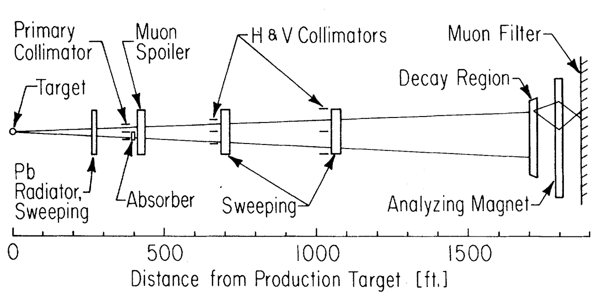

FIG. 1. Schematic of the $M4$ "double-beam" line.

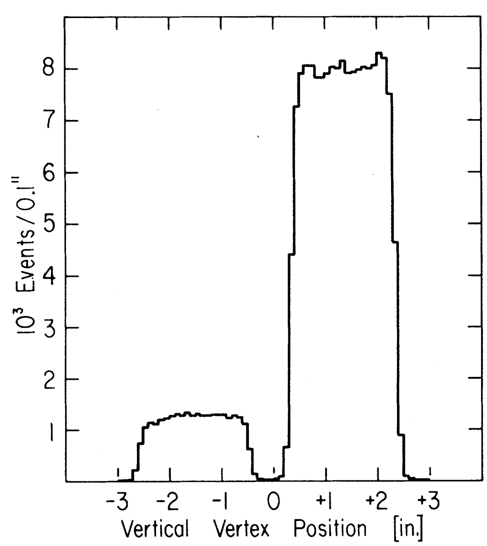

FIG. 2. Reconstructed vertex position of $K_{\mu 3}$'s for a sample of data with the (lead) absorber positioned in the lower beam.

constructed $K_{\mu 3}$ were collected; for carbon, the number was 2×10^5. The absorbers were each 2 (estimated) interaction lengths long, nearly the statistically optimal size.

For the reconstructed $K_{\mu 3}$'s, it was crucial that we know from which of the two beams the K_L decayed. Figure 2 shows a vertical profile of the reconstructed vertex position for a set of pulses with the absorber in the lower beam showing that one can associate each event with a particular beam with negligible ambiguity.

Since only the charged products are detected, the kinematics of the $K_{\mu 3}$ decays yields two solutions for the momentum of the parent kaon. For the present results, we have retained only the "unambiguous" sample (30% of the total), i.e., those events where the two solutions differ from their mean by less than 10%.

Two corrections were applied in the computation of σ_T: (a) correction for events which are scattered from one beam into the other, i.e., for beam cross talk. This scattering occurs primarily in a lead converter (see Fig. 1) located upstream of the primary collimator. This correction was determined by a Monte Carlo calculation using an optical-model prediction for the angular distribution of diffracted events. The probability of beam cross talk was of the order 0.2% and resulted in (a) correction to σ_T of 0.6% at 70 GeV; (b) correction for "imperfect geometry," i.e., for K_L's diffracted in the absorber but not removed from the transmitted beam. This correction was also computed from an optical model, and was typically of the order of 0.3% (Pb at 70 GeV). For all absorbers, the uncertainties in either correction were negligible as compared to the statistical errors. In addition, special runs were taken with one of the beams plugged and the direct measurements of beam cross talk and of diffraction obtained confirmed the Monte Carlo calculations.

As a check that there were no additional length-dependent corrections, we collected data with an absorber (Sn) about half the length of the prime target. The momentum-averaged σ_T was consistent to $(0.5\pm 0.7)\%$.

Our results are given in Table I and displayed in Fig. 3, together with some low-energy points.[6] In the same figure we also show our Glauber-Franco-model[7] predictions, including the correction for inelastic screening.[1] The importance of the latter is illustrated for one element (Cu),

TABLE I. Results for the K_L total cross sections in millibarns for twelve momentum bins. The average values for the cross sections above 40 GeV, where no momentum dependence is observed, are also given. This latter determination uses all $K_{\mu 3}$ events, assigning the mean of the two momentum solutions as the true momentum.

P (GeV/c)	C	Al	Cu	Sn	Pb
35	195.2 +/- 5.6	373.4 +/- 3.8	795.2 +/- 8.4	1316.8 +/- 16.3	2128.5 +/- 24.5
45	186.6 +/- 3.8	372.2 +/- 2.8	774.2 +/- 6.1	1326.5 +/- 11.1	2049.2 +/- 17.3
55	189.3 +/- 3.8	375.6 +/- 2.8	771.7 +/- 6.1	1292.3 +/- 10.9	2036.2 +/- 17.4
65	188.1 +/- 4.2	371.8 +/- 3.1	783.6 +/- 7.0	1291.8 +/- 12.4	2047.3 +/- 19.6
75	185.6 +/- 5.0	389.1 +/- 3.7	775.2 +/- 8.3	1307.1 +/- 14.9	2055.1 +/- 23.4
85	196.1 +/- 6.4	378.5 +/- 4.7	770.8 +/- 10.2	1289.3 +/- 18.3	2097.6 +/- 29.3
95	197.5 +/- 8.1	367.5 +/- 5.9	786.7 +/- 12.9	1289.0 +/- 23.2	2027.3 +/- 36.0
105	197.0 +/- 10.3	374.1 +/- 7.6	801.1 +/- 16.5	1306.9 +/- 29.4	2019.9 +/- 45.8
115	215.4 +/- 14.3	388.9 +/- 9.9	768.1 +/- 20.8	1311.0 +/- 37.4	1887.1 +/- 56.1
125	185.6 +/- 15.7	364.0 +/- 12.1	780.0 +/- 27.3	1270.3 +/- 47.6	1985.9 +/- 75.1
135	146.5 +/- 20.1	361.9 +/- 15.6	754.9 +/- 33.9	1358.9 +/- 64.5	2079.5 +/- 100.8
145	183.6 +/- 26.3	366.0 +/- 20.6	774.6 +/- 43.4	1226.5 +/- 77.2	1982.1 +/- 122.2
40 - 150	188.0 ± 1.0	371.7 ± 0.8	777.4 ± 1.6	1302.2 ± 2.9	2051.1 ± 4.9

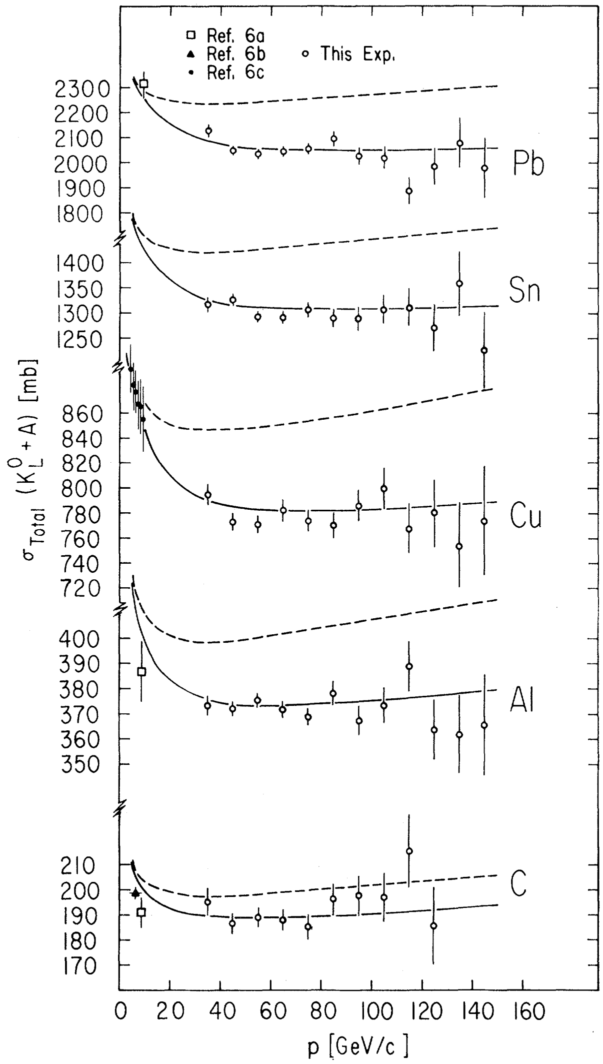

FIG. 3. Results for the total cross sections, including lower-energy determinations. The solid lines are Glauber-Franco–model predictions including the inelastic screening term (see text). The dashed lines are the predictions without this term.

where the uncorrected model predicts a rising σ_T in disagreement with our data. Above 40 GeV the cross sections show no momentum dependence and have in a typical momentum bin an $A^{0.84 \pm 0.01}$ dependence in contrast with $A^{0.77 \pm 0.01}$ for neutrons.[3] The average σ_T values for energies above 40 GeV, using all the $K_{\mu 3}$ events, are also given in Table I.

As inputs to the Glauber-Franco–model calculations, we used (i) nuclear density distributions with rms radii consistent with the electromagnetic ones[8]; (ii) imaginary parts of the K^0 and $\bar{K}^0$ forward amplitudes from Reggeized fits to K^+ and K^- total cross sections[9]; (iii) corresponding real parts from dispersion relations.[10] The forward dissociation cross section $d^2\sigma(t=0)/dt\,dm^2$ required for the inelastic screening correction was obtained as follows: for $m^2 > 2.8$ GeV^2, an m^{-2} dependence was taken normalized by scaling results[11] on proton dissociation in the ratio of the total cross sections; below that value, we took a broad enhancement at 1.3 GeV (the Q meson) which was normalized to the high-mass region by a finite-mass sum rule.[11] This gave a cross section consistent with data on exclusive Q production.[12] We estimate a 25% uncertainty in $d^2\sigma(t=0)/dt\,dm^2$ in the low-mass region which results in about a 15% uncertainty in the magnitude of the inelastic screening term in the middle of our momentum range.

The agreement of the predictions with the data is impressive and lends strong quantitative support to the theory of inelastic screening. We note that the input parameters used here also yield predictions which can be compared with our results[5,13] on K_s regeneration by the same nuclei.

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Precise Coherent K_S Regeneration Amplitudes for C, Al, Cu, Sn, and Pb Nuclei from 20 to 140 GeV/c and Their Interpretation

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We have determined the coherent K_S regeneration amplitudes on various nuclei, from 20 to 140 GeV/c, using a particularly systematics-free technique. Our results are well represented by $|(f-\bar{f})/k| = 2.23A^{0.758}p^{-0.614}$ mb. This p dependence corresponds to an *effective* "nuclear" intercept "$\alpha_\omega(0)$" $= 0.386 \pm 0.009$, whereas the elementary value is $\alpha_\omega(0) = 0.44 \pm 0.01$. Comparisons are made with data below 25 GeV/c, and with optical-model predictions. The latter work only if "$\alpha_\omega(0)$" is postulated to hold for the *elementary* amplitudes.

We present here measurements of the coherent regeneration amplitude on complex nuclei. The K_L beam and spectrometer used are described in the preceding Letter.[1]

Coherent K_S regeneration has long been recognized as a particularly effective means for determining the *difference* of particle/antiparticle forward-scattering amplitudes. This difference is, through the optical theorem, connected with the corresponding total-cross-section difference, $\Delta\sigma$, so that the latter can be determined *directly* (and hence with great accuracy) from the regeneration amplitude. The significance of these differences, both for elementary and nuclear targets, stems from the fact that they are dominated by the exchange of but a few $C=-1$ Regge trajectories, i.e., the ω and the ρ.

The interest of studying coherent regeneration by nuclear targets, in particular over a wide range of kaon momenta and of atomic number, is threefold:

(a) To establish to what extent a complex nucleus may be described, in terms of Regge exchanges, as an "elementary particle." In an earlier investigation[2] this assumption was tacitly made and a precise value, "$\alpha_\omega(0)$" $=0.39$, of the intercept of the (presumed) ω trajectory was determined from regeneration data on ^{12}C, an isoscalar nucleus. With increasing atomic number, departures from this simple-minded description might be expected. Note also that one expects in this simple picutre, as long as pure ω-exchange dominates, a universal power-law momentum dependence of the regeneration amplitude.

(b) Regeneration provides a particularly stringent test of models of meson-nucleus scattering. Since the regeneration amplitude for neutrons is much larger than for protons (a factor of 2 in the simple quark picture, about 2.2 in actual fact), regeneration is especially sensitive to possible differences in neutron and proton nuclear distributions.[3]

(c) The recently measured[1] K_L-nucleus total cross sections could well be fitted with the Glauber-Franco optical model,[4] using standard nuclear parameters, once allowance for inelastic screening[5] was made. It is of interest to verify whether the same assumptions yield good agreement with regeneration data.

We reproduce for convenience a few well-known relations.[6] The $\pi^+\pi^-$ decay rate at a proper time τ from the exit face of a regenerator is

$$I_{+-}(\tau) = N_L\Gamma_s B_{+-} e^{-\sigma NL} |\rho \exp[-\tau\Gamma_S(\tfrac{1}{2} - i\Delta m)] + \eta_{+-}\exp(-\tau T_L/2)|^2, \quad (1)$$