APPENDIX A

KINEMATICS FOR NEUTRAL CURRENT SCATTERING

HERA is presently the only asymmetric collider in the world, with the electron beam energy of 26.7GeV and proton beam energy of 820GeV. The HERA laboratory frame is neither the target rest frame nor the center of mass frame. Much effort has been devoted to studies of HERA kinematics by different physics topical groups. Some kinematical relations for neutral current process $ep \to e'X$ are summarized in this Appendix.

The Lorentz invariant variables of theoretical interest, Q^2, W^2, x, y, are defined in terms of scalar products of four-momenta of the beam electron(e), beam proton(p), scattered electron(e') and virtual photon($q = e - e'$). They can also be expressed in terms of the two scalar products ($e \cdot e'$) and $p \cdot e'$), and vice versa. Only two of all these variables are independent. The scalar products ($e \cdot e'$) and $p \cdot e'$) can be expressed in terms of energy and polar angle measured in the laboratory frame(or any frame), (E'_e, θ'_e), and vice versa. Then relations between (Q^2, W^2, x, y) and (E'_e, θ'_e) are found. In photoproduction regime($Q^2 \approx 0$), electron mass m_e may not be neglected in certain cases such as in $Q^2_{\min}$ determination. Approximations are explicitly noted in the equations. Approximation is usually unnecessary in computer aided theoretical studies.

Definitions of some standard kinematical variables	
$Q^2 = -(e - e')^2$	(A1)
$W^2 = (p + q)^2$	(A2)
$\tilde{s} = 2p \cdot e$	(A3)
$s = (p + e)^2$	(A4)
$x = \frac{Q^2}{2p \cdot q}$	(A5)
$y = \frac{2p \cdot q}{\tilde{s}}$	(A6)

Some relations between Q^2, W^2, x, y	
$\frac{Q^2}{\tilde{s}} = xy$	(A7)
$\frac{W^2 - m_p^2}{\tilde{s}} = y - xy$	(A8)
$x = \frac{Q^2}{W^2 - m_p^2 + Q^2}$	(A9)
$y = \frac{W^2 - m_p^2 + Q^2}{\tilde{s}}$	(A10)

(Q^2, W^2, x, y) expressed in terms of $(e \cdot e')$ and $(p \cdot e')$	
$Q^2 = 2(e \cdot e') - 2m_e^2$	(A11)
$W^2 = m_p^2 + 2m_e^2 + \tilde{s} - 2(e \cdot e') - 2(p \cdot e')$	(A12)
$x = \frac{2(e \cdot e') - 2m_e^2}{\tilde{s} - 2(p \cdot e')}$	(A13)
$y = 1 - \frac{2(p \cdot e')}{\tilde{s}}$	(A14)

$(e \cdot e')$ and $(p \cdot e')$ expressed in terms of (Q^2, W^2, x, y)	
$e \cdot e' = m_e^2 + \frac{Q^2}{2}$	(A15)
$p \cdot e' = \frac{\tilde{s} - (W^2 - m_p^2 + Q^2)}{2}$	(A16)
$e \cdot e' = \frac{\tilde{s}}{2} xy + m_e^2$	(A17)
$p \cdot e' = \frac{\tilde{s}}{2}(1 - y)$	(A18)

Relations between (E'_e, θ'_e) and $(e \cdot e')$, $(p \cdot e')$	
$e \cdot e' = E_e E'_e + \|\vec{e}\|\|\vec{e'}\| \cos\theta'_e$	(A19)
$p \cdot e' = E_p E'_e - \|\vec{p}\|\|\vec{e'}\| \cos\theta'_e$	(A20)
$E'_e = \frac{2(e \cdot e')\|\vec{p}\| + 2(p \cdot e')\|\vec{e}\|}{\tilde{s}}$	(A21)
$\cos\theta'_e = \frac{1}{\|\vec{e'}\|} \frac{2(e \cdot e')E_p - 2(p \cdot e')E_e}{\tilde{s}}$	(A22.a)
$\approx \frac{(e \cdot e')E_p - (p \cdot e')E_e}{(e \cdot e')\|\vec{p}\| + (p \cdot e')\|\vec{e}\|}$	(A22.b)
$\approx$ denotes the approximation $\|\vec{e'}\| \approx E'_e$	

(Q^2, W^2, x, y) expressed in terms of (E'_e, θ'_e)	
$\tilde{s} = 2E_e E_p + 2\|\vec{e}\|\|\vec{p}\|$	(A23)
$Q^2 = 2E_e E'_e + 2\|\vec{e}\|\|\vec{e'}\| \cos\theta'_e - 2m_e^2$	(A24)
$W^2 = m_p^2 + 2m_e^2 + \tilde{s} - 2(E_p E'_e - \|\vec{p}\|\|\vec{e'}\| \cos\theta'_e)$	
$-2(E_e E'_e + \|\vec{e}\|\|\vec{e'}\| \cos\theta'_e)$	(A25)
$x = \frac{E_e E'_e + \|\vec{e}\|\|\vec{e'}\| \cos\theta'_e - m_e^2}{\tilde{s}/2 - E_p E'_e + \|\vec{p}\|\|\vec{e'}\| \cos\theta'_e}$	(A26)
$y = 1 - \frac{E_p E'_e - \|\vec{p}\|\|\vec{e'}\| \cos\theta'_e}{\tilde{s}/2}$	(A27)

(E'_e, θ'_e) expressed in terms of (Q^2, W^2)	
$E'_e = (\frac{Q^2 + 2m_e^2}{s})\|\vec{p}\| + (1 - \frac{W^2 - m_p^2 + Q^2}{s})\|\vec{e}\|$	(A28)
$\cos\theta'_e = \frac{1}{\|\vec{e'}\|}((\frac{Q^2 + 2m_e^2}{s})E_p - (1 - \frac{W^2 - m_p^2 + Q^2}{s})E_e)$	(A29)
$\approx \frac{(\frac{Q^2 + 2m_e^2}{s})E_p - (1 - \frac{W^2 - m_p^2 + Q^2}{s})E_e}{(\frac{Q^2 + 2m_e^2}{s})\|\vec{p}\| + (1 - \frac{W^2 - m_p^2 + Q^2}{s})\|\vec{e}\|}$	(A30)

(E_e', θ_e') expressed in terms of (x, y)
$E_e' = ((1-y)\vert\vec{e}\vert + xy\vert\vec{p}\vert + \frac{2m_e^2}{\hat{s}}\vert\vec{p}\vert)\frac{E_pE_e+\vert\vec{e}\vert\vert\vec{p}\vert}{E_p\vert\vec{e}\vert+E_e\vert\vec{p}\vert}$ (A31)
$\cong ((1-y)\vert\vec{e}\vert + xy\vert\vec{p}\vert + \frac{2m_e^2}{\hat{s}}\vert\vec{p}\vert)$ (A32)
$\cos\theta_e' = \frac{-(1-y)E_e+xyE_p+\frac{2m_e^2}{\hat{s}}E_p}{\vert\vec{e'}\vert}\frac{E_pE_e+\vert\vec{e}\vert\vert\vec{p}\vert}{E_p\vert\vec{e}\vert+E_e\vert\vec{p}\vert}$ (A33)
$\cong \frac{-(1-y)E_e+xyE_p+\frac{2m_e^2}{\hat{s}}E_p}{\vert\vec{e'}\vert}$ (A34)
$\approx \frac{-(1-y)E_e+xyE_p+\frac{2m_e^2}{\hat{s}}E_p}{(1-y)\vert\vec{e}\vert+xy\vert\vec{p}\vert+\frac{2m_e^2}{\hat{s}}\vert\vec{p}\vert}$ (A35)
$\approx$ denotes the approximation $\vert\vec{e'}\vert \approx E_e'$
$\cong$ denotes the excellent approximation $\frac{E_pE_e+\vert\vec{e}\vert\vert\vec{p}\vert}{E_p\vert\vec{e}\vert+E_e\vert\vec{p}\vert} \cong 1$

Contours of constant θ_e' and E_e' in (x, y) plane
$x = \frac{(1-y)(E_e-\vert\vec{e}\vert\cos\theta_e')-\frac{2m_e^2}{\hat{s}}(E_p-\vert\vec{p}\vert\cos\theta_e')}{y(E_p-\vert\vec{p}\vert\cos\theta_e')}$ (A36)
$y = \frac{(E_e+\vert\vec{e}\vert\cos\theta_e')-\frac{2m_e^2}{\hat{s}}(E_p-\vert\vec{p}\vert\cos\theta_e')}{(E_e+\vert\vec{e}\vert\cos\theta_e')+x(E_p-\vert\vec{p}\vert\cos\theta_e')}$ (A37)
$x = \frac{E_e'-(1-y)\vert\vec{e}\vert-\frac{2m_e^2}{\hat{s}}\vert\vec{p}\vert}{y\vert\vec{p}\vert}$ (A38)
$y = \frac{E_e'-E_e-\frac{2m_e^2}{\hat{s}}\vert\vec{p}\vert}{x\vert\vec{p}\vert-\vert\vec{e}\vert}$ (A39)

Approximations
$\vert\vec{e}\vert = E_e\sqrt{1-\frac{m_e^2}{E_e^2}} = E_e(1-.183\times10^{-9}) \approx E_e$ (A40)
$\vert\vec{p}\vert = E_p\sqrt{1-\frac{m_p^2}{E_p^2}} = E_p(1-.654\times10^{-6})$ (A41)
$\frac{E_pE_e+\vert\vec{e}\vert\vert\vec{p}\vert}{E_p\vert\vec{e}\vert+E_e\vert\vec{p}\vert} = \frac{1-\frac{\vert\vec{p}\vert}{E_p+\vert\vec{p}\vert}(1-\frac{\vert\vec{e}\vert}{E_e})}{1-\frac{E_p}{E_p+\vert\vec{p}\vert}(1-\frac{\vert\vec{e}\vert}{E_e})}$
$= 1 + o(10^{-16}) \cong 1$ (A42)

Exact $Q^2_{\min}$ expression
$Q^2_{\min} = \left(\sqrt{(\frac{s+m_e^2-m_p^2}{2\sqrt{s}})^2 - m_e^2} - \sqrt{(\frac{s+m_e^2-W^2}{2\sqrt{s}})^2 - m_e^2}\right)^2 - (\frac{W^2-m_p^2}{2\sqrt{s}})^2$ (A43)

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To My Parents

ACKNOWLEDGMENTS

The ZEUS experiment was made possible by ten years of brilliant work from hundreds of physicists and engineers to whom I pay respect.

The present analysis grew out of the work by the J/ψ study group to whose members I express my deep gratitude for fruitful cooperation and, in particular, to my mentors J.N. Lim and M.Z. Wang for their continuous guidance and assistance which made this measurement a success. I would also like to acknowledge the following people, mostly from outside of the J/ψ group, for important technical helps. K. Tokushuku and D. Krakauer provided instrumental help in design and implementation of the J/ψ trigger. H.J. Kim, G. Levman, K.W. McLean and W.N. Murray enlightened me through numerous conversations. K. McLean also helped me to adjust to the thrilling HEP laboratory life in the early days. Daily discussions with D. Acosta during the long course of writing this thesis provided essential stimuli. B. Bylsma and L.S. Durkin patiently corrected thousands of mistakes to make the text readable. B. Bylsma is also thanked for undertaking the task of creating the TEXsis OSU Thesis format in which this thesis was written. Improved accuracy and clarity of this document is due to hundreds of comments and suggestions made by D. Acosta, B. Bylsma, L.S. Durkin, J.N. Lim and T.Y. Ling. I take this opportunity to thank C. Rush and his OSU electronics crew for their help in design and construction of the fast digital processor card.

I sincerely thank Tianjin University for permitting me to leave the teaching position and study in America back in 1987. I acknowledge the Ohio State University and the U.S. Department of Energy for financial support to my graduate study. Professors L.S. Durkin, T.Y. Ling and T.A. Romanowski are gratefully acknowledged for offering me the opportunity to become a high energy physicist. In particular, I would like to thank my research advisor L. Stanley Durkin for taking care of me through all these years and for his influence on my views of physics.

My deepest gratitude is reserved for hospitality, attention and morale support I continuously received from people immediately surrounding me and from my family and friends in China, in Germany and in America, who endowed meaning to my research career.

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FIELDS OF STUDY

Major Field: Physics

Studies in Experimental High Energy Physics with Professors L.S. Durkin, T.Y. Ling, K. Honscheid; in Experimental Condensed Matter Physics (Conducting Polymers) with Professor A.J. Epstein.

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