General features of total hadron-nucleus reaction cross sections

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Abstract. Total reaction cross sections for many hadronic projectiles (π^+, π^-, n, p, $\bar{p}$, K^+, K^-, $\bar{d}$) and bombarding energies (200 MeV to 300 GeV) on several target nuclei are compiled. Two remarkable features are discussed: (1) the average systematic behavior of data is well reproduced by the Glauber model, containing only the free projectile-nucleon total cross section σ; (2) deviations of the cross section data from an average smooth dependence on σ seem to vary periodically with σ^{-1}, independent of the projectile type and of the target nucleus.

The interaction of a hadronic projectile with a nucleus may be described in rather simple terms if the wavelength of the projectile and the nature of the interaction are such that only one target nucleon at a time is affected by the passage of the projectile. For example, in the optical limit of the Glauber model, making use of the eikonal approximation, one is able to express the total cross section σ_T, and the total reaction cross section σ_R, simply in terms of the nuclear matter distribution $\rho(r)$ and the projectile-nucleon forward amplitude $f(0)$. In addition, in the case of σ_R, the contribution of the real part of $f(0)$ vanishes, such that the expression for σ_R (Ref. [1] equation 98) becomes

$$\sigma_R = 2\pi \int_0^\infty [1-\exp(-\sigma S(b))]b\,db. \tag{1}$$

Here, σ is the elementary projectile-nucleon total cross section (averaged over spin and isospin) and $S(b)$, the target thickness or profile function, measures the number of target nucleons per unit area encountered along a straight-line trajectory with impact parameter b:

$$S(b) = \int_{-\infty}^\infty \rho\{(b^2+z^2)^{1/2}\}\,dz. \tag{2}$$

Since mass, charge and energy of the projectile do not enter equation (1), the only relevant parameter describing the projectile, needed to calculate σ_R, is the projectile-nucleon total cross section σ. The present work was prompted by the wish to investigate how well nature lives up to this simple theoretical prediction. The next three paragraphs address (1) the compilation of total reaction cross section data, (2) a comparision of the measurements with the Glauber model, and (3) the discussion of a possible systematic oscillatory deviation of the data from an average value which is speculative at the present stage.

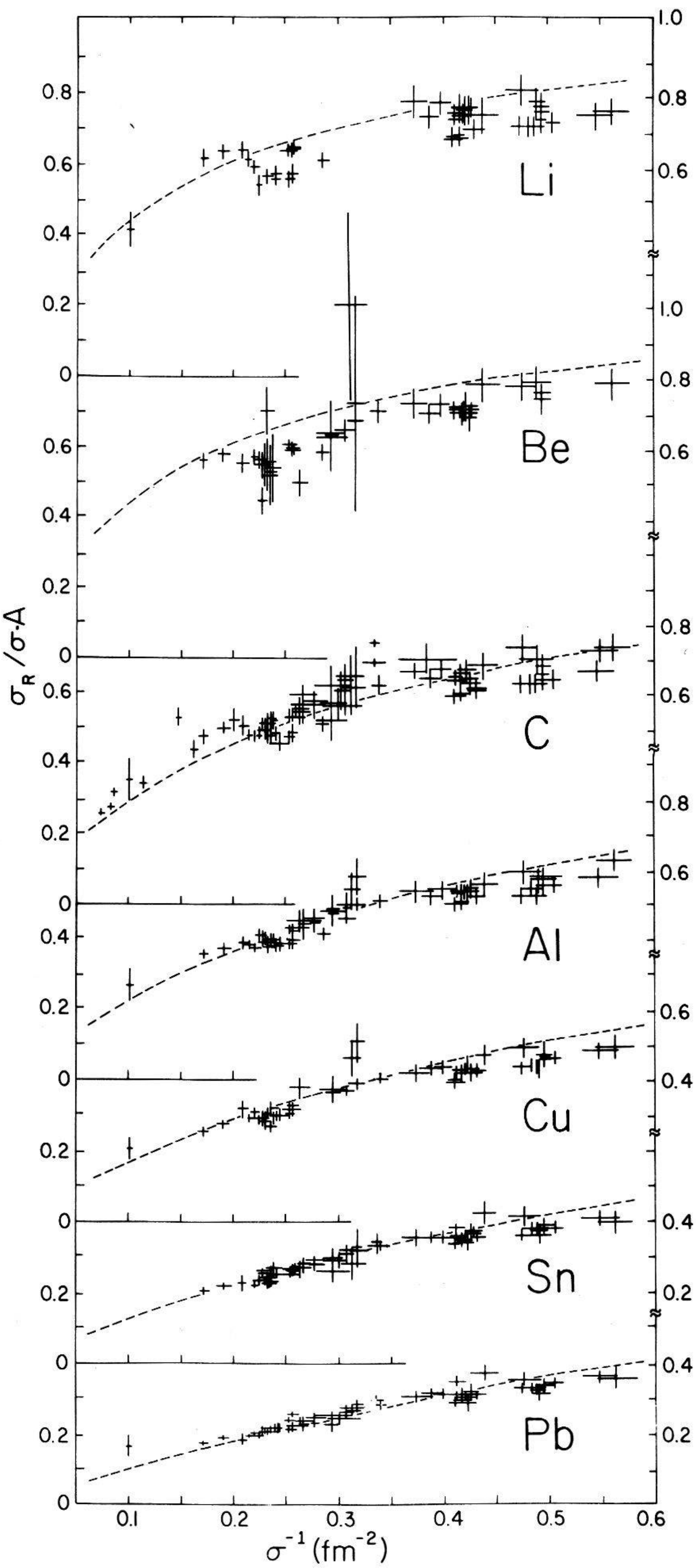

Figure 1.
Compilation of experimental total reaction cross sections σ_R normalized by $\sigma \cdot A$ displayed versus σ^{-1} for targets with $7 < A < 209$. The dashed curves represent the prediction of the Glauber model in the optical limit.

Total reaction cross sections σ_R involving a multitude of projectiles, target nuclei and bombarding energies have been compiled from Refs. 2–12. The projectiles considered include π^+ (incident laboratory energy 580 MeV – 280 GeV), π^- (120 MeV – 280 GeV), K^+ (29.5 – 280 GeV), K^- (6.18 – 280 GeV), p (180 MeV – 280 GeV), n (451 MeV – 1.73 GeV), $\bar{p}$ (5.78 – 280 GeV) and $\bar{d}$ (23.3 GeV). For every measurement of σ_R, the corresponding free projectile-nucleon total cross section σ has been evaluated at the same laboratory kinetic energy by averaging experimental values of the total cross section [2, 4, 13–15] for free protons and neutrons.

In Fig. 1, $\sigma_R/\sigma A$ is displayed versus σ^{-1}, a quantity which is a measure of the mean free path in nuclear matter. The measured σ_R has been normalized by $\sigma \cdot A$ (the total cross section which would be obtained if the target nucleons did not shadow each other) in order to make different target nuclei comparable. If it is correct that the measured σ_R can be described by a single parameter σ, then one would expect all data for a given target nucleus to lie on a common locus. From Fig. 1 it becomes clear that this is indeed the case for measured σ_R with projectiles which range in mass over an order of magnitude and in energy over three orders of magnitude, with adjacent data points rarely differing by more than the experimental error. Thus, the elementary σ seems to be the only relevant parameter, and in any model describing σ_R, it is not necessary to distinguish among different incident particles, at least not on the level of accuracy achieved by present experiments.

The dashed curves in Fig. 1 represent calculations of σ_R in the optical limit of the Glauber model (equation 1). The matter distribution $\rho(r)$ used to calculate the profile function $S(b)$ (equation 2) for the seven target nuclei has been obtained as follows: for the three light targets Li, Be and C, $\rho(r)$ has been calculated from the single particle shell model, using potentials consistent with electron scattering [16]. For all other targets, $\rho(r)$ has been set to the measured charge distribution [17], normalized to the number A of nucleons. We conclude from Fig. 1 that the simplest version of the Glauber approximation, explicitly independent of the mass, charge and energy of the projectile, is able to explain rather well the systematic behavior of σ_R.

Let us now examine the data for the target nucleus carbon, which has been favored most by experimentalists. Although the general trend of the data is well explained by the Glauber model, there are regions in σ^{-1} where the data lie systematically either above or below the prediction. Similar oscillations can also be seen for the other targets, although they seem to disappear gradually for increasing A and they are hard to recognize for Li and Be because of the limited amount of available data. Nevertheless, it appears that maximum deviations occur for the same values of σ^{-1}, independent of the target nucleus.

Let me present an attempt to investigate whether this oscillatory variation of the measured values could be a real physical phenomenon. First, a function of σ^{-1} is chosen which consists of a part which is smoothly dependent on σ^{-1} (a third order polynomial through the origin) and a part which is oscillatory in σ^{-1}. The oscillatory part was arbitrarily taken to be a sine function with adjustable amplitude, wavelength and phase. The parameters of this function were then adjusted to fit the 97 data points for carbon. The result is shown in the upper part of Fig. 2 with (solid line) and without (dotted line) the oscillatory part in the fitting function. Inclusion of the oscillatory part caused a decrease of the χ^2 per degree

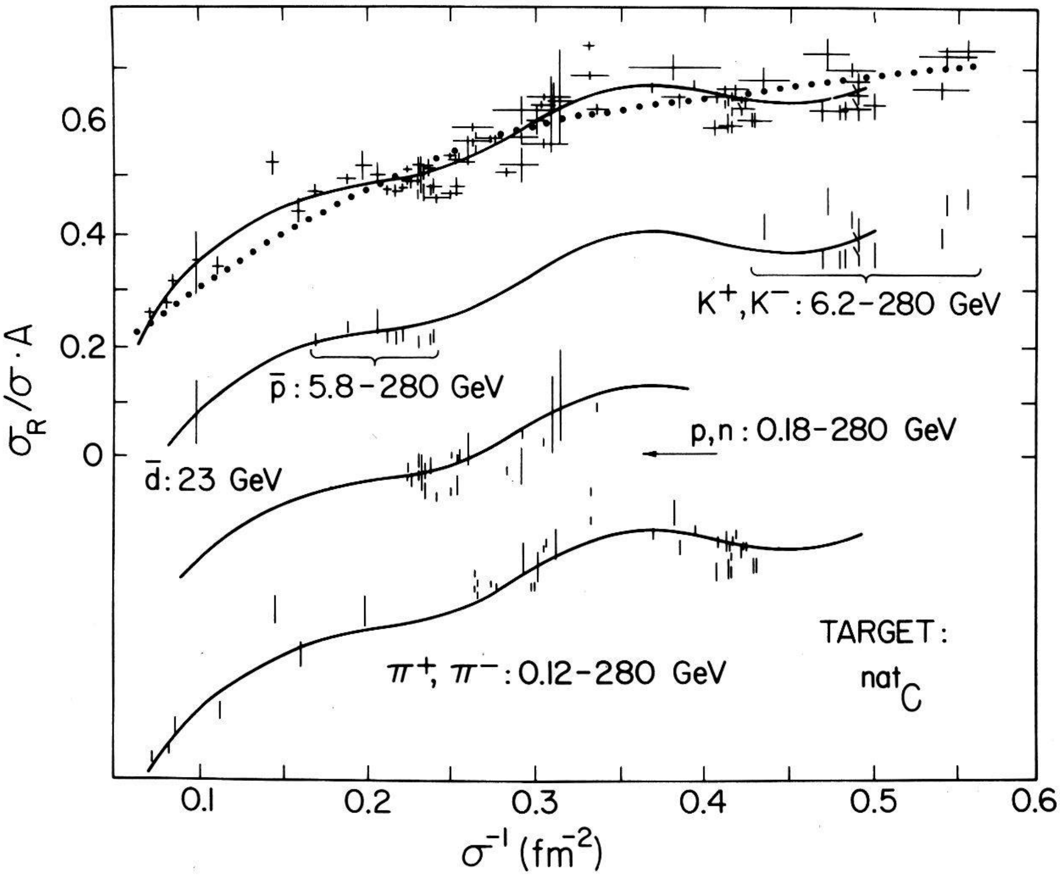

Figure 2.
Compilation for carbon of experimental total reaction cross sections σ_R normalized by $\sigma \cdot A$ displayed versus σ^{-1}. The curves represent a phenomenological interpretation of the data in terms of a function with (solid line) and without (dotted line) an oscillatory contribution. In the lower part, data from various projectiles are displayed separately.

of freedom from 8.3 to 5.6. These large values of χ^2 may arise from two sources. First, the fitting function used may be inappropriate to describe the data, since it has been chosen merely to separate a smooth behavior from an oscillatory one. Second, the data may not be distributed statistically, which is reflected in the fact that experimental errors of total cross sections are predominantly systematic. If these objections are ignored, the F-test yields a significance of 95 percent for the necessity of including the oscillatory part in the fitting function. In order to treat the rest of the target nuclei, the wavelength and phase of the oscillations were fixed to the values found for carbon. The remaining four parameters, i.e., the coefficients of the polynomial and the amplitude σ of the oscillation, were then adjusted individually for each target nucleus. For each target nucleus the phenomenological contribution α of an oscillatory function is thus found which best fits the data. The resulting coefficients α are shown in Fig. 3 as a function of mass number A. The displayed uncertainties of α are defined to represent an increase of χ^2 by $\Delta\chi^2$ when α is changed, with the polynomial coefficients readjusted. The value of $\Delta\chi^2$ for every target has been chosen to be equal to the decrease in χ^2 needed for a 90 percent significance of an additional parameter. The final argument is provided by the dashed line in Fig. 3, which corresponds to α proportional to $A^{-2/3}$. Since, for most probes considered here, the nucleus is strongly absorptive except in its surface region, a small change in the elementary

σ would affect only impact parameters in a narrow band near the nuclear surface. This causes a change in σ_R which, to first order, is proportional to the circumference of the nucleus, or to $A^{1/3}$. If the oscillations discussed in $\sigma_R/\sigma A$ are caused by a real physical effect, one would therefore expect their amplitude to scale with $A^{1/3}/A = A^{-2/3}$. The values found for α (see Fig. 3) are consistent with this expectation. Treating the wavelength and position of the oscillatory contribution as free parameters for each target does not yield a significant decrease in χ^2 but leads to the same dependence of α on A.

The possibility that the observed oscillations are an experimental artifact is greatly reduced by the fact that they are supported by measurements with many probes, taken at different laboratories. One may object that the oscillations are caused by individual contributions of different projectiles. The reader may convince himself that this does not seem to be the case from the lower part of Fig. 2 where the data for C are grouped according to projectile. Similarly, the clustering of very high bombarding energies in certain regions of σ^{-1} may be made responsible for the oscillations; however, a careful investigation of the deviation

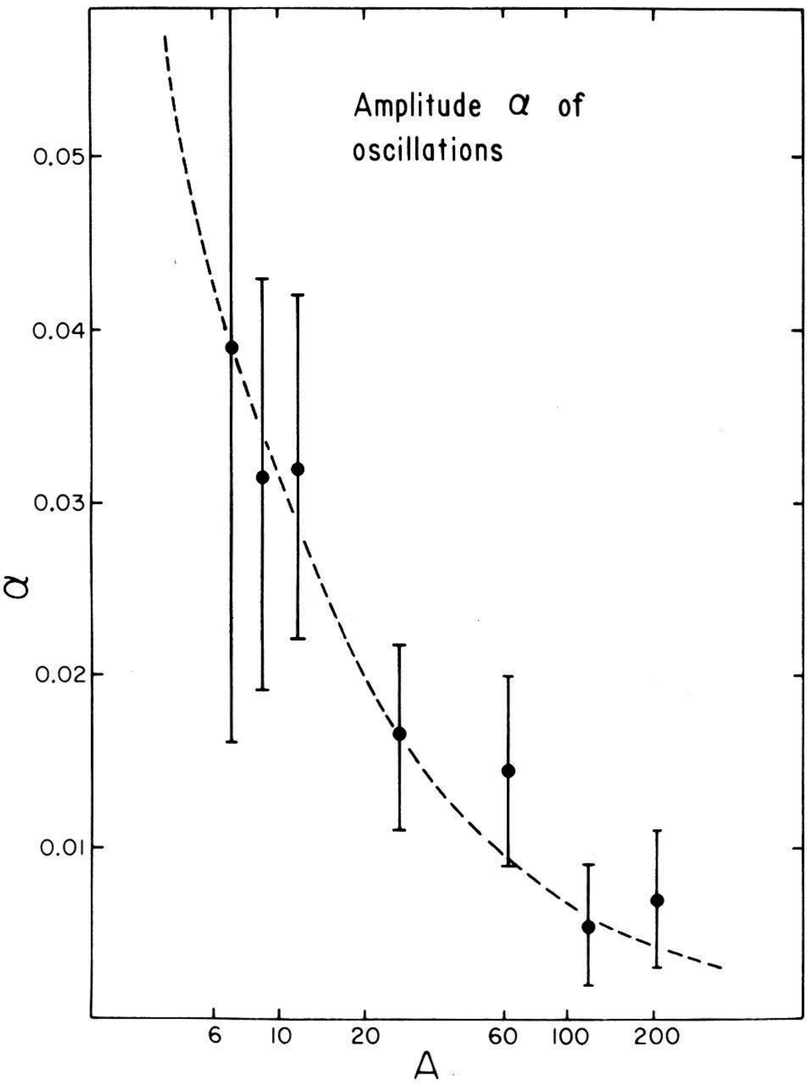

Figure 3.
Amplitude α of oscillations as determined by adjusting a phenomenological function. The dashed line is proportional to $A^{-2/3}$.

of the measured value from the dotted curve in Fig. 2 with respect to the corresponding bombarding energies did not reveal any correlation between the two parameters.

In conclusion, it has been found that the present world supply of total hadron-nucleus reaction cross sections is well explained by the simple Glauber model in the optical limit. The remaining discrepancies seem to be systematic and oscillatory as a function of σ^{-1}, the inverse of the spin and isospin averaged projectile-nucleon total cross section. Arguments are presented which suggest the physical reality of these oscillations, although, in view of the limited quality of the available data, their existence cannot be established beyond any doubt. In an attempt to understand the cause of these oscillations, some possible explanations may be ruled out quickly. A process, e.g., which depends not only on the free projectile-nucleon total cross section but also (explicitly) on projectile parameters such as wavelength, mass, charge, etc., must not be considered, since data points neighboring in σ^{-1} may correspond to quite different values of these parameters. Processes where individual detailed features of the target nucleus are important can also be rejected, since the observed oscillations occur at about the same σ^{-1} for all target nuclei considered. It seems that the effect would have to be explained as a (rather general) modification of the interaction of hadrons with nucleons in the nuclear environment. Attempts to find such modifications which lead to a correction of the calculated σ_R which is oscillatory in σ^{-1} so far have not been successful and are still in progress. The purpose of this communication is to draw attention to the possible existence of an unexplained phenomenon in hadron nucleus interactions. At present it seems most pressing to provide irrefutable experimental evidence. To this effect it is necessary to improve the available data by simultaneous accurate measurements of σ_R and σ in selected regions of σ^{-1}.

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