PROBING PERTURBATIVE QCD AND NUCLEI
WITH LARGE ANGLE ELASTIC SCATTERING*

DE88 015198

D.S. Barton, G.M. Bunce, A.S. Carroll, S. Gushue, Y.I. Makdisi
AGS Department, Brookhaven National Laboratory, Upton, NY 11973

S. Heppelmann

Pennsylvania State University, University Park, PA 16802

H.C. Courant, G.Y. Fang, K.J. Heller, M.L. Marshak, M.A. Shupe
University of Minnesota, Minneapolis, MN 55455

J.J. Russell

Southeastern Massachusetts University, North Dartmouth, MA 02747

INTRODUCTION

The experiment reported here (AGS Exp. 834) seems particularly appropriate for a conference on the intersections of particles and nuclear physics. We have performed a new probe of aspects of perturbative QCD (pQCD) and the time evolution of hadrons inside nuclei.¹ Simultaneously, we determined the momentum dependence of nuclear spectral functions.² That is, we measured the momentum distribution of nucleons inside nuclei with a sensitivity to components well beyond the edge of the normal Fermi distribution. References 1 and 2 describe this experiment with more care and precision.

MOTIVATION

Since the background of the physicists in the group was in particle physics, our original motivation was from that direction. We have been engaged in a program of studying exclusive two-body reactions at large momentum transfer, generally at $\theta_{cm} = 90^\circ$, corresponding to $p_1 \approx 2$ GeV/c. There is a remarkable relationship known as dimensional scaling which appears to hold for all exclusive processes at large momentum transfer.³ First, we consider the differential cross section of pp elastic scattering, shown in Fig. 1a. After decreasing by several orders of magnitude, from the forward direction, $d\sigma/dt$ becomes relatively flat in the central region. This is an indication of short ranged, hard processes, as opposed to the peripheral, soft processes of the forward direction. In Fig. 1b, we look at $d\sigma/dt$ at a fixed angle in the center-of-mass (for example, 90°), and then plot $d\sigma/dt$ as a function of the laboratory momentum, p . To good approximation, we see that the cross section falls as a power of s since the center-of-mass energy squared, $s = 2p$. For pp scattering the power law is s^{-10} and for np scattering it is s^{-8} . Brodsky and Farrar showed in the mid-1970's that this behavior is to be expected of any large angle scattering involving a number of constituents obeying a renormalizable vector field theory such as QED and QCD.³

* Work performed under the auspices of the U.S. Department of Energy and the National Science Foundation. Presented by A.S. Carroll.

Fig. 1(a) The differential cross section for pp elastic scattering is shown for an incident momentum of 10 GeV/c.

(b) The differential cross sections for pp and π^-p elastic scattering at 90° are plotted vs the incident lab momentum to demonstrate the dimensional scaling relationship.

Professor Mueller of Columbia, has presented a nice heuristic picture of what is happening. The elastic scattering of two-point particles such as e^+e^- goes as $1/t^2$. If we study the energy dependence at a fixed angle (a constant ratio of t/s), then $d\sigma/dt \propto 1/s^2$. Mesons and protons are not point particles, however, but are made up of at least two or three constituents, and generally more. A hadron will appear to be a point particle if all of its constituents are contained within a region small compared to a region probed by the interaction. The dimension of that region is $\Delta x \propto 1/\sqrt{t}$. Since Lorentz contraction makes the hadrons appear to be discs, we need only consider areas. So the probability that quarks in both the initial and final state meson will appear to be point-like is $(1/t \times 1/t)$. For protons, the probability that the three quarks will be the same area is $(1/t^2 \times 1/t^2)$. Substituting s for t , the power law dependence for πp processes is s^{-8} and pp process is s^{-10} . The general rule is $s^{-(n_a+n_b+n_c+n_d-2)}$. Starting at $p_{\text{lab}} \sim 5 \text{ GeV}/c$, this rule works!

Mueller, and independently, Brodsky, pointed out how this picture could be tested.⁴ If the elastic scattering took place on a proton inside a nucleus, then the attenuation of the hadrons leaving the nucleus provides a measure of their size. In more QCD-like language, the quarks with their color charges are very close together at the time of interaction and remain close together for some distance. This distance is somewhat larger than a nuclear radius. In this form, the quark pairs are nearly colorless, so that the hadrons have anomalously small cross sections.

Let me note that there are other pictures of how this exclusive scattering might take place. For example, Landsoff pointed out that

there is a singularity when all the quarks stay on shell and are scattered independently to the same angle.⁵ In this picture and others, there is no need for the hadrons to be small at the moment of impact. Learning whether or not the interaction selects the size of the hadrons interacting, clearly would be interesting, independent of the particular model.

THE EXPERIMENT

The apparatus used in this experiment was developed to study a variety of exclusive reactions at large momentum transfer.⁶ Exclusive reactions are those in which all final state particles are determined. We developed a trigger which required that the momentum of one of the particles be sufficiently close to the elastic limit so as to have a reasonable trigger rate. Since we were studying the elastic scattering of protons on the moving protons inside nuclei, (frequently known as quasielastic scattering), there was only a weak correlation in the angular relationship between the two outgoing protons. Hence, a large aperture system was needed to measure the angle of the recoil proton.

The setup which accomplished these tasks was a magnetic spectrometer for one proton, and a large aperture array of wire chambers to determine the angles of the other, as shown in Fig. 2. There were Čerenkov counters to determine the incident and outgoing particle types.

Fig. 2. Top and elevation views of the apparatus used in AGS Exp. 834.

We automatically normalized our experiment by passing the beam through two CH_2 targets which bracket the nuclear targets. Reconstruction of the interaction vertex allowed us to determine which target was struck. The five nuclear targets were Li, C, Al, Cu and Pb.

Two, three layer scintillation counters interspersed with 1.5 rad. length of lead above and below the targets tagged charged particles and gamma rays from inelastic collisions over $2/3$ of the solid angle.

NUCLEAR SPECTRAL FUNCTIONS

When we proposed this experiment, the AGS Program Committee had serious doubts as to whether or not we would be able to see the elastic signal of scattering from protons moving inside the nucleus. This happens to be one of those rare occasions when the experiment is easier than it was originally thought to be. In fact, the signal is sufficiently strong and clear as to provide a new technique for studying momentum dependence of nuclear spectral functions, $S(e, \vec{p})$. Because it is extremely difficult to get sufficient energy resolution at these high energies, we simply integrate over all values of the binding energies, e .

Previously this kind of study has been done by scattering electrons of 1 GeV or less from nuclei.⁷ The virtues of the simple electron probe have been noted many times before, but in these experiments the proton recoil momenta are comparable to the internal momenta within the nucleus. For incident momenta of 6 and 10 GeV/c, the outgoing momenta are 3.5 and 5.5 GeV/c at $\theta_{cm} = 90^\circ$. A q^2 of 9 (GeV/c)², probes nuclear distances of ~ 0.2 Fermi, so that the impulse approximation should be justified.

The four kinematic equations that we must solve are

$$E_1 + E_2 = E_3 + E_4, \quad \vec{p}_1 + \vec{p}_2 = \vec{p}_3 + \vec{p}_4$$

where 1 and 2 refer to the beam and target particles and 3 and 4 refer to the outgoing particles.

The energy of the bound target proton, E_2 , is set to m_p since the binding energy is small compared to the kinetic energies of the problem. With one unknown outgoing momentum, and the three components of the target momenta unknown, we have a zero constraint equation. A study of the scattering from hydrogen allows us to determine the resolution in the components of the momenta of the struck proton. For the z component, the resolution is 5 MeV/c and for the y component, it is 30 MeV/c.

Restricting the z component to be within ± 200 MeV/c of the origin, clear peak stands out above the background in the p_x - p_y plane. Most of our analysis is done by looking at the y component which is normal to the scattering plane (see Fig. 3). To a good approximation this component is not affected by the kinematics of the interaction and the acceptance varies by $< 10\%$ over the range of $|p_y| < 300$ MeV/c. The veto counters above and below the target provide a good method for estimating the background. If we look for events with a penetrating particle (two layers in the veto counter), then the elastic peak disappears. The shape of the background signal is in agreement with the shape of the total distribution for $|p_y| > 500$ MeV/c. After normalizing and subtracting this background, the y component of the target proton momentum is shown in Fig. 4 for five elements at 6 GeV/c and aluminum at 10 GeV/c.

Superimposed on these experimental distributions are the momentum distributions deduced from Fermi gas distribution fits to lower energy electron scattering experiments. In the central region ($|p_y| < 200$ MeV/c), our distributions are in good agreement with the

electron data. However, at momenta greater than Fermi momentum cutoff, we see a significant excess. A first, one might simply ascribe this excess to rescattering of the protons as they leave the nucleus. But the fraction of events within this tail is a constant $20\% \pm 3\%$ from lithium to copper.

Fig. 3. Distribution of the projection of the y component of the target momenta for aluminum at 6 GeV/c. The upper curve shows the events with 0 or 1 hit in the veto counter out the scattering plane. The lower curve is the background with 2 or more hits.

Fig. 4. Distributions of the y components of the target momenta for five elements at 6 GeV/c and aluminum at 10 GeV/c.

TRANSPARENCY

Having determined the momentum dependence of nuclear spectral function, we can turn to the question of determining the transparency of nuclei to large angle pp elastic scattering. In the absence of binding energy and Fermi momentum, the transparency is simply,

$$T = [d\sigma/dt(pp \text{ elas. in nucleus})] / [d\sigma/dt(pp \text{ elas. in Hyd.})]$$

Since the target protons have momenta, we must apply a number of corrections to the data. The measured transparency T which in general is a function of s and hence p_z , is an average over a range in p_z . We must correct for the fact that the acceptance changes over the range of target momenta, and that a particular band in p_z contains only a portion of the spectral function. So the measured T is the ratio of the number of observed elastic scattering events in the nuclei per proton to that from hydrogen, corrected by an integral calculated by the Monte Carlo Method.

$$T = (N_n^{\text{obs}}/N_H^{\text{obs}}) / \{ \iiint \int d\epsilon d\phi_x d\phi_y d\phi_z S(e, \vec{p}) A(\vec{p}) \left[\frac{d\sigma}{dt}(s, t) / \frac{d\sigma}{dt}(s_0, t_0) \right] \}$$

where the number of observed particles per target proton is given by N_n^{obs} , $S(e, \vec{p})$ is the nuclear spectral function and $A(\vec{p})$ is the experimental acceptance. We use measured values of $d\sigma/dt(s, t)$ in evaluating the variation of the differential cross section about the central values of s_0 and t_0 . The four-fold integral over target momentum and bending energy would be unity if the differential cross sections, $d\sigma/dt(s, t)$ were a constant.

What sort of transparencies do we expect in a conventional picture? The protons scatter elastically and the number observed is reduced by the attenuation length in nuclei of ~ 2.0 Fermi, corresponding to a constant absorption cross section of ~ 36 mb. Wood-Saxon distributions are used to specify the nuclear densities. These calculations result in transparencies of .12 for aluminum to 0.025 for lead. See Ref. 8 for details. The transparencies at 6 and 10 GeV/c as shown in Fig. 5a are both well above the calculated values. Caution should be used in interpreting this result. There is a large uncertainty in the absolute overall normalization ($\pm 25\%$) due to the uncertainties in treating off-shell scattering, in specifying the nuclear density distribution and in determining the interaction energies.

Fig. 5.(a) Transparencies for the five elements measured at 6 and 10 GeV/c, and for C and Al at 12 GeV/c for $-0.2 \text{ GeV/c} < p_z < 0.1 \text{ GeV/c}$.

(b) The transparency for aluminum subdivided into four effective incident momenta for each of the three nominal momenta.

Also, the values for 10 GeV/c are significantly higher than for 6 GeV/c. If we plot these transparencies as a function of lab momentum, then we see a consistent rise in all of the nuclei. If we had stopped there, we would have had results which were consistent with the color transparency idea derived from dimensional scaling. However, measurement at 12 GeV/c shows a sudden drop in the transparency indicating that the protons scattered have an increased absorption cross section again. This energy dependence can be seen in more detail for aluminum (see Fig. 5b) where we have used our large number of events to subdivide each incident momentum measurement into four p_z bins. Each bin corresponds to a different s , given by the approximate formula,

$$s \sim s_0 (1 - p_z/m_p) \quad .$$

Here we seen the transparency rising to a peak at 9 GeV/c and then falling again.

What to make of this result! First, the transparency is energy dependent, a result not expected from normal Glauber theory. Brodsky and de Teramond have suggested a possible model.⁹ They say that superimposed on the increasing transparency derived from the hard scattering of the pQCD picture is a soft resonance amplitude possibly associated with the charge threshold which has the normal nuclear attenuation. A soft resonance amplitude unlike the pQCD amplitude implies no decrease from the normal proton size. Such a resonance could also explain the spin dependence in pp elastic scattering.⁹ A determination of possible increased charmed production is contained in the data of AGS Exp. 766.¹⁰

Clearly, it would be useful to go to higher momenta and see if the transparency starts to increase again. Scattering at angles other than 90° would be informative since the cross section there shows much less energy dependence. Finally, interesting comparisons can be made with high energy, large momentum transfer (e,e'p) measurements when these are done at SLAC or CEBAF.

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