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A study of photon-nucleus collisions at high transverse energy

Zhu, Qiuang, Ph.D.
Rice University, 1993
RICE UNIVERSITY

A STUDY OF PHOTON-NUCLEUS COLLISIONS
AT HIGH TRANSVERSE ENERGY

by

QUAN ZHU

A THESIS SUBMITTED
IN PARTIAL FULFILLMENT OF THE
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September, 1992
Abstract

A STUDY OF PHOTON-NUCLEUS COLLISIONS
AT HIGH TRANSVERSE ENERGY

by

Qiu An Zhu

We have measured, for the first time, the atomic number dependence of photon-nucleus collisions at high transverse energy. The measurements were made at FNAL by using a large acceptance calorimeter with 50 – 400 GeV photons incident on LH2, LD2, Be, C, Al, Cu, Sn and Pb targets. The cross section is parameterized as \( \sigma_{\gamma A} = \sigma_{\gamma p} A^\alpha \), where \( \alpha \) is found to increase from 0.9 to 1.1 when the total transverse energy \( E_T \) is increased from roughly 6 GeV to 12 GeV; \( \alpha \) is also found to increase with the photon energy at fixed \( x_T \equiv E_T / \sqrt{s} \), but depends only weakly on the photon energy at fixed \( E_T \). The increase of \( \alpha \) with total transverse energy is qualitatively consistent with previous measurements from the hadron-nucleus collisions, but our \( \alpha \) values are somewhat lower. At high transverse energy, photon induced collisions are found to be more jet-like than pion induced collisions, revealing the point-like nature of the photons at high \( E_T \). The mean planarity in \( \gamma A \) collisions is independent of \( A \) in the kinematic range covered by this experiment.
ACKNOWLEDGEMENTS

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I. Introduction

It is widely believed by now that hadrons are made out of quarks, antiquarks and gluons. All hadronic interactions can, in principle, be described by the interactions between the quarks and the gluons, which are governed by the theory known as Quantum Chromodynamics (QCD). The success of QCD over the last 15 years comes largely from its description of the high transverse momentum (high-\(p_t\)) hadron-hadron collisions. A high-\(p_t\) collision is believed to be the result of a hard scattering between the constituents of the hadrons ([1], [2], [3]). A simple form of the QCD theory—the quark-parton model\(^1\), treats the hard scattering as between one parton (quark, antiquark or gluon) from the beam hadron and one from the target hadron ([4]). The scattered partons and the spectators then fragment into highly collimated groups of particles, known as jets. Indeed, it was the observations of jets and the measurements of their cross sections at the CERN \(\bar{p}p\) collider that firmly established QCD as the correct theory for strong interaction.

Because of the high concentration of protons and neutrons inside the atomic nuclei (especially heavy nuclei), nuclear targets were initially used in high energy experiments in order to achieve higher collision rate. The single nucleon cross section is then extracted from the data by dividing the total cross section by the atomic number, \(A\), of the target nucleus. But it was quickly discovered that for most type of collisions, the single nucleon cross section thus obtained usually depends on what target is being used (the so-called A-dependence). Experiments designed to study A-dependence effects have yielded many unexpected results, thus attracting a considerable amount of theoretical interest in this

\(^1\)The parton model was first used by Bjorken ([5]) to explain the \(e - p\) deep inelastic scattering data.
field\textsuperscript{2}. A notable example is the discovery made by the EMC experiment (The European Muon Collaboration) ([6]) in the early 1980's, and the subsequent large number of theoretical models it inspired.

The experiment that we are going to discuss in this thesis finds its roots in a classic experiment performed in 1973 by J. Cronin ([7], [8]). The Cronin experiment measured the invariant cross sections for single particle production ($\pi^\pm, K^\pm, p$ and $\bar{p}$) at large transverse momentum from hydrogen, beryllium, titanium and tungsten targets. The ratio of cross sections $\sigma(pA)/\sigma(pp)$ was found to be well described by the form $A^\alpha$. The $\alpha$ values were found to increase with the transverse momentum $p_t$ of the single hadrons, from roughly 0.8 to 1.2 (see figure 1). This means that at high $p_t$, the cross section per nucleus increases faster than the number of nucleons in the nucleus! The “Cronin Effect” caught most people by surprise at that time. By then, it was well known experimentally that the ratio of total hadronic cross sections behaves as $A^{2/3}$ ([9]). This was viewed theoretically as “nuclear shadowing”: since the mean free path for hadronic interaction is smaller than the size of the nucleus, not all nucleons inside the nucleus get an equal chance to interact with the hadron—some are “shadowed” by the nucleons at the front of the nucleus ([10]). It was then expected that high-$p_t$ interactions, which are rare, should yield an A-dependence with $\alpha = 1$ ([11], [12]). However, the Cronin Effect, also known as the “anomalous nuclear enhancement”, was later confirmed by several other experiments which found similar $\alpha$ values at high $p_t$ ([13], [14], [15], [16]).

The anomalous nuclear enhancement also manifests itself in other high-$p_t$ hadron nucleus collisions: (1) when a large amount of total transverse energy $E_t$ is required for the

---

\textsuperscript{2}“Nuclear physics is too important to be left in the hands of nuclear physicists” — James Bjorken.
FIG. 1: Plots of the power $\alpha$ of the A-dependence versus $p_t$ for the production of hadrons by 300 GeV protons [8]; (a) $\pi^+$, (b) $\pi^-$, (c) $K^+$, (d) $K^-$, (e) $p$ and (f) $\bar{p}$. 
final state particles ([22], [23], [24]); or (2) when high-$p_t$ jets are produced ([27], [28], [29]). Many theoretical models have been proposed to explain the anomalous nuclear enhancement (e.g., see [18], [19] and [20]), but the "true" nature of the nuclear enhancement is not well understood ([21]). We will discuss the theoretical models further at the end of this thesis.

This thesis discusses an experiment that investigates the A-dependence at high-$p_t$ by using a high energy photon beam. Unlike the hadrons, which are made out of quarks, antiquarks and gluons, the photons are expected to interact with the target nucleus in a point-like manner at high-$p_t$ (see [30], and the references contained therein). The cross sections for point-like photon-nucleon collisions at high-$p_t$ are easier to calculate theoretically in the framework of QCD than those for hadron-nucleon collisions ([30], [31]). In photon-nucleus collisions, for example, one should not expect multiple partons from the beam particle interacting simultaneously in the target nucleus. This was argued by some theorists as one of the possible causes for the anomalous nuclear enhancement seen in high-$p_t$ hadron-nucleus collisions ([19], [32], [33]).

However, it was believed that a photon is a complicated object when the collision is at medium or low $p_t$. At medium or low $p_t$, most of the features of photoproduction of hadrons are similar to those observed in hadroproduction. This is interpreted by the vector dominance model (VDM) which describes the photon as a superposition of vector mesons ([34]). The exact $p_t$ range of this "dominance" by the vector mesons is not precisely known theoretically. But experiments that studied the photoproduction of high-$p_t$ single charged hadrons or $\pi^0$'s have shown that, in a photon beam of roughly 100 GeV, the point-like photon interactions dominate over the VDM type interactions at $p_t > 4$ GeV ([35], [36]).
The experiment to be discussed in this thesis makes use of the world's highest energy photon beam, up to 400 GeV, at the Fermi National Accelerator Laboratory near Chicago, Illinois. High-\( p_t \) particles from photon-nucleus collisions are measured with a large solid angle calorimeter. The data was taken by the Fermilab E683 collaboration in 1991. A total of eight nuclear targets were used, with atomic number \( A \) ranging from 1 to 207. In chapter 2, we will present a detailed description of the photon beam line system. In chapter 3, a somewhat abbreviated description of the experimental apparatus is given. This is because most the setup was used by several previous experiments and detailed documents already exist. In chapter 4, we discuss the data analysis procedure and present the results on the \( A \)-dependence of high-\( p_t \) photoproduction. Some interpretations of the data and comparisons to results from high-\( p_t \) hadron-nucleus collisions will be given in the discussion part of chapter 4.
II. High Energy Photon Beams

Since the photon is a neutral particle, one can not obtain a high energy photon beam directly from an accelerator. It is necessary to collect photons through the interaction of charged particle beams with materials. Here, we discuss how photon beam is produced at the Fermi National Accelerator Laboratory.

A. Photon Beam from a Proton Accelerator

In order to achieve a photon beam with energy in the order of hundreds of $GeV$, one has to use beams provided by the proton accelerators. At present, most of the photoproduction experiments using high energy ($\gtrsim 100 GeV$) photons are performed at CERN and Fermilab. The production of a "clean" photon beam—one which is free of neutral hadrons—in a proton accelerator is a complicated process, requiring several steps. Here, we will describe in some detail how the "Wideband Photon Beam" is produced at Fermilab.

Shown in Figure 2 is a schematic of the Wideband beamline. The primary proton beam of 800 $GeV$ extracted from the Fermilab Tevatron Accelerator first interacts with the "primary target" and generates $\pi^0$'s, which decay almost immediately into two photons. Charged particles produced in the proton collision are removed by the "target box magnets" and we are left with a beam of photons and neutral particles such as neutrons and $K^0_L$'s. Next, photons are converted to $e^+e^-$ pairs in the "converter" and the high energy electrons are selected and guided away by the dipoles and quadrupoles of the "secondary beam transport". Finally, a beam of photons is obtained when the electrons bremsstrahlung in the "radiator".

Careful consideration must be given when choosing the type of material and thickness
FIG. 2: The Fermilab Wideband photon beamline
FIG. 3: Relative photon yields for production targets of Beryllium, liquid Deuterium, and Lithium.

of the primary target, the converter and the radiator. The primary target can not be too long because photons can convert as they travel from the production point to the end of the target. The type of material for the primary target has to contain a high ratio of radiation length to nuclear interaction length so that more proton-nucleon interaction can occur while allowing relatively few photons to convert. Liquid Deuterium was selected for these purposes. Figure 3 shows the relative photon yield in a Beryllium target as a function of its thickness [45]. In order to maximize the high energy electron yield in the converter, one chooses a material which contains a low ratio of radiation length to nuclear interaction length so that more photons can convert to $e^+e^-$ pairs while allowing few hadronic interactions to occur. The converter can not be made too long because the electron might radiate inside the converter and loose part of its energy, thus affecting the yield of high energy electrons.
As we see in Figure 2, it is not just the photons that reach the converter, there are also neutral hadrons, mostly neutrons and $K_L^0$'s. When they strike the converter a small fraction of these neutral hadrons may interact and produce high energy charged hadrons which are captured by the secondary (electron) beam transport (mostly $\pi^-$). The charged hadrons will eventually arrive at the radiator and may undergo a hadronic interaction. These hadronic interactions are only a problem if they produce neutral particles that are at such small angles that they will eventually strike the experimental target. Any charged particles produced in these collisions will be removed by the "electron sweepers" just downstream of the radiator.

This is the main source of hadronic contamination in the photon beam. It is typically quite small because it has to come from a sequence of events each of which has relatively low probability. The hadronic background can be estimated with a Monte Carlo calculation and is also measurable. For the Wideband Photon Beam, the hadronic background is approximately $10^{-5}$ neutrons per photon ([46]). Since the hadronic cross section for $\gamma p$ collisions is roughly 200 times smaller than that for $pp$ collisions, the number of events that are neutron induced is therefore under 1% of the total of photoproduction events.

Finally, in choosing the type of radiator one wants a material that is similar to the converter in order to reduce the hadronic background. It can not be too thick because then the electron will have a higher probability to radiate more than one energetic photon in the radiator, thus making the interpretation of the data more difficult. Normally, one uses a radiator with thickness of less than 20% of a radiation length.

Figure 4 shows the electron to proton yield for an incident 800 $GeV/c$ proton beam as a function of the electron energy [45]. For the Wideband Photon Beam, the central electron energy is set around 320 $GeV$ (Figure 5), and the electron energy has a $\pm13\%$ spread.
FIG. 4: Electron yield per incident proton. Solid curve is a fit to the data with the parameterization \( A (1 - x)^n \), where \( x = \) electron momentum/proton momentum, \( A = 9.3 \cdot 10^{-4} \) and \( n = 5.39 \).
FIG. 5: Electron momentum distribution.
around the central energy. The electron beam momentum is measured by five silicon strip detectors positioned around two dipole magnets. The silicon strip detectors are of identical construction with strip spacing of 300 $\mu m$. There are two silicon planes positioned in front of one dipole magnet to measure the incoming electron trajectory and two silicon planes positioned behind the other dipole magnet to measure the outgoing electron trajectory after the electron is deflected by the magnets. One silicon plane is placed in between the two dipole magnets to provide an extra measurement of the electron position. For the nominal Wideband electron beam momentum of 320 $GeV$, the dipole magnets provide a horizontal deflection of about 1 $GeV$.

The tracking of the electrons are done in two steps: (1) track finding (or sometimes called pattern recognition) and (2) tracking fitting. Since a good event should only have one electron per interaction, the tracking program therefore only attempts to do track fitting for single track event. If the program decides there are more than one track in this event, it will exit and return the number of tracks found but not the momentum of each track.

For an ideal event, each of the five silicon plane should register one and only one hit by the electron, one then fits a track through these five points by minimizing the $\chi^2$. This is done by performing a 3-parameter fit. They are: the incoming electron angle, the outgoing electron angle and the intercept at the middle plane, which is positioned in between the two dipole magnets. The electron momentum is then directly proportional to the inverse of the bending, i.e., the difference between incoming and outgoing electron angles.

For an actual event, noises and inefficiencies in the silicon planes complicate things. One has to decide which hit is a good hit and which hit is just a noise hit in the silicon plane. One also has to know how to deal with the situation when the electron didn't register
a hit in one or several of the five silicon planes due to limited geometrical acceptance of the planes. This is the job of the pattern recognition part of the tagging program. The general idea is to try to match the electron track measured at upstream of the magnets to the one measured at downstream of the magnets, they should almost intercept at the middle of the magnets. At the same time, the following special cases have to be considered:

1. The upstream track does match the downstream track, but no matching hit is found in the middle plane. This is probably due to the middle plane being inefficient. In this case, the electron track is fit through 2 upstream hits and two downstream hits.

2. No downstream track matches the upstream one (or vice versa). In this case, the program will try to there are match hits in the downstream planes and the middle plane. Track fitting is only possible when two hits are found among the downstream and the middle planes.

3. The electron is outside the acceptance of the planes, it does not leave enough hits in the silicon planes to fit a track.

4. If a upstream track matches several downstream tracks, the program will choose a match that returns the smallest $\chi^2$. This happens most often when several adjacent silicon strips are triggered by the electron in one of the silicon planes.

5. The program makes sure only one electron track candidate is found for this event before it performs a track fitting and returns an electron momentum.

For normal beam conditions, the electron tracks are quite clean and easy to identify since the majority of the events are of single multiplicity (Figure 6 is a plot of electron multiplicity
FIG. 6: Number of electrons in the same beam bucket as measured in the silicon detectors. Also, the silicon planes generally worked well during the run.

The photon energy spectrum follows the bremsstrahlung distribution, which goes approximately as $1/E_\gamma$, where $E_\gamma$ is the photon energy. The photon energy is measured by measuring the energy of the electron after it radiated in the radiator (the recoil electron). As we see in Figure 2, the recoil electron is deflected away from the photon by the "electron sweepers" and hits the RESH (Recoil Electron Shower Hodoscope). RESH is an array of Pb/scintillator sandwich modules designed to measure the electron energy. One can also
infer the energy of the recoil electron simply from knowing which RESH module got hit by the recoil electron. The recoil electron is bent by the sweeper magnet, so that position at the RESH is equivalent to electron energy. The average angle between the electron and the photon it radiated is given by ([47]):

$$\theta = \frac{m_e c^2}{E_e}$$

where $E_e$ is the energy of the electron beam and $m_e$ is the mass of the electron. So for a high energy electron beam, this angle is essentially zero. Therefore the initial direction of the recoil electron is the same as the electron beam direction. Table 2.1 lists the positions of these RESH counters with respect to the beam and the correspondence between recoil electron energy and positions of the RESH counters. A RESH hit map is shown in figure 7. If one were to use the pulse height information of the RESH counters, one would get a smoother distribution and better resolution for the recoil electron energy, but this requires a careful calibration of the RESH counters. In this thesis, we will use the recoil electron energy given by Table 2.1.

The photon energy measurement has an approximately 3% resolution \(^3\), which comes from the finite size of the RESH modules, and from the resolution for the electron momentum measurement. Under normal running conditions, the efficiency of the tagging is about 60%, due to the acceptance of the silicon detectors, multiple electrons in the same beam bucket, and the efficiency of the RESH counters.

\(^3\)According to [48], the photon energies calculated in this thesis are possibly 4 - 5% higher than the real photon energies. The effect is still under study.
<table>
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<td>79</td>
</tr>
<tr>
<td>5,6</td>
<td></td>
<td>75</td>
</tr>
<tr>
<td>6</td>
<td>20.32</td>
<td>70</td>
</tr>
<tr>
<td>6,7</td>
<td></td>
<td>66</td>
</tr>
<tr>
<td>7</td>
<td>22.90</td>
<td>62</td>
</tr>
<tr>
<td>7,8</td>
<td></td>
<td>59</td>
</tr>
<tr>
<td>8</td>
<td>25.48</td>
<td>55</td>
</tr>
<tr>
<td>8,9</td>
<td></td>
<td>53</td>
</tr>
<tr>
<td>9</td>
<td>29.81</td>
<td>50</td>
</tr>
<tr>
<td>9,10</td>
<td></td>
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<tr>
<td>10</td>
<td>37.56</td>
<td>-</td>
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<td>10,11</td>
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<td>-</td>
</tr>
<tr>
<td>11</td>
<td>4.50</td>
<td>49</td>
</tr>
<tr>
<td>11,12</td>
<td></td>
<td>46</td>
</tr>
<tr>
<td>12</td>
<td>4.75</td>
<td>26</td>
</tr>
</tbody>
</table>

TABLE 2.1: RESH geometry and the correspondence between the recoil electron energy and the positions of the RESH counters. Electrons can not reach RESH 10 because it is overshadowed by RESH 11 and 12, which are placed near the beam pipe and upstream from the rest of the RESH counters.
FIG. 7: Recoil electron momentum distribution as given by only the position information of the RESH.
III. Experimental Setup

The E683 detector system is located in the Wideband Experiment Hall at Fermi National Accelerator Laboratory. A top view of the detector is shown in Figure 8. It consists of several small scintillation counters for defining the beam, a steel hadron shielding block, a muon veto hodoscope, a target setup, 5 planes of multiwire proportional chambers, 17 planes of drift chambers, a dipole magnet for momentum analysis (which provides a roughly 70 MeV $p_t$ kick), the main calorimeter and a beam calorimeter.

Since the major components of the E683 detector were used in a similar setup in a previous Fermilab experiment E609, some details of the apparatus will be omitted in the following discussion. When necessary, readers are referred to previously published papers and theses for more details.

A. Main Calorimeter and Its Calibration

The main calorimeter is the primary device of the experiment. It is used to measure the energies of most of the final state particles produced in high $p_t$ collisions. It also provides the main trigger for the experiment. Since most of the data analysis done in this thesis is based on information from the main calorimeter, an abbreviated description of the detector follows here. For a detailed and thorough description of the main calorimeter, see reference [49].

The main calorimeter has 4 layers along the beam direction (the $A'$, $A$, $B$ and $C$ layer) and each layer consists of 132 modules. A tower is formed by 4 modules, each from a different layer. They line up to point roughly at the interaction target. The exact CM polar angle $\theta^*$ coverage of the main calorimeter varies with the photon energy (for 250 GeV
beam, the $\theta^*$ coverage is from $18^\circ$ to $123^\circ$). Module sizes in the transverse direction are shown in a front view of the calorimeter array (Figure 9). They are chosen so that in the center-of-mass (CM) frame, the cross sectional areas of the modules subtend roughly equivalent solid angles at the target ($\sim 0.07sr$ per tower).
<table>
<thead>
<tr>
<th>Sampling Frequency</th>
<th>Fe Plate Thickness</th>
<th>Pb Plate Thickness</th>
<th>Scint. Plate Thickness</th>
<th>Scint type</th>
<th>$X_{abs}$</th>
<th>$X_{rad}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>20 Gap</td>
<td>12.7 mm</td>
<td>12 mm</td>
<td>Roehm 1922</td>
<td>1.93</td>
<td>15.35</td>
<td></td>
</tr>
<tr>
<td>16 Gap</td>
<td>18.8 mm</td>
<td>12 mm</td>
<td>Roehm 1922</td>
<td>2.11</td>
<td>17.89</td>
<td></td>
</tr>
<tr>
<td>14 Gap</td>
<td>28.4 mm</td>
<td>8 mm</td>
<td>Roehm 2003</td>
<td>2.54</td>
<td>23.08</td>
<td></td>
</tr>
<tr>
<td>5 Gap</td>
<td>9.6 mm</td>
<td>8 mm</td>
<td>Roehm 2003</td>
<td>0.37</td>
<td>8.8</td>
<td></td>
</tr>
<tr>
<td>3 Gap</td>
<td>9.6 mm</td>
<td>12 mm</td>
<td>Roehm 1922</td>
<td>0.24</td>
<td>5.37</td>
<td></td>
</tr>
</tbody>
</table>

TABLE 3.2: Main calorimeter modules types, composition, and interaction lengths. For the $A'$ layer: the $2'' \times 4''$ and $4'' \times 4''$ modules are of 5 gap types, the $6'' \times 6''$ and $8'' \times 8''$ modules are of 3 gap types. For the $A$, $B$ and $C$ layer: the $2'' \times 4''$ modules and $4'' \times 4''$ modules are of 14 gap types, the $6'' \times 6''$ modules are of 16 gap types, the $8'' \times 8''$ modules are of 20 gap types. See figure 8 for the size and location of the calorimeter modules.

All modules are sampling types. The sampling frequencies and the longitudinal sizes of the modules are listed in Table 3.2. We see that the "electromagnetic" section (the $A'$ and $A$ layers) of the calorimeter has roughly 25 radiation lengths, and the whole main calorimeter has a combined total of about 7 absorption lengths. The various sampling thicknesses reflect the fact that at increasing CM angles a particle or cluster of particles which satisfy a high transverse momentum trigger will have decreasingly less energy. Since we wish the energy resolution to be uniform over the whole calorimeter at the trigger level, we must therefore decrease the sampling thickness as we go out in CM angle (a detailed discussion of energy resolution for sampling calorimeters can be found in [50]).

Calibration of the main calorimeter follows basically the same procedure as what has been done in E609 [49]. The calibration of the calorimeter begins with a muon beam which deposits its energy mostly through ionization loss in the calorimeter. The amount of muon
energy loss can be calculated analytically or obtained through Monte Carlo simulation. In the latter case, one can include other mechanisms like Bremsstrahlung, $\gamma$-ray production and $e^+e^-$ pair production, which are non-negligible for high momentum (above 100 GeV/c) muons. In general, the average muon energy loss in the calorimeter depends on the momentum of the muon; in E683, since we do not measure the momentum of the incoming muon, we have chosen to use the most probable value of muon energy loss to calibrate the calorimeter response, which is known to have a very weak dependence on the muon momentum ([49], [51]). For a given module type and full scale energy, the ADC counts corresponding to the most probable muon energy deposition $E_{\mu}^{\text{nop}}$ is calculated according to

\[ \text{balance pt.} = E_{\mu}^{\text{nop}} \cdot (3600/E_{\text{max}}) \cdot n_{\text{gain}} \cdot R_{e/\mu} \]

where $E_{\text{max}}$ is the full scale energy that corresponds to 3600 ADC counts, $n_{\text{gain}}$ is the amplifier gain and $R_{e/\mu}$ is the sampling fraction ratio for electrons and muons. In the above formula, only $R_{e/\mu}$ is not known precisely. An empirical value of 1.47 is used for $R_{e/\mu}$ in our muon calibration, which is known to be approximately right for most types of sampling calorimeters (for a detailed discussion of $R_{e/\mu}$, see [51]). A typical ADC distribution for a main calorimeter module traversed by muons is shown in figure 10.

The main purpose of muon calibration is to adjust the photomultiplier voltages of the calorimeter modules until they give the desired responses. A more precise determination of the calorimeter response is done through electron calibration. In this case, one brings a well focused 90 GeV electron beam into the center of each calorimeter tower and records the response of each module. One then applies corrections to these responses offline so that they add up to the right electron energy and give the best resolution. This is done in the
FIG. 10: Typical ADC distribution for the C layer modules of the main calorimeter traversed by muons. Mean: 741 counts, most probable: 629 counts.
the following way: assuming the correction factors for the $A'$ and $A$ layers are $c_{A'}$ and $c_A$, then the right correction factors should minimize the function

$$f = \sum (c_{A'} \cdot E_{A'} + c_A \cdot E_A + E_B + E_C - E_{\text{beam}})^2$$

where $E_{A',A,B,C}$ are energies in the four layers of the calorimeter and the summation is over events that passed the following cuts: (1) multiplicity in each of the drift chambers positioned in front of the calorimeter has to be less than or equal to 1. This is to ensure that the electron did not interact with other materials prior to reaching the calorimeter; (2) the $\chi^2$ for the electron momentum measurement has to be less than 2. This is to ensure that the electron momentum is measured with good resolution; (3) at least 90% (80%) of the shower energy is contained in one module of the $A'$ ($A$) layer; and (4) energy deposited in $B$ and $C$ layers of the calorimeter has to be less than 3% of the beam energy. This is to get rid of rare events resulting from the pion contamination in the beam. An electron would deposit all of its energy in the first two layers of the calorimeter and its shower is usually fully contained in one calorimeter module, thus allowing all 264 modules of the $A'$ and $A$ layers to be calibrated individually. Figure 11 illustrates the differences between the calorimeter response before and after it has been rebalanced with the above mentioned procedure (from a calibration run taken with 90 GeV electrons).

Figure 12 is a plot of these correction factors. The distribution has a mean of about 0.8 and a 15% spread around the mean. Since the electron deposits all of its energy in the first 2 layers of the main calorimeter (the $A'$ and $A$ layer add up to about 25 radiation lengths, see Table 3.2), the responses for the back 2 layers of the calorimeter (the $B$ and $C$ layers) cannot be accurately determined as in the case of the first 2 layers. We choose to simply scale the responses of the $B$ and $C$ layers determined from the muon calibration to that
FIG. 11: Typical distributions of $E_{\text{mcal}}/E_{\text{beam}}$ from a calibration run taken with $90\text{GeV}$ electrons. (a): before balancing, (b) after balancing. Details of balancing procedures are explained in the text.

FIG. 12: Distribution of the gain correction factors for all 132 modules of the A layer, as determined from the electron calibration.
of the $A$ layer module by module, since these 3 layers are of identical construction. This basically sets the average response of the $B$ and $C$ layers to that of the $A$ layers. In this thesis, no attempt is made to calibrate the $B$ and $C$ layers of the calorimeter module by module. For the results to be presented later, we anticipate the overall uncertainty in the energy scale of the main calorimeter to be around 10%, which is expected to improve in the future when a complete calibration is done involving both electrons and hadrons ([52]).

The hadronic response of the main calorimeter is measured with pion beams of various momenta and compared to the electromagnetic response measured with electron beams (the so called $e/h$ ratio). In general, for the same beam particle momenta, the hadron shower gives rise to a smaller signal in the scintillators of the calorimeter than that of an electron shower ($i.e.$, $e/h > 1.0$). This is mainly due to differences in energy loss mechanisms between hadrons and electrons([50]). Figure 13 shows the typical hadronic response of the main calorimeter from a calibration run with 100 GeV pions. The mean of the distribution would correspond to the inverse of the $e/h$ ratio. Figure 14 shows the $e/h$ ratios measured at different parts of the main calorimeter. These ratios agree well with several previous measurements done on this calorimeter ([55], [49]).

From the electron and hadron calibration, the energy resolution for the main calorimeter has been determined to be $\sigma/E = (43\pm8)/\sqrt{E(\text{GeV})} \oplus (2.5\pm0.8)$% for electromagnetic showers and $\sigma/E = (74\pm14)/\sqrt{E(\text{GeV})} \oplus (7.1\pm2.1)$% for hadronic showers (the symbol $\oplus$ signifies that the constant term is added in quadrature in the resolution). The constant term in the resolution for $EM$ showers comes mostly from the $\sim 2\%$ resolution in electron momentum measurements. These numbers are in good agreement with previous measurements ([49], [55]).
FIG. 13: Typical distribution of $E_{\text{mcal}}/E_{\text{beam}}$ from a calibration run taken with 100GeV pions.
FIG. 14: $e/h$ ratios measured at various parts of the main calorimeter from electron and hadron calibration
<table>
<thead>
<tr>
<th>Layer</th>
<th>no. of Scint.</th>
<th>Thick. of Iron (&quot;')</th>
<th>Radiation Lengths</th>
<th>Absorption Lengths</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6</td>
<td>8</td>
<td>11.5</td>
<td>1.15</td>
</tr>
<tr>
<td>2</td>
<td>8</td>
<td>10</td>
<td>14.4</td>
<td>1.44</td>
</tr>
<tr>
<td>3</td>
<td>16</td>
<td>24</td>
<td>34.6</td>
<td>3.46</td>
</tr>
<tr>
<td>4</td>
<td>16</td>
<td>24</td>
<td>34.6</td>
<td>3.46</td>
</tr>
</tbody>
</table>

**TABLE 3.3:** Beam calorimeter layer compositions. Radiation and absorption lengths do not include scintillators (1/4" polystyrene sheets).

During the course of the experiment, the gain stabilities of the calorimeter modules were monitored with a LED system and information was recorded on data tapes. For results to be presented later in this thesis, this information is not used.

**B. Beam Calorimeter and Its Calibration**

The beam calorimeter is used to measure energies of particles produced in the very forward direction passing through the 8" x 8" hole in the center of the main calorimeter. Details of the design and construction of the beam calorimeter can be found in [53].

The beam calorimeter has 4 layers in the beam direction. It is a sampling calorimeter with iron plates as the passive absorber and plastic scintillator slabs as the active material. The beam calorimeter is 2' x 2' wide and has a total of about 10 interaction lengths (Table 3.3), which is sufficient to contain at least 99% of most of the hadronic showers ([57]). Electromagnetic particles normally would deposit all of their energies in the first and second layers of the beam calorimeter (the so called electromagnetic section of the beam calorimeter, which has about 27 radiation lengths).
The calibration of the beam calorimeter proceeded in much the same way as that for the main calorimeter. It is simpler because each layer of the beam calorimeter has just one “module”. But the signals from the beam calorimeter module are read out by two photomultipliers mounted at the east and west side of the calorimeter. It is necessary to balance the relative response first between the two readouts before one balances the response between layers. This is done by finding a balancing coefficient $\lambda$ to minimize the function

$$f = \sum (E_{east} - \lambda E_{west})^2$$

Much details about the calibration of the beam calorimeter can be found in [54]. The energy resolution for the beam calorimeter has been measured to be $\sigma/E = 45\%/\sqrt{E(\text{GeV})} \oplus 2\%$ for electromagnetic showers and $\sigma/E = 75\%/\sqrt{E(\text{GeV})} \oplus 3\%$ for hadronic showers.

During the experiment, it was discovered that the beam calorimeter has been losing its signal at a steady rate. Although the exact cause for this was not completely understood (it was partially attributed to radiation damage to the scintillators), the time dependence of the beam calorimeter signal loss was monitored constantly throughout the course of the experiment, and the corrections to the calorimeter response were applied off-line on a run-by-run basis ([54]).

C. Drift Chambers and Multiwire Proportional Chambers

A total of 17 planes of drift chambers (DC) and 5 planes of multiwire proportional chambers (MWPC) were used in E683 to establish the event vertex and perform momentum analysis for charged particles. Since the data analysis done in this thesis did not use information from these tracking chambers, a discussion of these chambers will be omitted here. In reference [56] interested readers can find a detailed discussion of the construction and performance...
<table>
<thead>
<tr>
<th>Target</th>
<th>CAMAC pos.</th>
<th>A</th>
<th>$\rho (g/cm^3)$</th>
<th>d (cm)</th>
<th>$X_0$(cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pb(II)</td>
<td>7</td>
<td>207.19</td>
<td>11.35</td>
<td>0.127</td>
<td>0.72</td>
</tr>
<tr>
<td>Pb(I)</td>
<td>0</td>
<td>207.19</td>
<td>11.35</td>
<td>0.3683</td>
<td>0.72</td>
</tr>
<tr>
<td>empty</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sn</td>
<td>2</td>
<td>118.69</td>
<td>7.31</td>
<td>0.5042</td>
<td>1.556</td>
</tr>
<tr>
<td>Al</td>
<td>3</td>
<td>26.98</td>
<td>2.70</td>
<td>2.0066</td>
<td>11.443</td>
</tr>
<tr>
<td>Cu</td>
<td>4</td>
<td>63.55</td>
<td>8.96</td>
<td>0.6121</td>
<td>1.8386</td>
</tr>
<tr>
<td>Be</td>
<td>5</td>
<td>9.01</td>
<td>1.848</td>
<td>2.54</td>
<td>45.396</td>
</tr>
<tr>
<td>C</td>
<td>6</td>
<td>12.01</td>
<td>1.704</td>
<td>2.54</td>
<td>32.22</td>
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<tr>
<td>H</td>
<td>1</td>
<td>0.07072</td>
<td>50.75</td>
<td></td>
<td>1112</td>
</tr>
<tr>
<td>D</td>
<td>2</td>
<td>0.162</td>
<td>50.75</td>
<td></td>
<td>973</td>
</tr>
</tbody>
</table>

**TABLE 3.4:** Nuclear targets used in E683. $A$ is the atomic number, $\rho$ is the density, $d$ is the thickness and $X_0$ is the photon absorption length.

of most of these chambers when they were used in a similar setup in E609.

D. **Targets**

In E683, data were taken alternately from eight nuclear targets with atomic number, $A$, ranging from 1 to 207 (Table 3.4. Two different lead targets were used to measure possible target thickness dependence for heavy targets). The solid targets were mounted on a wheel and were changed between each spill by rotating the wheel, therefore reducing possible systematic errors. Interchange between the liquid hydrogen target and the solid targets happened every 3 ~ 4 hours per day throughout the course of the experiment. Target
empty rates were measured once per day for the hydrogen target and every 8 spills for the solid targets. Data from deuterium was also taken with liquid deuterium replacing liquid hydrogen in the hydrogen target vessel, however this did not happen regularly during the experiment. This might result in large systematic errors when we compare the deuterium data and the data from other targets.

E. Triggering and Data Acquisition

In E683, events were selected by requiring relatively large amounts of transverse energy to be observed in the main calorimeter. Two geometrically unbiased triggers were used. The global trigger requires the total transverse energy summed over all 132 towers of the main calorimeter \( E_T = \sum_{i=1}^{132} (E_T)_i = \sum_{i=1}^{132} E_i \sin(\theta_i^{ab}) \) to exceed a specific threshold, which was about 4 GeV. It is known from previous studies in pp collisions that events selected by the global trigger (at least for pp collisions) are generally non-jet-like ([25], [24]). We chose to use the global trigger in E683 mainly because it allows us to compare our results with these experiments.

The other trigger, called the two-high trigger, requires that the transverse energy deposited in any two towers on the main calorimeter exceed a specific threshold, which was about 0.7 GeV. This is a trigger designed to be sensitive to dijet events since jets tend to deposit all their transverse energy in relatively small areas of the calorimeter. The two-high trigger has been demonstrated as an efficient trigger for selecting jet-like events in pp collisions at fixed target energies ([22], [62]), and yet it is geometrically unbiased since it does not place any requirements on the relative locations of the two triggering towers.

The logic diagram in Figure 15 shows how these triggers are implemented in E683. The
decision to record an event onto tape is a relatively unsophisticated process. It is a logic AND of an interaction trigger and a high-$E_T$ trigger. The interaction trigger is defined as $(C_1 + B_2) \cdot C_2$ and a modest $E_T$ requirement from the main calorimeter, which is satisfied when a neutral beam particle interacts with the target ($C_1, B_2, C_2$ are beam scintillation counters shown in Figure 8). The high-$E_T$ trigger is either the global trigger or the two-high trigger defined by the main calorimeter.

The thresholds for the global trigger and the two-high trigger were set according to the E683 data-recording capability, so that the trigger rate is compatible with the ability of the data acquisition system to collect and transfer data to tape. An average event record contains 8 kbytes of information. Over the 6-month period of data taking, E683 collected about $10 \times 10^6$ events on 800 magnetic tapes.
IV. Data Analysis and Results

A. Data Compaction

For each event, the electronic signals from the detectors are recorded on tape in the form of ADC counts for the calorimeter modules, TDC counts for the drift chambers, hit information for various counters and MWPCs, and hit information for silicon strip detectors. This is known as the "raw data". Before we analyze the data, it is necessary to convert the raw data into physical quantities like energy depositions and particle trajectories or positions. Also, since some detectors are not used in the analysis done in this thesis (like TDC information from the drift chambers), there is no need to include them among the information presented for each event. All these reduce the "size" of the event considerably. I list here briefly the relevant detectors to be used in our analysis and the information they presented:

- **Silicon Microstrip Detectors**: As we mentioned in Chapter 2, the silicon microstrip detectors measure the momentum of the electron before it radiates in the radiator. For each event, we try to reconstruct electron tracks from the hit information in the detectors and determine the number of electrons present in the silicon detectors. If it is a single electron, then the momentum of the electron is calculated from the predetermined magnetic field distribution in the bending magnets.

- **Recoil Electron Shower Counter (RESH)**: The position of the RESH module (or modules, if they are adjacent) which was hit determines the recoil electron momentum.

- **Pileup Monitors**: They determine whether there are electrons present in the RF buckets adjacent to the current one.
• **Target:** Readouts from several position-switches determine which target is in the beam for the event.

• **Main Calorimeter:** Energy deposition in each module is calculated by subtracting the pedestal value from the ADC counts and multiplying by a constant that was determined in the calibration. Energy deposition in a main calorimeter tower was obtained by summing the energies in the modules that form the tower. There are 132 towers in the main calorimeter and they make up the majority of the information for the event.

• **Beam Calorimeter:** Energy deposition in each of its four layers is calculated in a similar way as the main calorimeter modules. But unlike the main calorimeter, the calibration constants for the beam calorimeter layers are different from run to run in order to account for their signal losses during the course of the experiment.

• **Various Beam Flux Monitors:** This includes readouts from the flux counters for the primary protons, the electrons, the recoil electrons, the photons and the $e^+e^-$ pairs from photon conversions in the target.

• **Various Latches and Scalers:** These provide various trigger information and dead time estimates.

For each event, this information forms an array which contains 196 real numbers (it represents a 10-fold reduction in event size from the raw data), and arrays are then grouped together to form a data base called *Ntuple*. *Ntuples* are designed to allow users to perform a variety of functions on the data in a fast, efficient and interactive way. They include making selection cuts on the data, histogramming, doing graphics and many others.
B. Event Selection

Before we can extract meaningful physics results from the data, it is important to ensure that the events in our data sample come from photons that interact hadronically in the target. Fortunately for the E683 data, it is relatively easy to isolate events that do not originate from the $\gamma A$ collisions. The major source of these “bad” events is from muons interacting in the main calorimeter which undergo hard bremsstrahlung—enough to satisfy the global trigger or the two-high trigger. The signature for these “muon-like” events in the main calorimeter is that they generally have much lower multiplicities than the average high-$p_T$ $\gamma A$ interactions. Figure 16 is a plot of the distribution of the number of main calorimeter towers hit. The “muon-like” events can be cut out by requiring the number of towers hit to be greater than 20 (this reduces the number of events by $\sim 24\%$ on the average for nuclear target runs, and $\sim 13\%$ for hydrogen target runs).

Additional requirements applied to the data are:

1. The electron momentum and the recoil electron momentum have to be well measured in the silicon microstrip detectors and the RESH counters, so that we know what the photon energy is ($E_\gamma = E_{\text{electron}} - E_{\text{recoil}}$).

2. The photon energy $E_\gamma$ has to be between 50 GeV and 400 GeV ($50 \text{ GeV} < E_\gamma < 400 \text{ GeV}$). The $E_\gamma$ distribution is plotted in figure 17 (the previous requirement and this one reduce the number of events by an additional 31%).

3. Total energy deposited in the beam calorimeter has to be less than the photon energy ($E_{\text{beam}} < E_\gamma$) (reduces the number of events by an additional 4%).

4. Total energy deposited in the main calorimeter has to be less than the photon
FIG. 16: Distribution of number of calorimeter towers hit. For each event, we say a tower is "hit" when the energy deposited in it exceeds 200 MeV. Events in the shaded area are cut out.
FIG. 17: Photon energy distribution for events triggered by E683 global and two-high trigger. In the final event selection, we require $50 \, \text{GeV} < E_{\gamma} < 400 \, \text{GeV}$.

energy plus 50 GeV ($E_{\text{mcal}} < E_{\gamma} + 50 \, \text{GeV}$) (reduces the number of events by an additional 2%).

5. Total energy deposited in the main calorimeter and the beam calorimeter has to be less than the photon energy plus 75 GeV and greater than 50% of the photon energy ($0.5 \, E_{\gamma} < E_{\text{mcal}} + E_{\text{bcal}} < E_{\gamma} + 75 \, \text{GeV}$) (reduces the number of events by an additional 2%).

Approximately 45% of the original data sample survived these cuts.
FIG. 18: Total transverse energy $E_T$ distributions for (a) two-high trigger events and (b) global trigger events at $200 \text{ GeV} < E_\gamma < 300 \text{ GeV}$ for $\gamma$-$\text{Pb}$ collisions (dashed) and $\gamma$-$\text{H}$ collisions (solid).

C. A-Dependence of $\gamma A$ Cross Sections

We now turn our attention to physics results. We present first the A-dependence of cross sections as a function of the total transverse energy deposited in the main calorimeter and the photon energy. Since we will be comparing the relative differences between cross sections for the different nuclei, no attempt is made in this thesis to calculate the absolute cross sections. That will be the topic of another thesis.

The distributions of the total transverse energy $E_T$ deposited in the main calorimeter for $\gamma p$ and $\gamma Pb$ collisions are plotted in figure 18. We notice some features: (1) the initial rising part of the distributions is determined by the hardware trigger thresholds. (2) for the two-high trigger, the $E_T$ distribution for the $\gamma Pb$ collisions is peaked at slightly higher $E_T$ value than that for the $\gamma p$ collisions. This reflects the fact that the event multiplicity is higher for the $\gamma Pb$ collisions: because of higher multiplicity, the $E_T$ of each particle generated in $\gamma Pb$ collisions is lower on the average than in $\gamma p$ collisions; in order to satisfy the two-high trigger threshold, it requires more total transverse energy from the $\gamma Pb$ collisions.
FIG. 19: $x_T$ distributions for (a) two-high trigger events and (b) global trigger events at $200 \text{ GeV} < E_\gamma < 300 \text{ GeV}$ for $\gamma$-Pb collisions (dashed) and $\gamma$-H collisions (solid).

We define a scaled transverse energy, variable $x_T$ by

$$x_T \equiv \frac{E_T}{\sqrt{s}}$$

where $\sqrt{s}$ is the center-of-mass energy of the $\gamma$-nucleon system. Since the beam energy is not fixed for this experiment (as we see in figure 17, $\sqrt{s}$ can vary between 9.7 GeV and 27.4 GeV), it is worthwhile to study the cross section dependence on $x_T$ as well. Figure 19 is a plot of the $x_T$ distributions.

As we see from both figure 18 and figure 19, it is necessary to limit our studies of cross sections in the $E_T$ and $x_T$ regions that are clear of any hardware trigger biases, i.e., we must be above the peak of the distributions. For the results to be presented in this section, events are required to have $E_T > 6 \text{ GeV}$ or $x_T > 0.3$.

To calculate the cross sections, we use the following formula:

$$\sigma = \frac{N}{L_0} \cdot \frac{A}{N_0 \rho \bar{d}}$$

\footnote{After the software $E_T$ or $x_T$ cut, the results are found to be insensitive to the triggering tower $E_T$ cut for two-high trigger events}
where $N$ is the number of selected events, $L_0$ is the beam flux, $A$ is the atomic number of the target material, $N_0$ is the Avogadro's constant, $\rho$ is the target density and $d$ is the target length in the beam direction (see table 3.4 for a list of targets used in E683). The beam flux is corrected for deadtimes for the muon hodoscope counter, the $C_2$ counter and the data acquisition computer deadtime. The ratio of cross sections for two different targets is then given by:

$$\frac{\sigma_1}{\sigma_2} = \frac{R_1}{R_2} \cdot \frac{A_1}{A_2} \cdot \frac{d_2}{d_1} \cdot \frac{\rho_2}{\rho_1}$$

where $R$ is the event rate normalized to the beam flux. For the results to be presented later, we will use the electron flux as our normalization $^5$.

Since some of our targets have thicknesses of the order of a radiation length (see table 3.4), flux attenuation inside the target volume has to be taken into account when calculating $R$. Assuming the radiation length and the hadronic interaction length are $X_0$ and $X_H$, then the beam intensity at depth $x$ is given by

$$L(x) = L_0 \cdot e^{-x/X_0}$$

then the total number of hadronic interactions taking place in the target is proportional to

$$\int_0^d L_0 \cdot e^{-x/X_0} \cdot \frac{dx}{X_H} = L_0 \cdot \frac{X_0}{X_H} \cdot (1 - e^{-d/X_0}).$$

Assuming $L_0'$ is the average beam intensity seen by all target nuclei, then the total number of hadronic interactions taking place in the target is also proportional to

$$\int_0^d L_0' \cdot \frac{dx}{X_H} = L_0' \cdot \frac{d}{X_H}.$$  

$^5$We have found that our results are insensitive as to which beam flux measurement to use (see Appendix A).
FIG. 20: Ratio $\sigma(\gamma A)/\sigma(\gamma p)$ versus $A$ for (a) two-high trigger and (b) global trigger at $200 \text{ GeV} < E_\gamma < 300 \text{ GeV}$ and $0.35 < x_T < 0.40$. The solid lines are fits to the data with the parameterization $\sigma(\gamma A) = \sigma(\gamma p) A^\alpha$.

From the above two equations, we obtain

$$\frac{L_0'}{L_0} = \frac{X_0}{d} \cdot (1 - e^{-d/X_0})$$

Values of this ratio vary from 0.783 for the lead target to 0.978 for the hydrogen target.

When studying the $A$-dependence of cross sections, we follow the traditional way of parameterizing the relationship between the cross section for the target with atomic number $A$ and the cross section for the target with $A = 1$ as

$$\frac{\sigma(\gamma A)}{\sigma(\gamma p)} = A^\alpha$$

Values of $\alpha$ less than 1.0 indicate that the cross section increases slower than the number of nucleons in the target nucleus (traditionally referred to as “shadowing”), whereas $\alpha > 1.0$ signifies “anomalous nuclear enhancement”.

For the E683 data, $\sigma(\gamma A)/\sigma(\gamma p)$ versus $A$ for both two-high triggers and global triggers are plotted in figure 20, at beam energies $200 \text{ GeV} < E_\gamma < 300 \text{ GeV}$ and $0.35 < x_T < 0.40$. We can see that the above mentioned power-law parameterization fits our data reasonably
FIG. 21: Ratio $\sigma(\gamma A)/\sigma(\gamma p)$ versus $A$ for two-high trigger events. (a) $E_\gamma = 50 - 150\, GeV$, $x_T = 0.30 - 0.34$. (b) $E_\gamma = 50 - 150\, GeV$, $x_T > 0.46$. (c) $E_\gamma = 300 - 400\, GeV$, $x_T = 0.30 - 0.34$. (d) $E_\gamma = 300 - 400\, GeV$, $x_T > 0.46$. The solid lines are fits to the data with the parameterization $\sigma(\gamma A) = \sigma(\gamma p) A^\alpha$.

well \footnote{In calculating $\sigma(\gamma A)/\sigma(\gamma p)$, we have subtracted the target empty rates, which amount to \sim 15\% of the target full rate for the hydrogen target and \sim 10\% for the solid targets.}. This is also demonstrated in figure 21, where we plot $\sigma(\gamma A)/\sigma(\gamma p)$ versus $A$ for events at several different beam energies and $x_T$'s.

From figure 20 and figure 21, one notices that the $A$-dependence of cross sections is different at different beam energies and $x_T$'s. This means that $\alpha$ is function of both $E_\gamma$ and $x_T$.

The dependence of $\alpha$ on $x_T$ is shown in figure 22. It is clear that at fixed beam energies,
FIG. 22: $\alpha$ versus $x_T$ for two-high trigger events with beam energies at (a) $E_\gamma = 50-150 GeV$ and (b) $E_\gamma = 300-400 GeV$.

$\alpha$ increases with $x_T$. Naturally, one would also expect $\alpha$ to increase with $E_T$ as well. This is shown in figure 23. As a comparison, in figure 23(b) we also plot the $\alpha$ value measured in a high-$p_t$ proton-nucleus collision experiment with a 400 $GeV$ proton beam (E609).

The beam energy dependences of $\alpha$ are shown in figure 24. We see that $\alpha$ increases with the beam energy at fixed $x_T$ (figure 24(a)), but varies only slowly with beam energy at fixed $E_T$ (figure 24(b)). The latter result is natural because $x_T$ decreases while increasing beam energy at fixed $E_T$, which tends to cancel out the increase of $\alpha$ due to the increase of beam energy.

In table 4.5, we list the $\alpha$ values for five bins of $x_T$ and five bins of $E_\gamma$.

The errors in all the plots that we have shown here are statistical only. Possible systematic errors arise mainly from fluctuations in beam flux measurements ($\sim 10\%$), uncertainties in hydrogen empty target subtractions ($\sim 5\%$), which was done only once per day during the run, and uncertainties in dead time corrections ($\sim 5\%$). Corrections to "raw" $E_T$ spectra, arising from calorimeter resolutions effects, were estimated from Monte Carlo studies performed on $pA$ data with this calorimeter ([22]). It was found that the corrections are
FIG. 23: \( \alpha \) versus total transverse energy \( E_T \) for two-high trigger events at (a) \( 50 \text{ GeV} < E_T < 150 \text{ GeV} \) and (b) \( 300 \text{ GeV} < E_T < 400 \text{ GeV} \). As a reference, the open circle is the data point measured in a high-\( p_T \) proton-nucleus collision experiment with a 400 \text{ GeV} \) proton beam (E609). The close circles are data points measured in this experiment.

FIG. 24: \( \alpha \) versus beam energy for two-high trigger. (a) \( 0.42 < x_T < 0.46 \). (b) \( 8 \text{ GeV} < E_T < 9 \text{ GeV} \).
TABLE 4.5: Lists of $\alpha$ values for five bins of $x_T$: $x_1 = 0.30 - 0.34$, $x_2 = 0.34 - 0.38$, $x_3 = 0.38 - 0.42$, $x_4 = 0.42 - 0.46$, $x_5 = 0.46 - 1.0$, and five bins of $E_T$: $E_1 = 50 - 150 \text{ GeV}$, $E_2 = 150 - 200 \text{ GeV}$, $E_3 = 200 - 250 \text{ GeV}$, $E_4 = 250 - 300 \text{ GeV}$, $E_5 = 300 - 400 \text{ GeV}$. Two-high trigger. $\chi^2$ values are per degree of freedom.

practically independent of $A$. This should apply to $\gamma A$ data as well since our $E_T$ spectra have similar slopes. We estimate that these effects would give rise to $\sim 15\%$ uncertainties in $\sigma(\gamma A)/\sigma(\gamma p)$ for all targets. This would lead to a systematic uncertainty of 0.015 in $\alpha$.

D. A-Dependence of Event Shapes

One variable that has often been used to describe the event shape in the transverse plane of the event (the plane normal to the beam axis) is planarity. One first finds an axis which maximises the $\sum p_T^2$ along this axis (say $A$ is the sum), then the axis perpendicular to this axis should minimize the $\sum p_T^2$ (say $B$ is the sum). The planarity is then defined as

$$P = \frac{A - B}{A + B}$$

For any event, planarity takes on a value between 0 and 1. An event that has a planarity value close to 1 would contain two narrow back-to-back jets or one narrow jet with few or no background particles. As a rule of thumb, an event with $P \geq 0.7$ appears jet-like to the naked eye. For isotropic events, $P$ is 0.
FIG. 25: Planarity distribution for $\gamma p$ collisions. Events with two-high trigger, $E_\gamma = 200 - 300 GeV$ and $x_T = 0.30 - 0.40$ are selected.

The planarity distribution for events selected by the two-high trigger in $\gamma p$ collisions is shown in figure 25. It is expected that the events with different $x_T$ or $E_T$ would have different mean planarity. In figure 26, we plot the dependence of mean planarity on $x_T$ for $\gamma p$ collisions at different beam energies. Several features of this plot are noteworthy: (1) At low $x_T$, high planarity is expected because events have to satisfy the two-high trigger threshold at low $E_T$. As $x_T$ increases, the event multiplicity also increases, which results in the decrease of the average planarity. After reaching some minimum, the average planarity then starts to increase with $x_T$. This indicates that hard scattering, which results in jet-like
FIG. 26: Mean planarity as a function of $x_T$ for two-high trigger. Events at different beam energies are plotted separately.
events, begins to dominate the $\gamma p$ collisions at higher $x_T$. (2) The fact that the minima for the planarity occur at approximately the same $x_T$ value for all beam energies is particularly interesting. This would suggest that the "hardness" of the $\gamma p$ collisions is best described by the absolute value of the kinematical variable $x_T$, regardless of the beam energy. (3) It is not surprising to see that the average planarity is generally lower for events with higher beam energy. This is natural since the event multiplicity increases with beam energy.

If one uses the planarity to describe the event shape, then as we see in figure 27 that, no apparent A-dependence of event shape is found in the beam energy and $x_T$ ranges covered by this experiment. In other words, the overall event topology is not affected by the presence of the nucleus.

In figure 28, we re-examine the A-dependence of $\gamma A$ cross sections by comparing the $\alpha$'s between events that are jet-like and events that are non-jet-like. We have plotted $\alpha$ for events with Planarity $< 0.5$ (non-jet-like) and for events with Planarity $> 0.8$ (jet-like). We find that $\alpha$ is smaller for jet-like events than for non-jet-like events. This is qualitatively consistent with the observations in high-$p_T$ $pA$ collisions [22].

D. 1 Comparison with Pion Data

The primary predicted characteristic of the $\gamma p$ collisions is that, at high $p_T$, jets would appear to be cleaner than in $\pi p$ or $pp$ collisions ([30]). In figure 29, we plot the average planarity versus $x_T$ for both $\gamma p$ and $\pi p$ collisions. One concludes that the $\gamma p$ collisions do appear to be more jet-like at high $x_T$ than $\pi p$ collisions.

---

7The pion data was taken with the same hardware trigger as the photon data, except $C1 \oplus B2$ is replaced by $C1 \oplus B2$ for the interaction trigger. During the data analysis, the same software event selection cuts were applied to both the photon data and the pion data (obviously, no RESH requirement is needed for the pion data).
FIG. 27: Mean planarity as a function of $A$ for two-high trigger in several different beam energy ranges and $x_T$ ranges.
FIG. 28: $\alpha$ versus $x_T$ for two-high trigger events with beam energies at $E_\gamma = 200 - 300\text{GeV}$. Open circles: $Planarity < 0.5$, closed circles: $Planarity > 0.8$. 
FIG. 29: Mean planarity as a function of $x_T$ for $\gamma - p$ and $\pi - p$ collisions. Events are selected to have the same beam energy ($E_\gamma = 200 - 300 GeV$) and satisfy the two-high trigger.
FIG. 30: For the pion data, the mean planarity is plotted as a function of $A$ for two-high trigger in two $x_T$ ranges. Beam energy range: $200 \text{GeV} < E, < 300 \text{GeV}$.

No apparent $A$-dependence of event shapes is found in the pion data (figure 30).

E. A-Dependence of Forward Energy Flow

As mentioned in Chapter 3, the beam calorimeter in E683 measures the energies of the particles produced in the very forward direction. Figure 31 shows the energy flow for both $\gamma A$ collisions and $\pi A$ collisions in the forward direction as measured by the beam calorimeter as a function of $A$. In order to avoid the complication of multiple bremsstrahlung in the photon beam, we use the energy deposited in layer 2, 3 and 4 (the so called "hadronic" section) of the beam calorimeter. The forward energy flows for both jet-like events (planarity > 0.8) and non-jet-like events (planarity < 0.5) are shown. We notice: (1) For both $\gamma A$ collisions and $\pi A$ collisions, there is a slight drop in forward energy flow as $A$ is increased (roughly 15% from the lightest to the heaviest target); (2) Forward energy flow is slightly higher for the $\pi A$ collisions than the $\gamma A$ collisions; (3) For $\pi A$ collisions, the amount of forward energy flow for the jet-like events is higher than that for the non-jet-like events by about 15%.
FIG. 31: Average beam calorimeter energy versus A for two-high trigger events at beam energies between 200 GeV and 300-300 GeV. (a) $\gamma A$, (b) $\pi A$. $E_{\text{beam}}$ is the energy deposited in the hadronic section of the beam calorimeter (layer 2, 3, and 4). Open circles: Planarity < 0.5, closed circles: Planarity > 0.8.

F. Discussion

The power-law dependence $\sigma(\gamma A)/\sigma(\gamma p) = A^\alpha$ we have been using throughout this thesis is, of course, just an empirical way of describing the A-dependence of photon-nucleus collision cross sections. Although there are no compelling physics reasons behind this power-law dependence, it nonetheless describes the data surprisingly well in both hadroproduction and photoproduction.

However, we should point out that the power-law dependence does not fit our data perfectly if one examines the plots in figure 20 and figure 21 carefully. One notices that in most of the plots, the data points exhibit a slight systematic downward bending with respect to the straight-line fit in the log-log plot. It is possible that this feature of the data might be the result of the fact that the point-like photon couples differently with the proton and the neutron when they interact through the QCD Compton process. According to the theory of Quantum Chromodynamics, the cross section for the QCD Compton process is
proportional to the square of the quark charge ([30]). If we assume that the photon interacts only with the valence quarks, then

\[ \sigma(\gamma p) \sim 2e_v^2 + e_s^2, \quad \sigma(\gamma n) \sim 2e_v^2 + e_u^2 \]

and furthermore, if we also assume that \( \gamma A \) collisions are dominated entirely by the QCD Compton process and quarks act independently inside the nucleus, then \( \sigma(\gamma A)/\sigma(\gamma p) \) can be calculated in a straightforward way for the targets that were used in this experiment. Figure 32 is a plot of the calculated \( \sigma(\gamma A)/\sigma(\gamma p) \) versus \( A \). One gets \( \alpha = 0.948 \) from the power-law fit, which is less than 1.0 as expected from the above formula. But the points in figure 32 do not exhibit the downward bending seen in the real data.

This feature of the data is not unique for the \( \gamma A \) collisions however. A similar type of downward bending has been observed in 400 GeV \( pA \) collisions ([22], [29], [58]), where the same number of targets were used. Thus it is not likely that this effect is caused by the difference in beam particles.

As we see in figure 22 and figure 23, the \( \alpha \) measured in \( \gamma A \) collisions is found to increase with both \( x_T \) and \( E_T \). It ranges from \( \alpha \approx 0.90 \) near our \( E_T \) trigger threshold to \( \alpha \approx 1.10 \) around \( E_T \approx 12 \text{ GeV} \). This increase of \( \alpha \) with total transverse energy is consistent with what was observed in previous investigations of high-\( p_T \) \( pA \) collisions ([24], [22], [23]). In terms of absolute values of \( \alpha \), our measurements are lower than what was found in \( pA \) collisions. This could simply be due to the fact that the \( E_T \) range covered by our experiment is lower (figure 23(b)).

Since we were using a bremsstrahlung beam, we were able to measure the energy dependence of \( \alpha \) over the beam energy range \( E_\gamma = 50 - 400 \text{ GeV} \) in this experiment. As we see in figure 24, \( \alpha \) was found to increase with \( E_\gamma \) at fixed \( x_T \), but appears to be
FIG. 32: Ratio $\sigma(\gamma A)/\sigma(\gamma p)$ versus $A$, assuming the photon interacts in a point-like manner only with the valence quarks inside the nucleons. The solid lines are fits to the data with the parameterization $\sigma(\gamma A) = \sigma(\gamma p) A^\alpha$. 

$\alpha = 0.947$
insensitive to $E_\gamma$ at fixed $E_T$. Comparison to $pA$ data is difficult in this case because previous $pA$ experiments were performed with fixed energy beams. Collecting $\alpha$'s measured by separate $pA$ experiments with different beam energies will not provide us with a meaningful comparison because experiments usually use different triggers and different sets of targets.

As we mentioned in the introductory part of this thesis, many theoretical models have been proposed trying to explain the "anomalous nuclear enhancement" observed in hadron-nucleus collisions. The majority of these models are centered around the concept of multiple scattering by either the initial or final state partons inside the target nucleus. Multiple scattering can easily explain the fact that there is an "enhancement" of cross section in the presence of nuclei. This is because cross sections are steeply falling functions of either $E_T$ or single particle $p_T$, and any small amount of multiple scattering would enhance the cross section at any given $E_T$ or $p_T$. But it is difficult to come up with quantitative $\alpha$ values to compare with experimental measurements. Different versions of the multiple scattering model take into account effects like: (1) Fermi motion of the partons inside the nucleus ([11]); (2) simultaneous scattering involving multiple partons in the beam particle ([19], [32], [33]); or (3) structure function of the nucleus as measured by various deep-inelastic scattering experiments or proposed by the authors themselves ([17], [18]). Most of these models were able to explain qualitatively some general features of the experimental results (like the increase of $\alpha$ with $E_T$ or single particle $p_T$), but failed at making detailed comparisons. Most importantly, none of the hadron-nucleus experiments performed so far have been able to favor any specific model over the others.

Specific theoretical models aimed at calculating $\alpha$'s for high-$p_T$ photon-nucleus collisions are rare. This is not because the calculations are more complicated, but rather because of
the lack of experimental data. However, one recent theoretical paper ([63]) has attempted to calculate α's for photon-nucleus collisions without introducing any type of multiple scattering. The authors of the paper have calculated α's as functions of single particle or jet \( p_T, x_T, x_F \) and \( E_\gamma \). They have shown that the nuclear enhancement is present in photon-nucleus collisions, and it can be described naturally in perturbative QCD, in terms of a non-leading power, or "higher twist" formalism ([64], [65]). However, it is difficult to make detailed comparisons between the results of this model and our data, since the α values presented in this thesis are functions of global \( x_T \), \( E_T \) and \( E_\gamma \). Still, the fact that nuclear enhancement in photoproduction can be derived in the framework of perturbative QCD in an almost model-independent manner is quite promising. We hope our \( \gamma A \) data will present a new challenge for future efforts along this direction.

In this thesis, we have studied the event structure in high \( p_T \) photoproduction in terms of the event shape variable planarity. It is well known by now that hard scattering processes dominate the event structure in hadron-hadron collisions at high center-of-mass energies \( \sqrt{s} \) when sufficiently large transverse energy \( E_T \) is required ([59], [60], [61]). What we have shown in E683, as seen in figure 26 and figure 29, is that at sufficiently high \( x_T \) the event structure in photoproduction is also dominated by hard scattering in the relatively low \( \sqrt{s} \) range that we study (from 9.7 \( GeV \) to 27.4 \( GeV \)). When compared with \( \pi p \) collisions at the same \( \sqrt{s} \), we have shown that \( \gamma p \) collisions appear to be more jet-like at high \( x_T \) than \( \pi p \) collisions (figure 29). This agrees with the theoretical expectation ([30]) that photon would interact primarily as a point-like particle at high \( p_T \), which would result in cleaner jet structure. For \( \gamma p \) collisions, we have found that the "hardness" of the collision scales approximately as \( x_T \) when the beam energy is varied.
In terms of average planarity, we have not found any systematic variations among the events originating from the various nuclear targets. But when very high planarity events \((P > 0.8)\) are selected, one generally gets lower values of \(\alpha\) than that for the lower planarity \((P < 0.5)\) events (figure 28). The \(\alpha\) values for these high planarity events seem to be independent of \(x_T\), at around \(\alpha \approx 0.96\). Similar behavior has also been found in \(pA\) collisions ([22], [23]). In [23] \((800\ GeV\ pA\ collisions)\), \(\alpha\) was found to be around 1.1 or less for highly planar events as compared to \(\alpha\) around 1.6 for non-planar events. Values of \(\alpha\) approaching 1.0 were also found by the same experiment when events with high-\(p_T\) jets are selected ([28]). It was then concluded that for hard collisions, there was little or no nuclear enhancement. But in a study of jets from 400 \(GeV\ pA\ collisions\) ([62]), it was argued that events which are very planar have not undergone significant multiple scattering in the nucleus, and by selecting only high planarity events, one concentrates only on a subgroup of the hard scattering events. Therefore, without a detailed study of jets from the \(\gamma A\) collisions in this experiment, it would be premature to draw any definite conclusions from the results shown in figure 28.

The study of energy flow in the forward direction (figure 31) shows that, for events with \(x_T > 0.28\), the amount of forward energy flow is slightly higher for \(\pi A\) collisions than for \(\gamma A\) collisions. The difference becomes larger when jet-like events are selected, indicating the presence of an energetic beam jet in jet-like events of \(\pi A\) collisions. A slight drop in forward energy flow with atomic number \(A\) (\(\sim 15\%\) overall) is observed in both \(\gamma A\) and \(\pi A\) events. This indicates that particles going in the forward direction suffer a slight amount of attenuation due to the presence of the nuclei. Similar behavior has also been found in \(pA\) collisions ([22], [28]), but the drop is more significant (\(\sim 40\%\) overall). Similar to what
we have shown in figure 31(b) for πA collisions, a difference in forward energy flow between jet-like and non-jet-like events was also observed in pA collisions ([22], [28]).

Finally, we offer a few remarks on future studies that can be performed on the γA data. In this thesis, no attempt has been made to extract the point-like photon interactions from the γA collisions. It is reasonable to assume that the majority of our events come from photons interacting as vector mesons (the Vector Meson Dominance [34]). The α measurements presented in this thesis are not inconsistent with results from pA collisions (figure 23). If events originating from the point-like photon interactions can be isolated, it will be interesting to see how the α values compare to the measurements presented in this thesis. Furthermore, if the different QCD processes that contribute to the point-like photon interactions, like the photon-gluon fusion, the QCD Compton ([30]) or the higher-twist effect ([66]) can also be isolated, then it may be possible that predictions for the A-dependence from the different theoretical models can be more thoroughly compared.
V. Appendices

A. An Example of Cross Section Calculations

We present here an example of how $\sigma(\gamma A)/\sigma(\gamma p)$ are calculated from the event rates.

We first list the number of two-high trigger events from each target that satisfy the following kinematic cuts:

1. $150 \text{ GeV} < E_\gamma < 200 \text{ GeV}$
2. $0.38 < x_t < 0.42$

The event rates after our standard event selection cuts (as discussed at the beginning of chapter 4) are listed in Table 0.6. EMP(I) and EMP(II) are the target empty rates from the empty liquid hydrogen target vessel and the empty slot on the solid target wheel. Pb(I) and Pb(II) are two lead targets with different thicknesses (see table 3.4 in chapter 3). They are used in this experiment to see if target thickness will affect our cross section measurements for heavy targets. Also listed are two different flux measurements. They will be used as normalizations when we calculate the cross sections.

As we mentioned in chapter 4, the cross section ratios are calculated with the following formula:

$$\frac{\sigma_1}{\sigma_2} = \frac{R_1}{R_2} \cdot \frac{A_1}{A_2} \cdot \frac{d_2}{d_1} \cdot \frac{\rho_2}{\rho_1}$$

where $R$ is the normalized event rate after subtraction of the empty target rate, $A$ is the atomic number, $d$ is target thickness and $\rho$ is the target density. The target empty rates come mostly from beam interacting with the beam scintillation counters and the target tent. For different targets, the target empty rates should be slightly different than EMP(I)
<table>
<thead>
<tr>
<th>Target</th>
<th>Event Rates</th>
<th>Elec. Flux ($\times 10^{10}$)</th>
<th>Bcal Flux ($\times 10^9$)</th>
</tr>
</thead>
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<tr>
<td>H</td>
<td>2857</td>
<td>46.1665</td>
<td>13.0087</td>
</tr>
<tr>
<td>D</td>
<td>865</td>
<td>7.4320</td>
<td>2.3101</td>
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<td>13.5648</td>
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<td>1.6123</td>
</tr>
<tr>
<td>C</td>
<td>427</td>
<td>5.8695</td>
<td>1.6243</td>
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<td>1.6886</td>
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<td>1.6405</td>
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</tr>
<tr>
<td>EMP(II)</td>
<td>49</td>
<td>7.0364</td>
<td>1.9681</td>
</tr>
</tbody>
</table>

**TABLE 0.6:** List of events rates, gated electron flux and bcal flux (corrected for dead time) for two-high trigger events satisfying: (1) $E_\gamma = 150 - 200 GeV$ and (2) $x_t = 0.38 - 0.42.$
or EMP(II). This is because EMP(I) or EMP(II) are measured with the target out of
the beam; when target is in, flux attenuation inside the target should modify EMP(I) or
EMP(II) approximately by the following factor:

\[ \lambda = 0.5 + 0.5 \cdot e^{-d/X_0} \]

where we have assumed that 50% \(^8\) of the target empty rate comes from the materials
upstream of the target.

Flux attenuation inside the target should also modify our normalization as is men-
tioned in chapter 4. Unlike the similar corrections mentioned above for the target empty
subtractions, this correction is fairly significant for the heavy targets, and it directly affects
the value of the cross section. As shown in Chapter 4, the “effective” flux over the total
flux is given by

\[ \frac{L'_0}{L_0} = \frac{X_0}{d} \cdot (1 - e^{-d/X_0}) \]

Table 0.7 lists the cross section ratios \(\sigma(\gamma A)/\sigma(\gamma p)\) as calculated with the above mentioned
formulas.

Finally, we have a few comments about the flux measurements listed in table 0.6: (1)
the electron flux is measured by an ionization chamber called PB6IC. There is typically a
\(~5\%) pedestal associated with its reading, the flux we used for the normalization as listed
in table 0.6 did not have the pedestals subtracted. Dead or very weak spills are not include
in the flux. (2) the bcal flux as listed in table 0.6 is measured by the bcal scaler called
BCAL\(_{\text{max}}/2\), which basically counts the number of photons which give pulse heights in the
bcal that are above some fixed threshold. Since we only deal with relative cross sections in

\(^8\)It is not critical to know exactly what this number should be, since the target empty rates are typically
only 15% of the target-in rates. Our final systematic error estimate shall include uncertainties like this in
the target empty subtraction.
this thesis, we did attempt to correct this measurement for the bcal signal loss (as discussed in Chapter 3). (3) Systematic uncertainties of the relative cross sections arising from the uncertainties of these flux measurements are estimated to be $\sim 10\%$. As one can see from table 0.7, the relative cross sections are not sensitive to the choice of normalizations. Possible long term systematic drifts were checked by comparing measurements done at different times (typically one month apart), results were found to be very stable.

\footnote{For a smaller data sample, we have compared the cross section ratios by using several other flux measurements. Results are found to be consistent with each other.}
<table>
<thead>
<tr>
<th>Target</th>
<th>$L'_0/L_0$</th>
<th>$A/\rho d$</th>
<th>$e^{-d/X_0}$</th>
<th>$\sigma_A/\sigma_p$ (ele. flux)</th>
<th>$\sigma_A/\sigma_p$ (bcal flux)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>0.9775</td>
<td>0.2786</td>
<td>0.9554</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>D</td>
<td>0.9744</td>
<td>0.2434</td>
<td>0.9492</td>
<td>1.90 ± 0.10</td>
<td>1.73 ± 0.09</td>
</tr>
<tr>
<td>Be</td>
<td>0.9725</td>
<td>1.920</td>
<td>0.9456</td>
<td>9.16 ± 0.60</td>
<td>9.59 ± 0.63</td>
</tr>
<tr>
<td>C</td>
<td>0.9616</td>
<td>2.775</td>
<td>0.9242</td>
<td>14.07 ± 0.90</td>
<td>14.43 ± 0.93</td>
</tr>
<tr>
<td>Al</td>
<td>0.9172</td>
<td>4.98</td>
<td>0.8392</td>
<td>30.46 ± 1.85</td>
<td>31.52 ± 1.92</td>
</tr>
<tr>
<td>Cu</td>
<td>0.8506</td>
<td>11.59</td>
<td>0.7168</td>
<td>59.32 ± 3.98</td>
<td>61.56 ± 4.13</td>
</tr>
<tr>
<td>Sn</td>
<td>0.8542</td>
<td>32.20</td>
<td>0.7232</td>
<td>94.77 ± 8.10</td>
<td>98.05 ± 8.37</td>
</tr>
<tr>
<td>Pb(I)</td>
<td>0.7828</td>
<td>49.56</td>
<td>0.5996</td>
<td>171.43 ± 14.01</td>
<td>181.26 ± 14.75</td>
</tr>
<tr>
<td>Pb(II)</td>
<td>0.9168</td>
<td>143.74</td>
<td>0.8382</td>
<td>173.48 ± 23.98</td>
<td>176.90 ± 24.42</td>
</tr>
<tr>
<td>$\alpha$</td>
<td></td>
<td></td>
<td></td>
<td>0.984 ± 0.007</td>
<td>0.992 ± 0.008</td>
</tr>
</tbody>
</table>

**TABLE 0.7**: List of cross section ratios $\sigma(\gamma A)/\sigma(\gamma p)$ (errors are statistical). For comparison, two different normalizations are used. $\alpha$ is the result of a fit to the parameterization $\sigma(\gamma A) = \sigma(\gamma p) A^\alpha$. 
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