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Backward Pi-minus Charge Exchange at Intermediate Momentum*

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We report on an experiment of unusually good momentum transfer resolution carried out at the Brookhaven A.G.S. to measure the differential cross section for pi-minus, proton charge exchange scattering in the backward hemisphere at fourteen values of the incident pion momentum from 2 to 8 GeV/c. This paper presents partial results obtained at 3.5, 4.3, and 6.0 GeV/c.

The data was taken photographically using an array of scintillation counters and steel-plate spark chambers which covered the entire 4π solid angle surrounding the target. The liquid hydrogen target of mean length 13.8 cm. was surrounded by a set of counters to veto charged products. Outside, to the rear and sides of the target were five nested spark chambers with approximately 8 radiation lengths of steel in 2 mm. (0.1 rad. length) plates. The forward hole in the side spark chamber array was filled with a veto shower counter consisting of a seven-radiation-length, lead-scintillator sandwich array to prevent triggering on events with forward going gammas. A neutron detector consisting of alternated steel spark chamber modules and scintillators was located downstream from the shower counter. The spark chambers were fired when a pion disappeared in the target with no charged products, no forward gammas, and with a signal in at least two adjacent neutron counters. Some of the data taken during the run was triggered without the neutron signal requirement, but recorded on the film in order to provide a check on the neutron detection efficiency.

The photographs were scanned for good triggers with one or more gamma showers in the spark chambers. The results presented here are based on the analysis of approximately 16K good triggers at 3.5 GeV/c, 10K at 4.3, and 20K at 6.0. Using measured positions and directions of the gammas, a chi-squared fit was performed for the interaction point along the measured beam line with results which showed an r.m.s. uncertainty in the gamma directions in the lab of approximately 3 degrees giving a mean uncertainty in the interaction location of about 2.5 cm.

The analysis leading to the present results has been carried out using only the events in which a neutron has been detected. Our selection of charge exchange events is somewhat novel in that it encompasses both the two-gamma events and those with only one gamma detected. In addition, the events of higher multiplicity have been used to correct for background. The analysis of the two-gamma events is based on the characteristic peaked distribution of opening angles between the gamma pairs, and on the correlation between the neutron and pi-zero directions in the production center-of-mass system (CMS). The opening angle distribution exhibits a minimum angle which is a function of the velocity of the decaying particle. Figure 1 shows the distribution of opening angles obtained for all two-gamma events with neutron at 6.0 GeV/c. The location of the minimum angle is indicated for the pi-zero and also for the two gamma decay of the eta. It is a useful aspect of this method that other two-gamma parent events do not produce opening angles in the charge exchange region. Unfortunately this is not true of events of higher parent multiplicity for which only two gammas may be detected. Spark chambers of this amount and granulation of material have an efficiency for detecting gammas which rises gradually from zero to one hundred percent as a function of gamma energy from approximately 20 to 80 MeV. The exact efficiency depends sensitively on the chamber and run characteristics and is very difficult to determine. This low energy loss and geometric inefficiencies cause some events of each parent multiplicity to be detected in a lower one. In particular, the opening angle distribution for the two-gamma events is expected to show a significant contamination due to background events from three and four gamma parents. This distribution alone can provide a useful, but not very clean, separation of charge exchange events from the background. We have been able to obtain the CMS opening angle because we may apply the Lorentz transformation to the directions without knowing the energies of the gammas. If, in addition, we assume for a sample within a reasonable opening angle cut that the reaction is charge exchange, there are two possible solutions for the pi-zero direction. These solutions lie symmetrically on either side of the bisector with an angle ϕ between the solution and the bisector given by

$$\cos \phi = \cos (\theta/2)/\cos (\theta_{min}/2)$$

where θ is the opening angle. We then calculate the relative angle between each of the pi-zero solutions and the reflection of the CMS neutron direction obtained by performing a Lorentz transformation in which we assume charge exchange. We choose as the Relative Angle Solution for the event that one associated with the smaller of these two angles. Monte Carlo simulation of this data has shown that the relative angle distribution for charge exchange is sharply peaked and falls to nearly zero beyond approximately 6 degrees. There is a wide, but almost negligible tail to the distribution due to diffractive scattering of neutrons on the hydrogen in the shower counter scintillator. The advantages of using the relative angle distribution to isolate the charge exchange events are seen in two different aspects of the analysis. First, in regard to background events in the two-gamma sample from three and four-gamma parents, the relative angle provides a much cleaner separation than can be obtained with the opening angle cut alone. The opening angle distribution obtained from pairing the two most energetic showers in the three gamma events exhibits a sharp peak displaced only a few degrees from the minimum opening angle for charge exchange. Without a reliable way of measuring the exact falldown rate between multiplicities we cannot discount a rather large subtraction in the region of the trailing edge of the charge exchange opening angle distribution; however, with cuts applied to the relative angle of the event it is possible to apply only a moderately tight opening angle cut. Figure 2 shows a typical relative angle distribution for two-gamma events at 6.0 GeV/c, and of those with an opening angle between 7 and 21 degrees. The second advantage of an analysis using the relative angle is that it can be applied with similar success to the one-gamma events which are expected to include approximately 25 to 30 percent of the charge exchange sample in the data. The distribution of relative angle between the reflected neutron direction and the single gamma exhibits almost as narrow a peak as for the two-gamma pi-zero solution, falling to zero by approximately 8 degrees. This is true because the lost gamma is almost always the gamma with the lower of the two CMS energies and is therefore at a large angle with respect to the pi-zero direction. The remaining gamma has a high probability of being well correlated with the neutron direction.

The value of the momentum transfer u used to obtain the angular distribution for the two-gamma events is obtained by taking a weighted average of the u(neutron) and u(pi-zero solution). The wieghting function which was estimated from the Monte Carlo simulation of the data turns out to be very close to a universal function of the CMS cosine in this momentum range. The relative weight for the pi-zero solution with respect to the neutron varies from approximately a factor of three very near u_{max} to one-half in the wide angle region. In all of these results the resolution of the u measurements has an rms value smaller than the bin widths imposed by statistical limitations.

Background subtractions have been made to the relative angle distributions of the data using shapes obtained from the higher multiplicity events by discarding small showers. We have been able to detect no appreciable u-dependence of the background shape in relative angle. The subtractions are normalized to the tail region of the relative angle distribution and have been calculated with limited statistical significance as a function of u in large bins. The subtractions are found to have a u-dependence similar to the raw data distribution, and for the two-gamma events varies from 6 to 15 percent. The subtraction in the one-gamma events varies from 7 to 25 percent with somewhat larger uncertainties. By utilizing both the one and two-gamma events we believe we avoid a potentially troublesome aspect of Monte Carlo analysis, the estimation of the relative one- to two-gamma detection probability. In addition to minimizing the effects of spark chamber inefficiency, we feel that the inclusion of the one-gamma events reduces the uncertainty due to scanning inefficiency. We expect that missed showers primarily have a low spark count, just those showers best accounted for by this analysis. This conclusion is confirmed by the results of a rescan of several thousand frames which shows a negligible loss of charge exchange events into the zero-gamma category.

The experimental angular distribution must be corrected for geometric efficiency for detecting gammas and for gamma veto probabilities. In addition, since we have required a neutron for this sample of the data, we must correct for the attenuation and scattering of neutrons in the shower counter, as well as for the detection efficiency of the neutron detector. The attenuation of neutrons in the shower counter has been estimated by the direct measurement of the additional attenuation produced by a second shower counter module of identical construction as the one used for the major data run. The results of this measurement agree within a few percent with an estimate made from published neutron cross sections. The attenuation length for neutrons in the neutron detector has been obtained from the distribution of neutron interaction points in the data. This estimate is also in close agreement with a calculation using published cross sections. In addition, we have checked our result with data for which the neutron signal was not required for the trigger and again we find consistency within a few percent. These results have then been used as input for the Monte Carlo simulation of the data which imposes the additional geometric constraints of the equipment to yield the detection efficiency for charge exchange events as a function of u. The differential cross section is then calculated using the electronic trigger cross section normalized by the ratio of the corrected number of events satisfying the selection criteria for each Δu interval and the total number of good triggers used in obtaining the sample. The beam contamination was not subtracted electronically during the run. Instead, special runs were made at several values of the beam momentum to measure the electron and muon contamination by measuring interactions of the beam in the steel plates, and to measure the kaon and antiproton contamination with a threshhold Cerenkov run. The final cross sections have been corrected for these effects.

The measured differential cross sections are shown in Figure 3 and the data are listed in Table 1 with statistical errors, and in addition the bin width, the mean value of u, and the resolution in u for each bin. The overall normalization uncertainty is estimated to be approximately 15 percent. The largest part of this uncertainty is in the measurement of the full target triggering rate, with smaller contributions from the determinations of the pionic beam fraction, the neutron veto and attenuation fraction in the shower counter, and by the uncertainty in the amount of backscattering veto at the front of the neutron detector. Resolution unfolding has been carried out on the data at 6.0 and 4.3 GeV/c with only very slight changes in the angular distribution. This procedure has not yet been carried out at 3.5 GeV/c where it is expected to have an even smaller effect.

In the backward direction we can compare these results with those of four previous experiments. We are in fairly close agreement with the results of Kistiakowsky et al.[1] at 3.5 and at 6.0 GeV/c. Our result is somewhat lower than their value at 4.3 GeV/c. This comparison is of particular interest because we have made a separate measurement of our neutron detector efficiency, the subject of a question raised concerning the discrepancy between the results of Kistiakowsky *et al.* and Chase *et al.*[2] Our value at 6.0 GeV/c averaged over the two backward bins lies about two standard deviations higher than the comparable measurement by Chase *et al.* Our value at 180 degrees is approximately 30 percent lower than the results of Boright *et al.*[3] and Schneider *et al.*[4] Our results at 3.5 GeV/c are higher than the values of Chase *et al.* at 3.0 GeV/c and much higher than value interpolated between their 3.0 and 4.0 GeV/c measurements.

All of our cross sections exhibit clear minima at $u = -0.3$, but at 6.0 GeV/c the dip region is considerably flatter than the results of either Chase *et al.* or Boright *et al.* This comparison is particularly interesting because this analysis has sufficiently good resolution that unfolding does not deepen the dip. Another feature of our data is the suggestion of a shoulder near $u = 0.05$ at 3.5 GeV/c.

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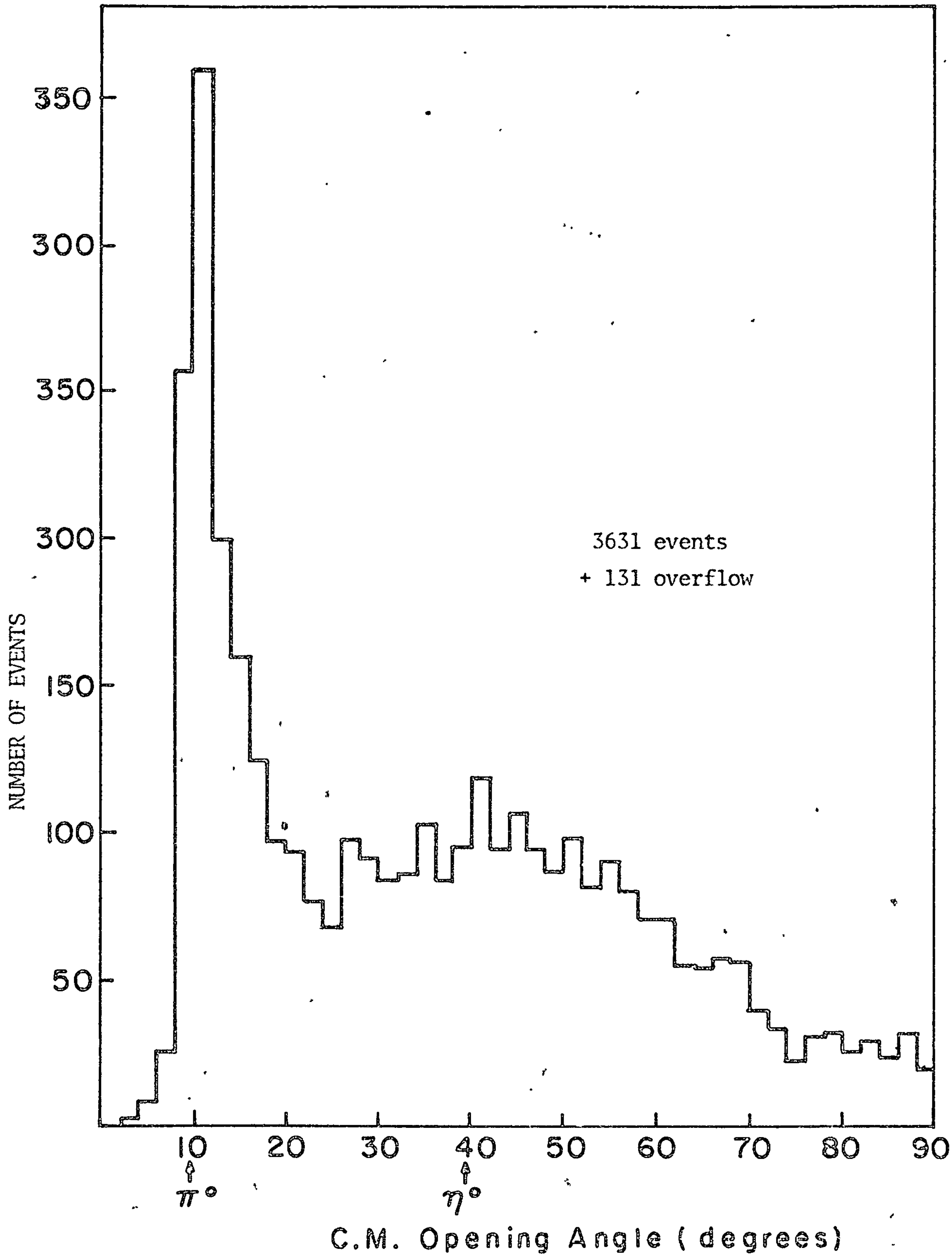

Figure 1. C.M. Opening Angle for two-gamma events with neutron detected.

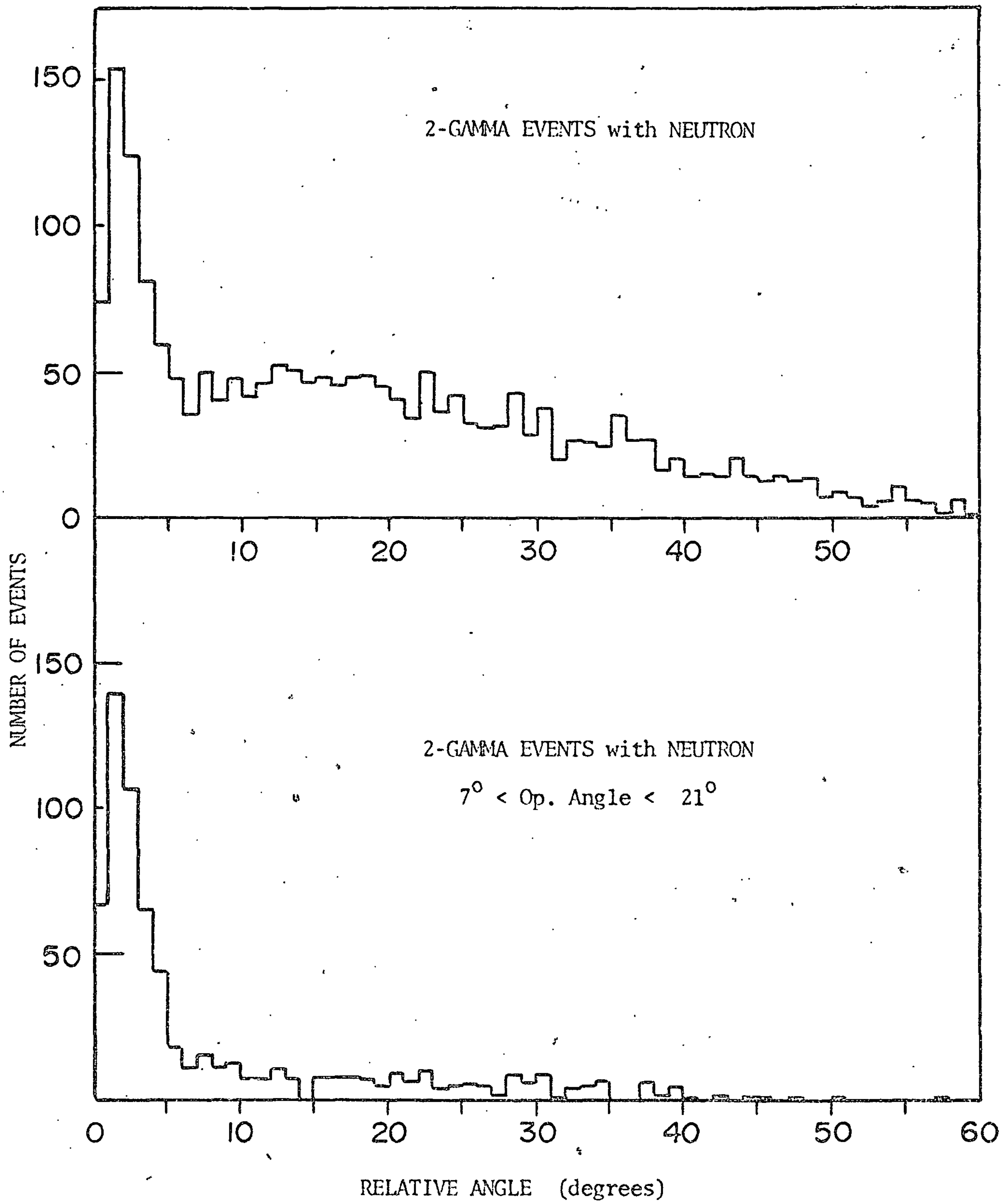

Figure 2. C.M. Relative Angle between Reverse of Neutron Direction and π^0 Solution before and after Opening Angle Cut.

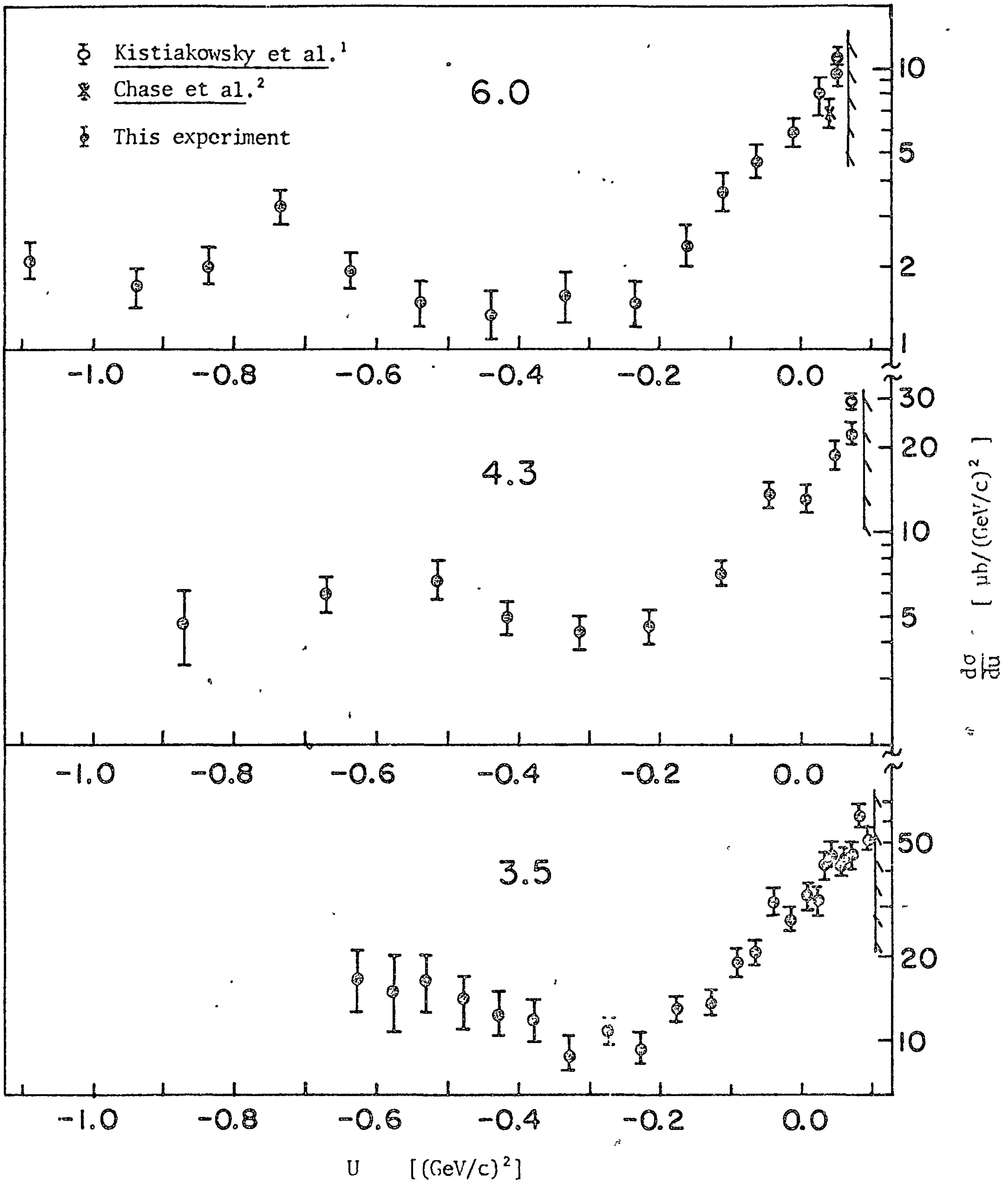

Figure 3. Charge Exchange Differential Cross Section. Errors are statistical only.

Table I. Charge Exchange Differential Cross Section

Momentum	$\bar{u}$ $(GeV/c)^2$	bin width	rms error(u)	$\frac{d\sigma}{du}\left(\frac{\mu b}{(GeV/c)^2}\right)$	$\Delta\left(\frac{d\sigma}{du}\right)$
3.5	0.0948	.0096	.0030	50.5	5.1
	0.085	.010	.0035	61.7	5.8
	0.075	.010	.0045	45.6	4.9
	0.065	.010	.006	43.3	5.1
	0.055	.010	.008	42.6	5.5
	0.045	.010	.009	45.3	5.1
	0.035	.010	.010	41.2	4.2
	0.025	.010	.011	31.6	3.7
	0.010	.020	.013	33.3	3.2
	-0.013	.025	.014	26.6	2.5
	-0.038	.025	.015	30.9	2.7
	-0.063	.025	.017	20.3	2.2
	-0.088	.025	.018	18.6	2.2
	-0.125	.05	.019	13.3	1.3
	-0.175	.05	.021	12.8	1.3
	-0.225	.05	.023	9.0	1.2
	-0.275	.05	.025	10.5	1.4
	-0.325	.05	.027	9.6	1.5
	-0.375	.05	.030	11.8	1.9
	-0.425	.05	.032	12.3	2.3
	-0.475	.05	.034	13.7	2.9
	-0.525	.05	.035	16.4	4.1
	-0.575	.05	.037	15.0	4.7
	-0.625	.05	.038	6.5	3.9
4.3	0.0705	.025	.004	22.1	1.9
	0.0455	.025	.006	18.3	1.7
	0.008	.05	.011	12.8	1.5
	-0.042	.05	.015	12.0	1.5
	-0.117	.10	.020	7.0	0.7
	-0.217	.10	.024	4.5	0.6
	-0.317	.10	.028	4.3	0.6
	-0.417	.10	.031	4.9	0.7
	-0.517	.10	.035	6.6	1.1
	-0.667	.20	.039	5.9	0.8
	-0.867	.20	.044	4.7	1.4
6.0	0.0487	.025	.004	9.4	1.3
	0.0237	.025	.006	7.8	1.2
	-0.0138	.05	.012	5.8	0.7
	-0.0638	.05	.017	4.6	0.6
	-0.1138	.05	.021	3.6	0.6
	-0.1638	.05	.024	2.3	0.4
	-0.2388	.10	.029	1.4	0.2
	-0.3388	.10	.034	1.6	0.3
	-0.4388	.10	.040	1.3	0.2
	-0.5388	.10	.043	1.4	0.2
	-0.6388	.10	.044	1.8	0.3
	-0.7388	.01	.051	3.1	0.4
	-0.8388	.01	.054	1.9	0.3
	-0.9388	.01	.057	1.6	0.3
	-1.0888	.20	.061	2.0	0.3
	-1.2888	.02	.066	1.2	0.3