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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

A. Gsponer,[(a)] J. Hoffnagle, W. R. Molzon, J. Roehrig, V. L. Telegdi,[(a)] and B. Winstein
Enrico Fermi Institute, University of Chicago, Chicago, Illinois 60637

and

S. H. Aronson,[(b)] G. J. Bock, D. Hedin, and G. B. Thomson
Physics Department, University of Wisconsin, Madison, Wisconsin 53706
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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

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

where N_L is the incident K_L rate, Γ_S (Γ_L) the K_S (K_L) decay rate, B_{+-} the $K_S \to \pi^+\pi^-$ branching ratio, σ the K_L total cross section, L the length of the regenerator, Δm the K_L-K_S mass difference, and ρ the regeneration amplitude[6,7] viz.

$$\rho = i\pi NL[f(0) - \bar{f}(0)]/k. \qquad (2)$$

Here N is the number density of the regenerator, k the kaon wave number, and f ($\bar{f}$) the relevant forward-scattering amplitudes of K^0 ($\bar{K}^0$). In (1), η_{+-} is the CP-invariance-violation amplitude. $|\rho|$ was determined by the "ρ^2 method,"[8] i.e., by counting the $K_{\pi 2}$ decays per K_L in a short decay region, where the CP-nonconserving terms in (1) contribute at most 10%. The K_L flux was monitored via the $K_{\mu 3}$ decays in the same region. To do this, we exploited again the double-beam technique described in Ref. 1. Two identical blocks (say, of Pb), approximately 2 interaction lengths long, were used. One, the regenerator, was placed in one of the beams just at the beginning of the decay region. The other, the absorber, was placed in the other beam far upstream of that region. $K_{\pi 2}$ decays from the first beam and $K_{\mu 3}$'s from the second were recorded simultaneously. The roles of the two beams were interchanged, by displacing the blocks, every machine pulse. This way of monitoring is considerably less prone to systematic errors than the single-beam approach where K_L decays downstream of the regenerator are detected.

The regenerator was located within a magnet in order to sweep low-energy secondaries away from the spectrometer. A high-efficiency anticounter downstream of the regenerator was essential to veto the large rate of inelastic events. Event-selection criteria were as follows: Only events with vertices in the decay region upstream of the first trigger element were accepted; only $K_{\mu 3}$'s giving a "unique" kaon momentum[1] were retained; the $K_{\pi 2}$'s had to yield a di-pion mass $m_{\pi\pi}$ within 20 MeV of the K^0 mass [see Fig. 1(a)].

Figure 1(b) shows a typical P_T^2 distribution of the $K_{\pi 2}$ events. The number of coherent events was obtained by subtraction of the small background (diffraction and inelastic regeneration, semileptonics) extrapolated under the coherent peak.

The K_L flux was corrected for beam cross talk and diffraction.[1] A correction for CP-invariance violation [i.e., for the initially neglected terms in (1)] was applied to the coherent $K_{\pi 2}$ signal. For this correction, one must know η_{+-} and $\arg(f - \bar{f}) \equiv \varphi_{21}$. For the latter, we used the value

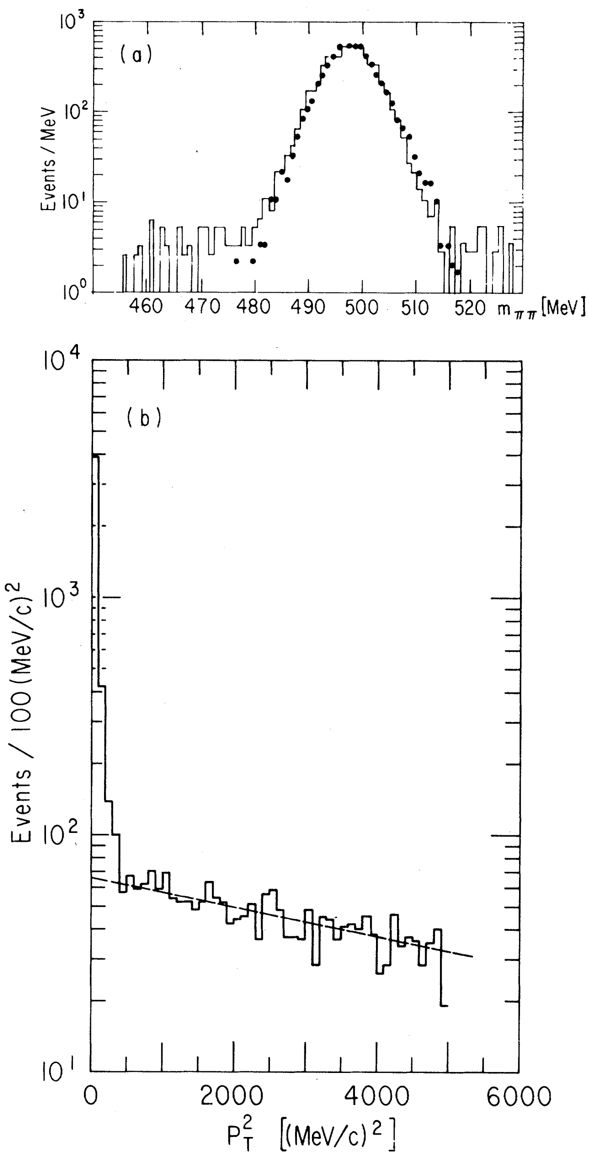

FIG. 1. (a) $m_{\pi\pi}$ distribution from one element in a typical momentum bin (50–60 GeV/c) for events with $P_T^2 < 150$ (MeV/c)^2. The dots represent the Monte Carlo prediction. (b) The distribution in P_T^2 for events in the same momentum bin. A cut of 497 ± 20 MeV on $m_{\pi\pi}$ has been applied. The dashed line shows the background extrapolated under the coherent peak.

measured[2] for carbon. Both measurements on lead by us[9] and theoretical calculations indicate that this phase does not vary appreciably with A. As the CP correction was small, uncertainties in φ_{21} and/or in η_{+-} had in any case a negligible influence on our results.

Our results for $|(f - \bar{f})/k|$ are collected in Table I and are graphically displayed, together with those of Ref. 2, in Fig. 2. This figure shows also

TABLE I. K_S coherent regeneration on nuclei. Results in millibarns for $|f(0)-\bar{f}(0)/k|$.

p GeV/c	Al	Cu	Sn	Pb
25.	3.92 +/- .22	8.18 +/- .55	12.02 +/- .66	16.90 +/- 1.01
35	3.12 +/- .06	6.25 +/- .15	9.42 +/- .19	13.97 +/- .31
45	2.64 +/- .04	4.98 +/- .09	8.04 +/- .12	11.95 +/- .19
55	2.42 +/- .04	4.60 +/- .08	7.23 +/- .10	10.65 +/- .17
65	2.21 +/- .04	4.00 +/- .08	6.52 +/- .10	9.64 +/- .17
75	2.01 +/- .04	3.69 +/- .08	5.90 +/- .11	8.69 +/- .18
85	1.83 +/- .04	3.42 +/- .09	5.32 +/- .12	7.96 +/- .20
95	1.74 +/- .05	3.31 +/- .12	5.10 +/- .14	7.55 +/- .24
105	1.67 +/- .06	3.17 +/- .15	4.74 +/- .18	7.11 +/- .30
115	1.72 +/- .08	3.21 +/- .19	4.83 +/- .23	6.76 +/- .36
125	1.40 +/- .09	2.36 +/- .16	4.92 +/- .34	6.87 +/- .49
135	1.29 +/- .11	2.55 +/- .27	4.71 +/- .44	5.36 +/- .52

the lower-energy data available from other experiments.[10] Several features should be noted:

(a) The momentum dependence of all our data is consistent with the same power law as was established for carbon over *all* momenta, viz. p^{-n}, with $n = 0.614 \pm 0.009$.

(b) For Cu and Pb, there is a *clear break* in the momentum dependence, the data above 20 GeV/c falling off more steeply. Making separate fits in each region, the difference in the exponents is 0.17 ± 0.05 for Pb, and 0.20 ± 0.03 for Cu.

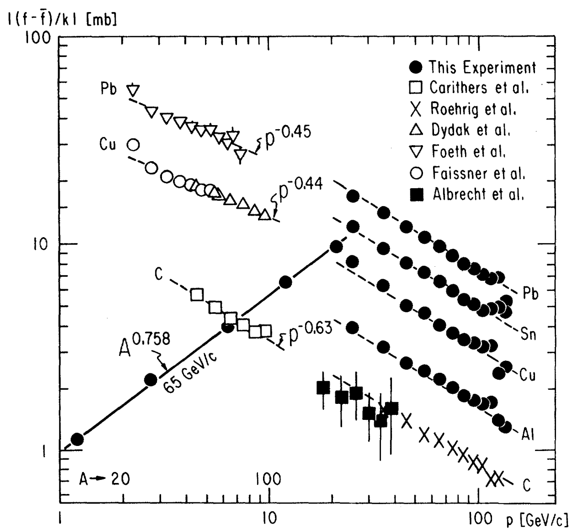

FIG. 2. Measured values of $|(f-\bar{f})/k|$ vs momentum. Our data (including ^{12}C) are jointly fitted with $2.23A^{0.758} \times p^{-0.614}$. The low-energy data are individually fitted with the indicated power laws. The full line, to be read with the auxiliary scale on the bottom axis, illustrates the A dependence of $|(f-\bar{f})/k|$ at $p = 65$ GeV/c.

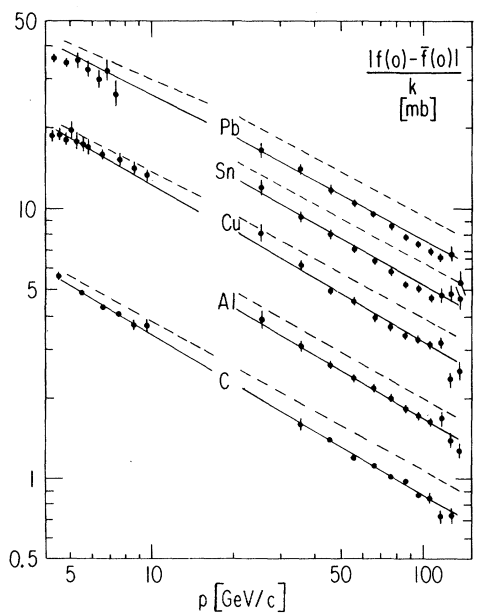

FIG. 3. $|(f-\bar{f})/k|$ data with optical-model predictions, including inelastic screening. The data are the same as in Fig. 2. Dashed lines are predictions using elementary inputs, i.e., $\alpha_\omega(0) = 0.44$; full lines use the effective intercept "$\alpha_\omega(0)$" $= 0.39$.

(c) The A dependence of all data above 20 GeV/c can be represented as A^m, with $m = 0.758 \pm 0.003$. Hence an overall fit is

$$|f - \bar{f}|/k = 2.23 A^{0.758}[p(\mathrm{GeV}/c)]^{-0.614} \text{ mb}. \quad (3)$$

To obtain $\Delta\sigma$, one has to multiply (3) according to the optical theorem by $4\pi \sin\varphi_{21}$.[2] This yields

$$\Delta\sigma = \sigma_T(\bar{K}^0) - \sigma_T(K^0) = 23.2 A^{0.758}[p(\mathrm{GeV}/c)]^{-0.614} \text{ mb}. \quad (3')$$

There appear to be no published high-energy data for charged-kaon total-cross-section differences off complex nuclei. We note, however, that the data[11] for D agree very well with the prediction of (3′) for $A = 2$.

The features just described are easily interpreted qualitatively. The power-law momentum dependence at high energy, with an exponent equal to that found for ^{12}C, represents the ω dominance. The break (or, rather, the curvature) in that dependence, increasing with A stems from the momentum-dependent transparency of nuclei. It can be traced to the fall of the kaon-nucleon total cross sections which substantially decreases the *elastic* screening at high momentum. The $A^{0.76}$ dependence for the cross-section *differences* can be contrasted with the $A^{0.84}$ dependence for the average of the cross sections.[1] This shift is in the expected direction since it is the edge of the nucleus which contributes largely to the regeneration amplitude,[3] and hence to $\Delta\sigma$.

A Glauber-Franco[4] optical-model calculation, including inelastic screening[5,12] and using the same parameters which gave a good fit to the K_L total cross sections[1] yields results in *clear disagreement* with the present data, as evidenced in Fig. 3. Noting that the Regge intercept "$\alpha_\omega(0)$" $= 0.39 \pm 0.01$ corresponding to the p dependence (3) does *not* agree with the value $\alpha_\omega(0) = 0.44 \pm 0.01$ obtained from nucleons,[13] we have then *phenomenologically* adopted this "nuclear" intercept as the effective "$\alpha_\omega(0)$" in the elementary input amplitudes. As shown in Fig. 3, this *Ansatz* yields good agreement; the agreement with the data of Ref. 1 is not affected. We do not find it necessary to have different radii for the neutron and proton nuclear distributions.

The optical model predicts $\varphi_{21} = -132°$ for Pb, in contradiction with the experimental value[9] $\varphi_{21} = -122° \pm 2°$. This may be due to our lack of understanding of how inelastic screening contributes to the small difference in forward amplitudes. For example, one may have to include nondiffractive intermediate states. This and the effective "$\alpha_\omega(0)$" are questions for future theoretical investigations.

As this work is closely related to that of Ref. 1, the acknowledgments therein are equally appropriate. Furthermore, one of us (B. W.) would like to acknowledge stimulating discussions with H. Miettinen and J. Pumplin. This work was supported in part by the National Science Foundation and in part by the U. S. Department of Energy.

(a) Present address: Laboratory for High Energy Physics, Swiss Federal Institute of Technology, Villigen 5234, Switzerland.

(b) Present address: Brookhaven National Laboratory, Upton, N. Y. 11973.

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