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Study of Charm Production Mechanisms at the Fermilab Tagged Photon Spectrometer: $\gamma Be \rightarrow D\bar{D}\ x$ and $\gamma A \rightarrow \psi x$*

T. Nash
Fermi National Accelerator Laboratory,
Batavia, Illinois 60510

Based on work by the Tagged Photon Spectrometer Collaboration

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University of California, Santa Barbara
Carleton University, Ottawa
Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro
University of Colorado, Boulder
Fermi National Accelerator Laboratory
National Research Council, Ottawa
Universidad de São Paulo
University of Toronto

This paper describes recent work on charm photoproduction mechanisms based on data from Experiment 691 at the Fermilab Tagged Photon Spectrometer. Preliminary results on open charm production in the energy range 80-190 GeV are reported based on a preliminary analysis of 3000 charm events, comprising 30% of the data sample. These results include fits to $P_{\perp}$ and X_F distributions, a measurement of the total charm production cross section on Be and its increase with energy from 100 to 200 GeV, as well as a measurement of the relative fraction of $\bar{D}$, D, and D^* production. Also reported is data based on a special closed geometry run to study the A dependence of ψ photoproduction. For the first time in a single experiment, relative cross sections on H, Be, Fe and Pb for both the coherent and incoherent components of the signal have been measured with reduced systematic errors and these results are reported here.

1. Introduction

The data from the Tagged Photon Spectrometer experiment (E691), which has produced important results on charm decay (see M.Witherell's talk, this volume), also contains much valuable information about production mechanisms. I report here on work carried out by M.Purohit and M.Sokoloff on D and Ψ production, respectively. Since the Ψ results have been published recently[1], I will mention them only briefly concentrating on the work in progress on D production.

In the spirit of Moriond a brief philosophical introduction to this subject will, hopefully, be tolerated. Like the two ends of an elephant seen by blind men, the appearance of charm photoproduction depends on whether one is studying hidden or bare charm. These processes are traditionally described by two very different mechanisms, vector meson dominance (VMD) and photon gluon fusion (γGF). Like the blind men, perhaps we are missing something larger when we probe only one end of the elephant. As important as is understanding the phenomenology at the two ends of charm production, we need to remember that the body of the matter is QCD which is what we really care about. This motivates efforts (in which some of us are involved) to try to find new algorithm/computer hardware combinations that may allow better lattice gauge understandings of QCD. Related is the question of whether perturbative QCD can properly address the "low mass" charm phenomena represented, finally, in this experiment by a large amount of good data. Must we really wait (how long?) for similar samples of B data before adequately testing [perturbative] QCD?

Perhaps less controversial is to say that the production (and decay) of heavy quarks represents an excellent (if not the best) opportunity to study non-perturbative, phenomenological, QCD. Photoproduction is arguably the best channel to study gluon fusion phenomena. The leading order diagrams for charm hadroproduction and photoproduction (Fig.1) require a fudge factor (more professionally referred to as a K factor) to bring leading order calculations into agreement with experiment. The K factor for hadrons is typically at least 3 and only 1-1.5 for photons. Perhaps this can be understood qualitatively by noting that for hadroproduction there are two, rather than one, primary gluon vertices with large coupling constants, and color factors, that are involved in higher order diagrams and corrections. Quantitative understanding of K factors will have to wait for careful theoretical calculation.

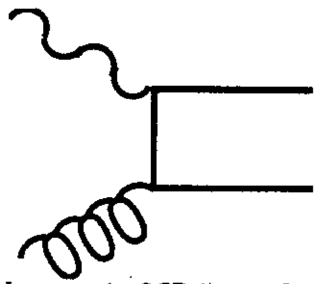
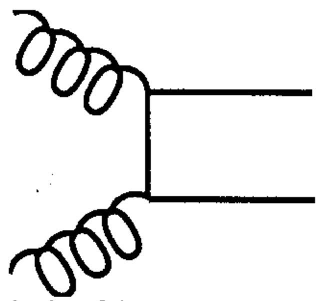


Figure 1a. Lowest order QCD diagram for photoproduction of charm



b) hadroproduction of charm.

This experiment represents the second in a series of long planned experiments in the Tagged Photon Spectrometer. The first (E516) was (perhaps mis-) directed at diffractive production of charm. This one focuses on photoproduction with an unbiased trigger based essentially on the mass of the forward going system. Preparing to run during the summer of 1987 is E769 which will study hadroproduction with a similar forward system trigger. Taken together, the experiments represent a reasonably complete study of charm quark production (and decay) phenomenology. Perhaps, someday, similarly clean data will become available for b quarks where the theory may be easier[2], but until then this will have to do.

2. Open Charm Photoproduction

The Tagged Photon Spectrometer is a two magnet spectrometer of large acceptance, with drift chambers, Cerenkov counters, and electromagnetic and hadronic calorimetry. It was augmented for this experiment with nine silicon microstrip detectors (SMDs) which were installed downstream of a 5 cm beryllium target. These detectors, with 50 μm strip spacing, provided measurement of charged tracks with enough precision to resolve the charm vertex for approximately half of the decays. The trigger required a total transverse energy (E_T) in the calorimeters of at least 2.2 GeV. This is an unbiased charm trigger which effectively is a cut on the mass of the forward going system of particles being at least 2.5 GeV. It is about 80% efficient for charm while suppressing the total hadronic rate by about 3.3. About 90 million events were taken under this trigger and another 10 million with an open hadronic event trigger. Since each event requires about 5 VAX seconds of time to reconstruct, this large sample of data represents a huge amount of computing. The reconstruction has been all but completed at this writing using the ~100 VAX equivalent ACP Multiprocessor System at Fermilab. The results reported here are based on an analysis of 30% of the data and should be considered preliminary.

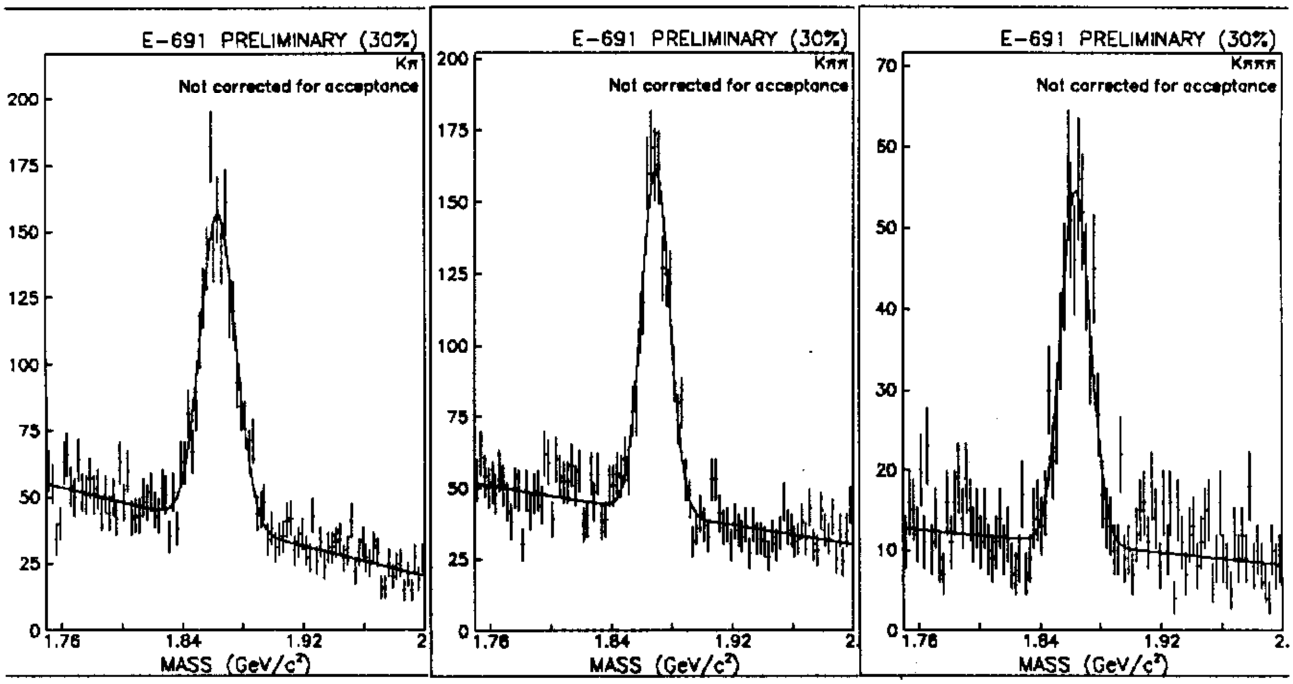


Figure 2 a) $D^0 \rightarrow K^- \pi^+$ b) $D^+ \rightarrow K^- \pi^+\pi^+$ c) $D^0 \rightarrow K^- \pi^+\pi^+\pi^-$

The two keys to the success of this experiment are clearly the SMD system and the ACP Multiprocessor. The former makes possible the enormous suppression of the combinatorial background that has plagued all previous charm experiments. The resulting charm peaks (Fig. 2) are spectacular, especially to those of us who have struggled in this business for so long. The second major innovation is the use of the highly powerful ACP computer. It allowed us to contemplate taking 100 million events in an unbiased way which would otherwise have required more than three years to process.

The 3000 charm events in this 30% sample come from photon interactions with 80 GeV $< E_\gamma <$ 220 GeV, with $< E_\gamma >$ ~ 125 GeV. This analysis of production mechanisms concentrates on the three decay channels shown in Fig. 2,

$D^0 \rightarrow K^- \pi^+$, $D^+ \rightarrow K^- \pi^+\pi^+$, and $D^0 \rightarrow K^- \pi^+\pi^+\pi^-$, for which the detector acceptance including wire chamber efficiencies is > 40%. (Charge conjugate reactions are implied throughout this paper.) The event selection was simple, based on Cerenkov counter particle identification and SMD vertexing. The joint probability for particle identification being correct for a given channel was required to be > 0.2 . In addition the identification probability for the slow pion in the $K3\pi$ channel was required to be > 0.5 . Tracks at the primary and secondary vertices were required to have $\chi^2/DF <$ 6 and 3.5, respectively. The separation of the two vertices was cut at $\Delta Z/\sigma_Z > 8$, 10, and 5 for the three channels. Typically, $\sigma_Z \sim 450$ μM, about 10% of the average charm track length. Adjusting the vertex separation cut allows control of the cleanliness of the signal versus the size of the signal. The cuts used here are relatively clean with signal to noise of about 2:1. About 25% of events survive both Cerenkov and SMD cuts. Including geometry and detector and trigger efficiencies the overall acceptance is 8%, very high and unbiased for experiments of this type.

Results that can be reported from this analysis now include inclusive D production distributions in $P_\perp$ and X_F, energy dependence and absolute value of the total charm photoproduction cross section, and the ratio of $\bar{D}$ to D and D^* to D. In the future, we expect the production ratios to include $D^* : D^0 : D^+ : F : \Lambda_C$, and when the full data sample is available there will be 400-1000 events with both c and $\bar{c}$ reconstructed allowing a good measurement of the gluon structure function G(x) and the assumptions that go into lowest order diagram predictions.

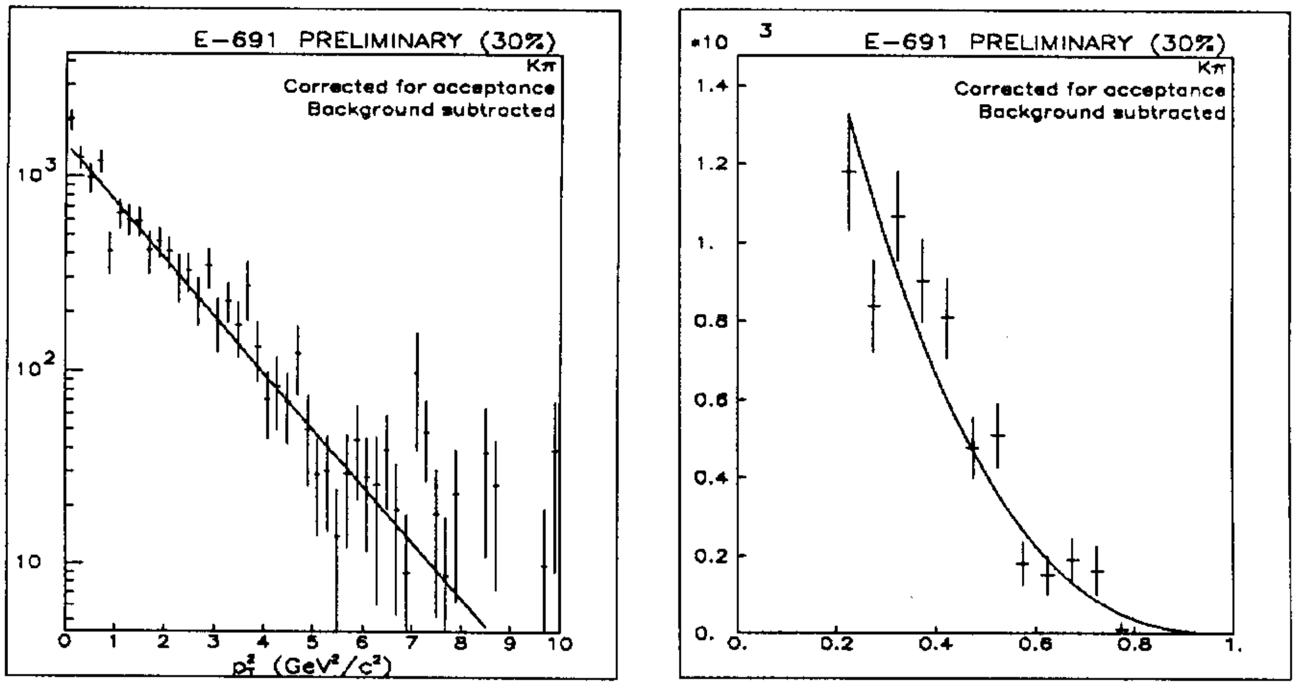


Figure 3. a) $P_\perp^2$ distribution for $D^0 \rightarrow K^-\pi^+$. b) X_F distribution for $D^0 \rightarrow K^-\pi^+$.

Examples of distributions in $P_\perp^2$ and X_F (for the $D^0 \rightarrow K^-\pi^+$ channel) are in Figure 3. These data samples were fit to an exponential in $P_\perp^2$ and the form $(1 - X_F)^n$ in X_F for $X_F > 0.2$. The fits are shown as solid lines in the plots. The $P_\perp^2$ fits are very similar to typical hadroproduction of charm values of $<P_\perp^2> \sim 1$ GeV^2. It is difficult to compare the X_F distributions with hadroproduction where results range over $1 < n < 7$ because of leading particle effects and X_F acceptance. The results are given in the following table:

Mode	$< P_\perp^2 >$	n	$\bar{D}/D$
$D^0 \rightarrow K^- \pi^+$	1.37 ± .06 ± .08	2.7 ± .2 ± .4	0.99 ± .07
$D^+ \rightarrow K^- \pi^+\pi^+$	1.29 ± .09 ± 08	2.6 ± .2 ± .4	1.03 ± .07
$D^0 \rightarrow K^- \pi^+\pi^+\pi^-$	1.34 ± .13 ± .08	2.8 ± .3 ± .6	1.07 ± .12
Combined	1.34 ± .05 ± .08	2.7 ± .1± .6	1.02 ± .05
Monte Carlo	1.35	2.5	

A full experiment Monte Carlo simulation was developed for acceptance correction and phenomenological model analysis of the results. The event generator was based on the YGF model with Λ = 200 MeV and m_c = 1.6 GeV and the Lund Monte Carlo with "off the shelf" parameters for hadronization. The results fit the data very well in terms of multiplicities, chamber distributions, etc. In addition, as can be seen from the table this experiment's combined results from the three decay channels provide no surprises from the "conventional wisdom" as expressed in the Monte Carlo.

The production ratio $\bar{D}/D$ speaks to a long standing question: to what extent does photoproduction of charm involve the associated production channel $\Lambda_C \bar{D}$ along with $\bar{D} D$? The combined result for this ratio given in the table above indicates a limit of about 12% of all charm for associated production at the mean energy of this experiment of about 125 GeV. Comparing with previous experimental measurements[3] of this ratio shows a clear energy dependance:

Experiment	$< E\gamma >$	Fraction Associated Production
E691	125 GeV	< 12% [preliminary]
E516	95 GeV	< 14% [with $\sigma_{c\bar{c}}$ =.42 μb]
WA58	40 GeV	28 ± 13 %
SLAC Hybrid	20 GeV	71 ± 11 ± 6%

This can be interpreted as a clue to the hadronizing mechanism (Figure 4). The charm quark needs to combine with a target diquark of the corresponding anti color to produce a Λ_C. This can happen much more easily at low energies when the rapidity gap between the forward going c quark and the target diquark is smaller. The relative production of D^* : D was also determined. The fraction of D^0 from D^* decays in the channel $D^0 \rightarrow K^- \pi^+$ was measured as 31.3 ± 2.4%. Assuming the Particle Data Group's 1986 branching ratio, this implies σ_{D^*}/σ_D = 3.4 ± .3 .

The total charm photoproduction cross section has been measured from these samples of D decay data, using PDG branching ratios, and correcting for missing acceptance (primarily below x_F = 0) and for F and Λ_C production using the Monte Carlo described earlier. The preliminary result is $\sigma_{c\bar{c}}$ = 3.17 ± .22 ± .8 μb, *per Be nucleus*. The A^α dependence could conceivably range from α = .7 to 1. Over this range the *per Be* cross section extrapolated to *per nucleon* would vary by a factor of two.

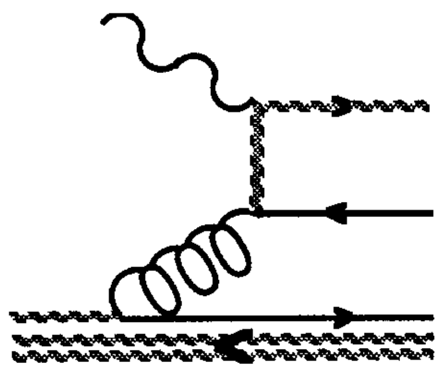


Figure 4. Diquark- c quark color matching.

However, we need not be very bold to expect the A dependence to fall between that measured for the total photoproduction cross section[4], $\alpha = .92$ and that measured for incoherent Ψ production (described later in this paper[1]), $\alpha = .94$. This would would imply that $\sigma_{c\bar{c}} = .40 \pm .03 \pm .1\ \mu b$, *per nucleon.*

The rate of rise of the cross section with energy is, given the γ GF model, a sensitive measure of the power n of $(1-x)^n$ in the gluon structure function. We find $\sigma(E_\gamma = 200\ GeV) / \sigma(E_\gamma = 100\ GeV) = 1.83 \pm .29 \pm .37$. This agrees, within the present statistics, with previous results from EMC[5] ($1.53 \pm .2$), BFP[6] ($1.44 \pm .2$), and E401[7] ($1.56 \pm .2$) . The gluon structure function exponent n = 5 if this energy dependence ratio is 1.6 and n = 9 if the ratio is 2, given standard assumptions about model parameters ($\Lambda = 200$ MeV and $m_c = 1.6$ GeV).

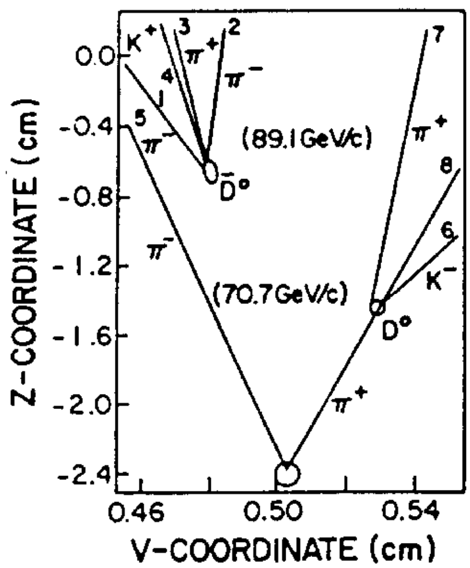


Figure 5. An event with two charm decays.

As we have noted, what has been reported here is based on 30% of the data. To see what may be available with the full sample, we have made a quick search for events in which both charm events are fully reconstructed and with little effort have found 125 events like the one in Fig. 5. So with all the data analyzed we should find between 400 and 1000 events with both charm. This will be an exciting opportunity to measure the gluon structure function, G(x), and, most likely, other parameters in the gluon fusion process such as m_c. When it is not necessary to integrate over an unseen charm particle, it becomes possible to look more carefully at how well the lowest order QCD prediction in fact fits the data.

3. A Dependence of Ψ Photoproduction

Discrepancies between earlier measurements of incoherent Ψ photoproduction carried out with real and virtual photons were at one time attributed by some to the possibility that the per nucleon cross section on Fe was higher than on lighter nuclei.[4] A subsequent analysis of hydrogen data to compare with previously reported Fe data was reported recently by the European Muon Collaboration (EMC). For energies of 250/280 GeV they found[8] $[\sigma(Fe) / \sigma(H,D)]_\Psi = 1.45 \pm 0.12 \pm 0.22$. An early SLAC experiment[9] had measured $[\sigma(Ta)/\sigma(Be)]_\Psi = 0.83 \pm .06$. Expressed in terms of a power law variation, A^α, these measurements correspond to $\alpha_{EMC} = 1.10 \pm .03 \pm .04$ and $\alpha_{SLAC} = 0.94 \pm .03$.

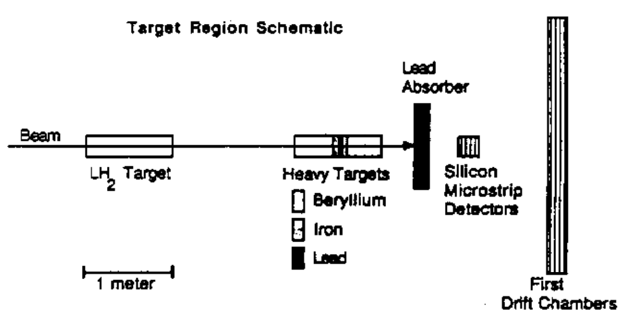
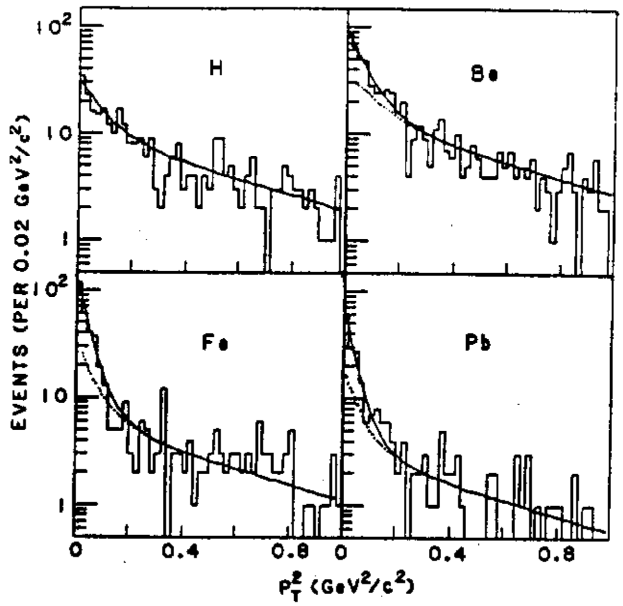


Figure 6. Target region for E691 Ψ run.

This somewhat confused situation motivated a special 2½ week run at the end of E691 in which the target region was modified as shown in Fig. 6. A thick (.53 X_0) radiator generated bremsstrahlung photons from a 210 GeV electron beam. Photons in the range $80 < E_\gamma < 190$ GeV were used for the analysis. A 1 m liquid hydrogen (LH_2) target was followed by one of three ~ 2.7 X_0 heavy targets, Be, Fe, and Pb, which were alternated regularly. A 30 X_0 lead wall shielded the detector from the electromagnetic showers initiated in the targets. Dimuons from leptonic Ψ decays were detected in the same Tagged Photon Spectrometer used for the D experiment described earlier.

Figure 7. $P_\perp^2$ distributions for dimuons in mass range 2.9-3.3 GeV. Solid curves are projections of maximum likelihood fit. Dotted curves are sum of background and incoherent signals. Difference is coherent signal.



The resolution in $P_\perp^2$ was good, allowing a uniquely clean separation of coherent and incoherent signals. As a result we have been able to extract the A dependence of both incoherent and, for the first time, coherent production of Ψ. A complete maximum likelihood fit agreed with the simple technique of selecting the incoherent signal with a cut at $P_\perp^2 = 0.15$ GeV^2. After corrections for t_{min} and Pauli exclusion effects the results are as shown in the table below with all cross sections normalized to that of incoherent production on Be:

Target	σ_{incoh}/A	σ_{coh}/A
H	1.02 ± .05	----
Be	1.00 ± .05	0.32 ± .04
Fe	0.76 ± .05	0.73 ± .07
Pb	0.76 ± .08	1.11 ± .12

The A^α dependence of the coherent signal is $\alpha_{coh} = 1.40 \pm .06 \pm .04$. This agrees with the simple understanding of the process as a diffractive one for which $A^{\sim 4/3}$ is expected. The incoherent data yields $\alpha_{incoh} = 0.94 \pm .02 \pm .03$. This agrees with the SLAC measurement which was made at such low energies (15 GeV) that t_{min} effects precluded any significant coherent cross section. If the $P_\perp^2$ dependence of the incoherent process, which is now available (e.g. Fig. 7), is used in analysis of the EMC data it is likely that experiment and this one would have results in agreement. Using traditional vector dominance model assumptions, the A dependence we have measured for the incoherent cross section is consistent with shadowing and absorption in the target nucleus with $\sigma_{tot}(\Psi N) = 1.2 \pm .7$ mb.

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