

To: Dr. Ted Barnes, Department of Energy

From: Oliver K. Baker, Professor of Physics, Yale University *Oliver K. Baker*

Date: August 20, 2013

Re: DE-FG02-97ER41035 report on work done at Hampton University

Professor Baker was a faculty member at Hampton University in Hampton, Virginia, and, jointly, a Staff Physicist at Jefferson Lab in nearby Newport News from September 1989 to July 2006. The Department of Energy (DOE) funded the grant DE-FG02-97ER41035 Electromagnetic Studies of Mesons, Nucleons, and Nuclei, while Baker was in this joint appointment. Baker sent a closeout report on these activities to Hampton University's Sponsored Research Office some years ago, shortly after joining Yale University in 2006. In the period around 2001, the research grant with Baker as the Principal Investigator (PI) was put under the supervision of Professor Liguang Tang at Hampton University. Baker continued to pursue the research while in this joint appointment, however the administrative responsibilities with the DOE and with Hampton University rested with Professor Tang after 2001, to my recollection. What is written in this document is from Baker's memory of the research activities, which he has not pursued since joining the Yale University faculty.

The main effort supported by this grant was the electromagnetic production of hadronic systems with strangeness degrees of freedom, that is, systems that included a constituent strange quark. This list of systems included K-mesons (kaons), hyperons, mainly Lambda (Λ^0) and Sigma (Σ) hyperons, and hypernuclei. These studies form a core component of the goals of intermediate-energy nuclear physics; to understand the structure and interactions between nucleons, mesons, and nuclei in terms of sub-nucleonic degrees of freedom (quarks and gluons). The experimental work was carried out exclusively at Jefferson Lab using the Continuous Electron Beam Accelerator Facility (CEBAF).

The elementary interaction studied was $e + p \rightarrow e' + K^+ + Y(\Lambda, \Sigma)$ where an initial electron scatters from a hydrogen target producing a scattered electron (e'), a kaon (K^+), and a hyperon (Y). Both Λ and Σ hyperons were identified from the missing mass spectra. The cross section for the reaction using unpolarized electrons and with no polarization determined in the final state is expressed as

$$\begin{aligned} \frac{d\sigma}{dE_e d\Omega_e d\Omega_K} &= \Gamma \frac{d\sigma(\gamma^*, K)}{d\Omega_K} \\ &= \Gamma \left[\sigma_T + \varepsilon \sigma_U + \varepsilon \sigma_{TT} \cos 2\Phi + \sqrt{2\varepsilon(\varepsilon+1)} \sigma_{LT} \cos \Phi \right] \end{aligned}$$

where $\varepsilon^{-1} = 1 + 2|\vec{q}|^2 / Q^2 \tan^2(\theta_e / 2)$ is the photon polarization parameter, θ_e is the electron scattering angle, $\vec{q}(Q)$ is the electron three (four) momentum, and Φ is the angle between the leptonic plane (defined by the incoming and outgoing electrons), and the reaction plane (defined by the virtual photon and the kaon 3-momentum). This is shown in the following figure.

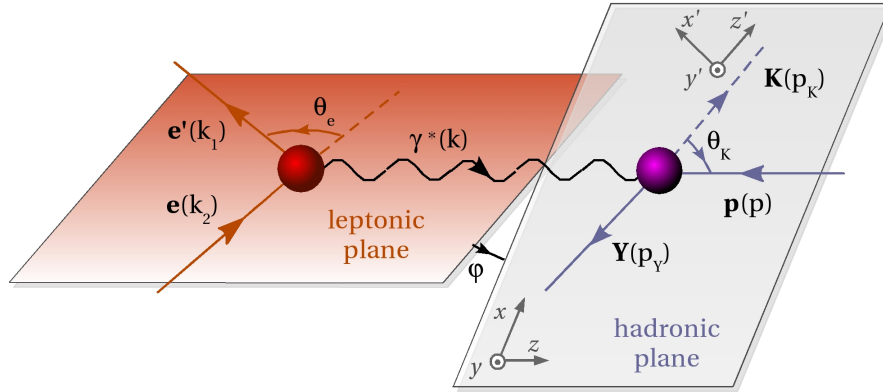


Figure 1. Kinematics for the reaction $e + p \rightarrow e' + K^+ + Y(\Lambda, \Sigma)$. The reaction is described more fully in the text.

The missing mass spectrum, where the hyperons that are associatively produced, is shown in Fig. 2 for the elementary reaction. Reactions with both hyperons are studied in the elementary process on protons, as well as in more complex nuclear systems.

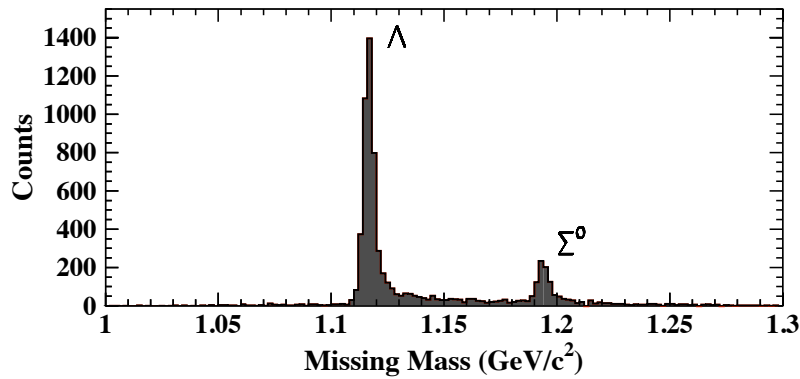


Figure 2. The associated hyperons that are produced in the elementary reaction on the proton.

The experimental program that was supported by DE-FG02-97ER41035 was the very first to provide accurate determination of the first two terms in the electroproduction equation above; the σ_U and σ_L terms (longitudinal and transverse cross sections). Subsequent work on this grant included studies on deuterium and helium nuclei, the simplest systems what would include a strange hyperon in the final state.

After extracting first results in the elementary reaction on the proton, the group supported by this grant studied nuclear systems that included a strange hyperon. This work, hypernuclear spectroscopy, was studied using the CEBAF electron beam in the reaction shown in Fig. 3. In the figure, an electron scatters from a nucleus that includes only protons and neutrons. The production of a kaon that is detected signals the formation of a hypernucleus, a nucleus that contains a hyperon. These studies are important in intermediate energy nuclear physics as well as in astrophysics (strange star dynamics, for

example). These were the very first hypernuclear results using an electron beam in the formation process.

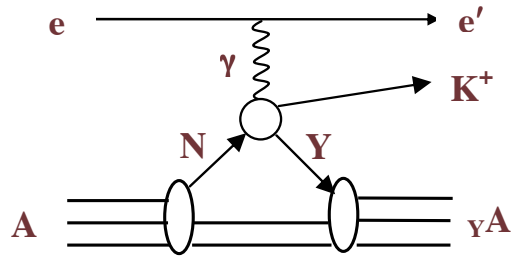


Figure 3. The electromagnetic production of a hypernucleus, a nucleus that includes a strange hyperon. The scattered electron and the kaon are detected in the reaction.

Baker was the PI on several of the experiments that included strangeness electroproduction. He and his students and postdoctoral researchers that were supported by the grant designed and constructed equipment for the experimental studies used in all of the Hall C experiments, mainly the multiwire drift chambers for particle tracking. The group supported by this grant also played crucial roles in all of the initial experiments in Hall C and in several experiments in Halls A and B during the early experimental program. The results of the work supported by this grant led to some of the very first publications based upon the experimental program at Jefferson Lab. And some of the first students to graduate with a doctoral degree at the Lab were supported by this grant.

The work supported by this grant was one of the major components of the doctoral degree program in the Department of Physics at Hampton University, the very first PhD degree program at this Historically Black College of University (HBCU). During the time of this award, the following postdoctoral researchers were supported or supervised by the PI of DE-FG02-97ER41035: Shelton Beedoe (91-93); Kevin Beard (1993-95); Tom Eden (1995-96); Paul Gueye (96-99); Geoff Savage (96-98); Ketevi Assamagan (1995-2001); Alicia Uzzle (02-2005). All of these postdoctoral researchers went on to work in academia, a national laboratory, or in industry. The graduate students directly supervised by Baker, or co-supervised during the time of this grant were: Supervised Ph.D. Diss. "Quasifree Kaon Electroproduction on He" by A. Uzzle (2002); Supervised Ph.D. Diss. "L/T Separation in Kaon Electroproduction" by G. Niculescu (1998); Supervised Ph.D. Diss. "Search for Narrow Sigma Hypernuclear States" by W. Naing (2000); Co-supervised Ph.D. Diss. "Kaon Electroproduction on Deuterium" by J. Cha (2001); Co-supervised Ph.D. Diss. "Quasielastic Production of Kaons" by W. Hinton (2001); Supervised M.S. Thesis "Planar Multiwire Drift Chamber" by W. Naing (1993); Supervised M.S. Thesis "Straw Tube Drift Chamber" by T. Shin (1993).

Among the service performed by the PI during the time of this grant that are specifically related to nuclear physics are: Fermi National Accelerator Laboratory Director Search Committee (2004); Harvard University Department of Physics Visiting Committee; NSF/DOE Nuclear Science Advisory Panel (NSAC) (1999-2001); Member, Jefferson Lab Director Search Committee (1999-2000);

And finally, selected publications based upon the work supported by this grant are listed in the following pages.

Selected publications resulting from support of DOE grant DE-FG02-97ER41035

Longitudinal-transverse separations of structure functions at low Q^{*2} for hydrogen and deuterium

V. Tvaskis (Vrije U., Amsterdam & NIKHEF, Amsterdam), M.E. Christy (Hampton U.), J. Arrington (Argonne), R. Asaturyan (Yerevan Phys. Inst.), O.K. Baker (Hampton U.), H.P. Blok (Vrije U., Amsterdam & NIKHEF, Amsterdam), P. Bosted (Jefferson Lab), M. Boswell (Randolph-Macon Woman's Coll.), A. Bruell (MIT), A. Cochran (Hampton U.) *et al.*. Nov 2006. 4 pp.

Published in **Phys.Rev.Lett.** **98** (2007) **142301**

JLAB-PHY-06-577

DOI: [10.1103/PhysRevLett.98.142301](https://doi.org/10.1103/PhysRevLett.98.142301)

e-Print: [nucl-ex/0611023](#) | [PDF](#)

The Onset of Quark-Hadron Duality in Pion Electroproduction

T. Navasardyan, G.S. Adams, A. Ahmidouch, T. Angelescu, J. Arrington, R. Asaturyan, O.K. Baker, N. Benmouna, C. Bertoncini, H.P. Blok *et al.*. Aug 2006. 11 pp.

Published in *Phys.Rev.Lett.* **98** (2007) 022001

JLAB-PHY-06-536

DOI: [10.1103/PhysRevLett.98.022001](https://doi.org/10.1103/PhysRevLett.98.022001)

e-Print: [hep-ph/0608214](#) | [PDF](#)

Polarization transfer in the H-2(polarized-e, e-prime polarized-p) n reaction up to $Q^{*2} = 1.61-(\text{GeV}/c)^{*2}$

B. Hu (Hampton U.), M.K. Jones, P.E. Ulmer (Old Dominion U.), H. Arenhovel (Mainz U., Inst. Kernphys.), O.K. Baker (Hampton U.), W. Bertozzi (MIT), E.J. Brash (Regina U.), J. Calarco (New Hampshire U.), Jian-Ping. Chen, E. Chudakov (Jefferson Lab) *et al.*. Jun 2006. 7 pp.

Published in *Phys.Rev.* **C73** (2006) 064004

JLAB-PHY-06-458

DOI: [10.1103/PhysRevC.73.064004](https://doi.org/10.1103/PhysRevC.73.064004)

e-Print: [nucl-ex/0601025](#) | [PDF](#)

Measurements of the neutron electric to magnetic form-factor ratio $G(E_n) / G(M_n)$ via the H-2(polarized-e, e-prime polarized-n)H-1 reaction to $Q^{*2} = 1.45-(\text{GeV}/c)^{*2}$

Jefferson Laboratory E93-038 Collaboration (B. Plaster (MIT, LNS & Caltech) *et al.*). Nov 2005. 41 pp.

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JLAB-PHY-06-504

DOI: [10.1103/PhysRevC.73.025205](https://doi.org/10.1103/PhysRevC.73.025205)

e-Print: [nucl-ex/0511025](#)

Future hypernuclear program at JLab Hall C

JLab E01-011 Collaboration (S.N. Nakamura (Tohoku U.) *et al.*). 2005. 9 pp.

Published in **Nucl.Phys. A754 (2005) 421-429**

JLAB-PHY-05-27

Nuclear transparency from quasielastic C-12 (e, e-prime p)

E97-006 Collaboration (D. Rohe (Basel U.) *et al.*). Jun 2005. 8 pp.

Published in **Phys.Rev. C72 (2005) 054602**

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e-Print: [nucl-ex/0506007](https://arxiv.org/abs/nucl-ex/0506007)

Measurement of $R = \sigma(L) / \sigma(T)$ and the separated longitudinal and transverse structure functions in the nucleon resonance region

Jefferson Lab Hall C E94-110 Collaboration (Y. Liang (American U. & Hampton U.) *et al.*). Oct 2004. 5 pp.

JLAB-PHY-04-45

e-Print: [nucl-ex/0410027](https://arxiv.org/abs/nucl-ex/0410027)

Precision Rosenbluth measurement of the proton elastic form-factors

I.A. Qattan (Northwestern U. & Argonne), J. Arrington (Argonne), R.E. Segel (Northwestern U.), X. Zheng (Argonne), K. Aniol (Cal State, L.A.), O.K. Baker (Hampton U.), R. Beams (Argonne), E.J. Brash (Regina U.), J. Calarco (New Hampshire U.), A. Camsonne (Clermont-Ferrand U.) *et al.*. Oct 2004. 5 pp.

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Correlated strength in nuclear spectral function

D. Rohe (Basel U.), C.S. Armstrong, R. Asaturyan, O.K. Baker, S. Bueltmann, C. Carasco, D. Day, R. Ent, Howard C. Fenker, K. Garrow *et al.*. May 2004. 4 pp.

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JLAB-PHY-04-42

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e-Print: [nucl-ex/0405028](https://arxiv.org/abs/nucl-ex/0405028) |

Hypernuclear spectroscopy using the (e,e-prime K+) reaction

HNSS Collaboration (L. Yuan (Hampton U.) *et al.*). Aug 2004. 24 pp.

Published in **Phys.Rev. C73 (2006) 044607**

JLAB-PHY-04-50

DOI: [10.1103/PhysRevC.73.044607](https://doi.org/10.1103/PhysRevC.73.044607)

e-Print: [nucl-ex/0408011](https://arxiv.org/abs/nucl-ex/0408011)

Near threshold electroproduction of the omega meson at $Q^2 \approx 0.5\text{-GeV}^2$
Jefferson Laboratory E91-016 Collaboration (P. Ambrozewicz (Temple U. & Jefferson Lab & Mississippi State U. & Florida Intl. U. & Argonne, PHY) *et al.*). Mar 2004. 10 pp.
Published in **Phys.Rev. C70 (2004) 035203**
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e-Print: [nucl-ex/0403003](https://arxiv.org/abs/nucl-ex/0403003)

Measurements of electron proton elastic cross-sections for $0.4 < Q^{*2} < 5.5$ (GeV/c)**2
E94110 Collaboration (M.E. Christy (Hampton U.) *et al.*). Jan 2004. 16 pp.
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JLAB-PHY-04-216
DOI: [10.1103/PhysRevC.70.015206](https://doi.org/10.1103/PhysRevC.70.015206)
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A new hypernuclear experiment with the High resolution Kaon Spectrometer (HKS) at JLab Hall C
Jlab E01-011 Collaboration (S.N. Nakamura (Tohoku U.) *et al.*). Jun 2003.
JLAB-PHY-03-209
Prepared for International Symposium on Electrophoto Product Conference: C03-06-16.8, p.273-282

Measurement of the neutron electric form factor via recoil polarimetry
Jefferson Laboratory E93-038 Collaboration (T. Reichelt *et al.*). 2003. 3 pp.
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DOI: [10.1140/epja/i2002-10296-0](https://doi.org/10.1140/epja/i2002-10296-0)
Prepared for Conference: C02-06-09 Proceedings

The electric form factor of the neutron via recoil polarimetry to $Q^{*2} = 1.47\text{-(GeV/c)**2}$
B. Plaster, R. Madey, A.Yu. Semenov, S. Taylor, A. Aghalarian, E. Crouse, G. MacLachlan, S. Tajima, W. Tireman, C. Yan *et al.*. 2003. 5 pp.
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Prepared for Conference: C02-09-09.1, p.625-629

Neutron electric form factor up to $Q^{*2} = 1.47\text{-(GeV/c)**2}$
R. Madey, A.Yu. Semenov, S. Taylor, A. Aghalarian, E. Crouse, G. MacLachlan, B. Plaster, S. Tajima, W. Tireman, C.Y. Yan *et al.*. 2003. 5 pp.
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DOI: [10.1140/epja/i2002-10169-6](https://doi.org/10.1140/epja/i2002-10169-6)
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Measurements of $G(E)n / G(M)n$ from the $H-2(\text{polarized-}e, e\text{-prime polarized-}n)$ reaction to $Q^{*2} = 1.45 \text{ (GeV/c)}^{*2}$

E93-038 Collaboration (R. Madey *et al.*). Aug 2003. 5 pp.

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JLAB-PHY-03-224

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A Study of the quasielastic ($e, e\text{-prime p}$) reaction on C-12, Fe-56 and Au-97

JLab E91013 Collaboration (D. Dutta (Northwestern U. & MIT, LNS) *et al.*). Mar 2003. 19 pp.

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Hypernuclear spectroscopy of $(\Lambda)B-12$ in the $(e, e' K^+)$ reaction

J. Reinhold, T. Miyoshi, M. Sarsour, L. Yuan, X. Zhu, A. Ahmidouch, P. Ambrozewicz, D. Androic, T. Angelescu, R. Asaturian *et al.*. Mar 2002. 4 pp.

JLAB-PHY-02-169

Prepared for 9th International Conference on the Structure o Conference: [C02-03-03.2](#), p.589-592

Electroproduction of strangeness on light nuclei

F. Dohrmann, D. Abbott, A. Ahmidouch, P. Ambrozewicz, C.S. Armstrong, J. Arrington, R. Asaturian, K. Assamagan, S. Avery, K. Bailey *et al.*. Mar 2002. 4 pp.

Prepared for 9th International Conference on the Structure o Conference: [C03-06-16.8](#), Prepared for 9th International Conference on the Structure o Conference: [C02-03-03.2](#)

Neutron electric form factor via recoil polarimetry

Jefferson Lab E93-038 Collaboration (R. Madey *et al.*). Mar 2002. 5 pp.

JLAB-PHY-02-156

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Weak production of strangeness at threshold with polarization observables

O.Keith Baker (Jefferson Lab). 2002.

Published in **Phys.Lett.** **B548 (2002) 52-57**

JLAB-PHY-02-20

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Polarization transfer in the He-4 (polarized-e, e-prime polarized-p) H-3 reaction up to $Q^2 = 2.6-(\text{GeV}/c)^2$

Jefferson Lab E93-049 Collaboration (S. Strauch (Rutgers U., Piscataway) *et al.*). Nov 2002. 5 pp.

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e-Print: [nucl-ex/0211022](https://arxiv.org/abs/nucl-ex/0211022)

High resolution spectroscopy of the B-12(Lambda) hypernucleus produced by the (e, e-prime K+) reaction

HNSS Collaboration (T. Miyoshi (Tohoku U.) *et al.*). Nov 2002. 11 pp.

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JLAB-PHY-02-127

DOI: [10.1103/PhysRevLett.90.232502](https://doi.org/10.1103/PhysRevLett.90.232502)

e-Print: [nucl-ex/0211006](https://arxiv.org/abs/nucl-ex/0211006)

Measurement of pion transparency in nuclei

K.R. Garrow, R. Carlini, D.G. Meekins, R. Ent, Howard C. Fenker, M.K. Jones, A. Lung, D. Mack, G. Smith, S.A. Wood (Jefferson Lab) *et al.*. Jun 2001. 23 pp.

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First experiment on spectroscopy of Lambda hypernuclei by electroproduction at JLab

L. Tang, T. Miyoshi, M. Sarsour, L. Yuan, X. Zhu, A. Ahmidouch, P. Ambrozewicz, D. Androic, T. Angelescu, R. Asaturian *et al.*. Jul 2001. 13 pp.

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JLAB-PHY-01-18

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Prepared for Conference: [C01-07-02.5](https://arxiv.org/abs/C01-07-02.5), p.173-185

Measurement of longitudinal and transverse cross-sections in the He-3 (e, e-prime pi+) H-3 reaction at $W = 1.6\text{-GeV}$

D. Gaskell (Oregon State U. & Argonne), A. Ahmidouch (North Carolina A-T State U.), P. Ambrozewicz (Temple U.), H. Anklin (Florida Intl. U. & Jefferson Lab), J. Arrington (Argonne), K. Assamagan, S. Avery (Hampton U.), K. Bailey (Argonne), O.K. Baker (Hampton U. & Jefferson Lab), S. Beedoe (North Carolina A-T State U.) *et al.*. Dec 2001. 5 pp.

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Electroproduction of kaons on light nuclei

B. Zeidman, D. Abbott, A. Ahmidouch, P. Ambrozewicz, C.S. Armstrong, J. Arrington, R. Asaturian, K. Assamagan, S. Avery, K. Bailey *et al.*. 2001. 6 pp.

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JLAB-PHY-01-102

DOI: [10.1016/S0375-9474\(01\)00999-X](https://doi.org/10.1016/S0375-9474(01)00999-X)

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Longitudinal electroproduction of charged pions from H-1, H-2, He-3

D. Gaskell (Oregon State U. & Argonne), A. Ahmidouch (North Carolina A-T State U.), P. Ambrozewicz (Temple U.), H. Anklin (Florida Intl. U. & Jefferson Lab), J. Arrington (Argonne), K. Assamagan, S. Avery (Hampton U.), K. Bailey (Argonne), O.K. Baker (Hampton U. & Jefferson Lab), S. Beedoe (North Carolina A-T State U.) et al.. 2001. 5 pp.

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DOI: [10.1103/PhysRevLett.87.202301](https://doi.org/10.1103/PhysRevLett.87.202301)

Nuclear transparency from quasielastic A(e,e-prime p) reactions up to $Q^{*2} = 8.1$ - $(\text{GeV}/c)^{*2}$

K. Garrow (Jefferson Lab), D. McKee (New Mexico State U.), A. Ahmidouch, C.S. Armstrong, J. Arrington, R. Asaturyan, S. Avery, O.Keith Baker, D.H. Beck, H.P. Blok et al.. Sep 2001. 11 pp.

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Electroproduction of kaons and light hypernuclei

J. Reinhold, D. Abbott, A. Ahmidouch, P. Ambrozewicz, C.S. Armstrong, J. Arrington, R. Asaturian, K. Assamagan, S. Avery, K. Bailey et al.. 2001.

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O.K. Baker (Jefferson Lab & Hampton U.). Jul 2000. 11 pp.

JLAB-PHY-00-106

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Kaon production at large space-like momentum transfer

E93018 Collaboration (O.Keith Baker (Hampton U. & Jefferson Lab) for the collaboration). May 2000.

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Strangeness production using electrons

O.Keith Baker (Hampton U. & Jefferson Lab). Jul 2000.

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Experimental verification of quark hadron duality

I. Niculescu (Hampton U.), C.S. Armstrong (William-Mary Coll.), J. Arrington (Caltech), K.A. Assamagan (Hampton U.), O.K. Baker (Hampton U. & Jefferson Lab), D.H. Beck, C.W. Bochna (Illinois U., Urbana), R.D. Carlini (Jefferson Lab), J. Cha (Hampton U.), C. Cothran (Virginia U.) et al., 2000.

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Evidence for valencelike quark hadron duality

I. Niculescu (Hampton U.), C.S. Armstrong (William-Mary Coll.), J. Arrington (Caltech), K.A. Assamagan (Hampton U.), O.K. Baker (Hampton U. & Jefferson Lab), D.H. Beck, C.W. Bochna (Illinois U., Urbana), R.D. Carlini (Jefferson Lab), J. Cha (Hampton U.), C. Cothran (Virginia U.) et al., 2000.

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T. Angelescu, L. Teodorescu (Bucharest U.), O.Keith Baker, P. Gueye (Hampton U. & Jefferson Lab). 2000.

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Jefferson Lab F(pi) Collaboration (J. Volmer (NIKHEF, Amsterdam & Brussels U., IIHE) et al.). Oct 2000. 5 pp.

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Separated spectral functions for the quasifree C-12 (e, e-prime p) reaction

D. Dutta (Northwestern U.), D. van Westrum (Colorado U.), D. Abbott (Jefferson Lab), A. Ahmidouch (Kent State U.), Ts.A. Amatuni (Yerevan Phys. Inst.), C. Armstrong (William-Mary Coll.), J. Arrington (Caltech), K.A. Assamagan (Hampton U.), K. Bailey (Argonne), O.K. Baker (Jefferson Lab & Hampton U.) et al., 2000. 5 pp.

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K+ electroproduction in exclusive e(pol.) + p --> e'(pol.) + K+ + Lambda reaction
T. Angelescu, A. Mihul, L. Teodorescu (Bucharest U.), O.Keith Baker, P. Gueye, G. Niculescu, I. Niculescu (Hampton U.). 1999.

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O.Keith Baker (Hampton U. & Jefferson Lab). May 1999.

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