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HYPERON AND GLUEBALL ELECTROMAGNETIC PRODUCTION

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An analysis of new kaon electroproduction measurements at Jefferson Lab is presented for both proton and deuteron targets. Calculations based upon quantum hadrodynamics are compared to the experimental longitudinal and transverse separated cross sections for elementary $K\Lambda$ production. Also confronted by data are model predictions for d(e,e'K^+)YN inclusive measurements with YN = Λn, Σ^0n and Σ^-p. In general, both proton and deuteron target experiments are reasonably well described. Finally, glueball production, possible with the anticipated Jefferson Lab beam energy upgrade, is discussed in conjunction with results from a QCD Hamiltonian calculation for the low-lying gluonia spectrum.

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1. Introduction

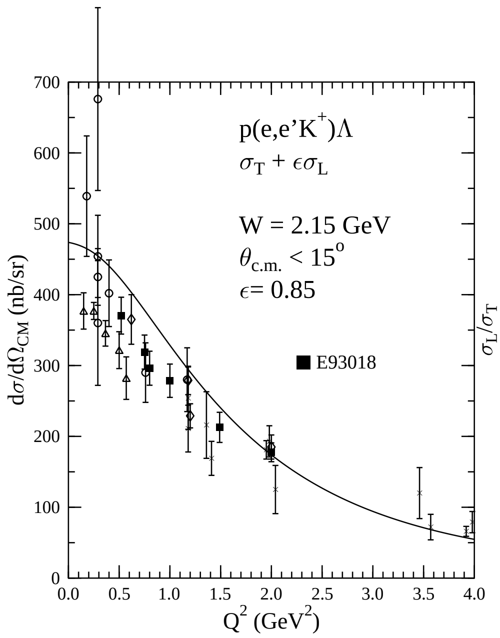
Among the very first experiments [1,2] conducted at Jefferson Lab (JLAB) have been those involving strangeness electroproduction utilizing Hall C. The unprecedented high count rate for exclusive p(e,e'K^+)Λ measurements has permitted extracting the most accurate transverse and longitudinal elementary cross sections to date. Also noteworthy is the first kinematically-complete inclusive measurement of d(e,e'K^+)YN for YN = Λn, Σ^0n and Σ^-p. The focus of this work is a theoretical analysis for both of these experiments highlighting the strengths and weaknesses of current models. Section 2 details quantum hadrodynamic (QHD) calculations for the elementary production process. In Section 3, a coupled-channels final state interaction study is documented for the d(e,e'K^+)YN measurements.

Also addressed in this paper, in Section 4, is the possibility of future glueball electromagnetic production investigations at JLAB which would be energetically feasible with the proposed CEBAF beam upgrade to 12 GEV. The feasibility study of gluonia is motivated in part by results from a new many-body QCD approach to hadron structure [3–5]. This effective Hamiltonian formulation of QCD, which has impressively reproduced lattice gauge "measurements" for the glueball spectrum, is a constituent picture and, therefore, provides new insight into the structure of hadrons with explicit gluon degrees of freedom.

2. *Elementary kaon electroproduction*

The principal motivation for investigating K^+ electromagnetic production and the crossing-related K^- radiative capture process is to understand the fundamental reaction mechanism at the quark level and the attending structure of the participating hadrons. Comparison between precision data, now becoming available, and fundamental QCD calculations will provide this information. The formidable challenge of nonperturbative QCD still necessitates the utilization of QHD for field-theoretical reaction calculations. This entails an effective Lagrangian at the hadron level, usually computed in the tree approximation. Accordingly, unless the coupling constants are rather small, these formulations will in general violate unitarity and are also not renormalizable. Nevertheless, this approach has many phenomenological successes and embodies several important features including field theory, gauge and Lorentz invariance, duality (Regge theory) and crossing symmetry. It is a continuing debate whether improvements to this approach will permit extracting the hadronic coupling constants, however, it should be adequate for determining electromagnetic vertices and form-factors which in turn can be calculated more easily from QCD. This is the philosophy of the current work.

In Ref. 6, the present QHD procedure is detailed in an analysis of the world's limited kaon photoproduction and radiative capture cross section and polarization data for Λ, Σ and $\Lambda(1405)$ formation for photon energies in the 1 to 2.5 GeV region. This comprehensive χ^2 fitting generated several sets of phenomenologically equivalent coupling constants. The approach was then generalized to electroproduction by introducing hadron form-factors from an extended vector-meson-dominance model. Figure 1 shows a prediction of this model and the new JLAB data [1] at $\sqrt{s} = W = 2.15$ GeV for virtual photon mass squared, Q^2, between 0 and 4 GeV^2. Solid squares represent data from experiment E93-018. The remaining, older data, are from Ref. 7. Note that the data are reasonably well described and that no parameters from Ref. 6 have been changed. Because the uncertainty in the new data is between 5 and 7 % in the absolute cross section, it is now possible to extract a more accurate Rosenbluth L/T separation of the transverse, σ_T, and longitudinal, σ_L, cross sections. This is shown in Fig. 2 where the ratio σ_L/σ_T is compared for theory and experiment. Significantly, the JLAB data (boxes) are three times more precise than the only prior measurement (triangles are from Ref. 8). In contrast to the results in Fig. 1, it was found necessary to adjust either the kaon or proton electric form-factor so that their Q^2 dependence was similar. This permitted describing the data which are essentially flat versus Q^2. This appears to conflict with vector-meson dominance and QHD which together predict that σ_L/σ_T scales as the kaon to proton form-factor, a ratio which rises with Q^2 (i.e. monopole to dipole). Clearly, further study is necessary, however, since the theoretical value for σ_L is quite sensitive to kaon form-factor and because the measured value for σ_L is large, it may be possible to determine this form-factor by performing a Chew-Low extrapolation. This would permit confrontation with more fundamental QCD approaches which are in progress [9].



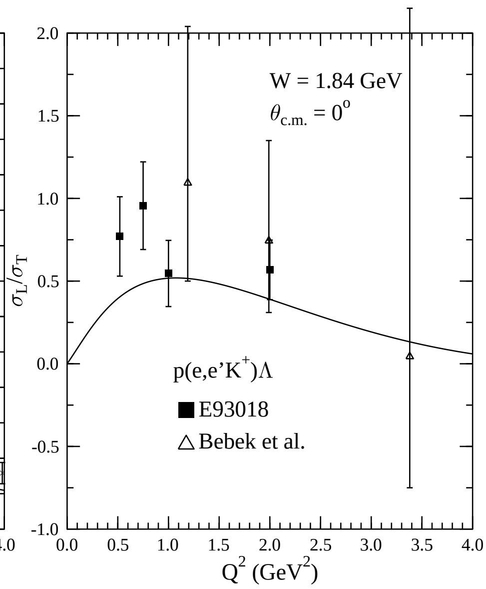


Fig. 1. Theoretical predictions and data for p(e,e'K$^+$)Λ.

Fig. 2 (right). Longitudinal to transverse cross section ratio for p(e,e'K$^+$)Λ.

3. Kaon production from the deuteron

The original motivation for producing two-body YN systems, with Y a strangeness-1 baryon, was to search for strange dibaryons. After extensive experimental study, it now appears that such six-quark states do not exist. Accordingly, the physics emphasis in d(e,e'K$^+$)YN measurements now centers upon extracting elementary amplitudes for kaon production from the neutron. The calculation for this reaction reported in this work is a continuation of previous theoretical effort [10,11] and entails a coupled-channels, final-state formulation. Specifically, the YN potential D, provided by Nagels and de Swart [12], is diagonalized and the wave functions are then used to compute the virtual photoproduction amplitude for d(γ_v, K$^+$)YN in the impulse approximation. The complete amplitude, $T_{\rm YN}$, is given by

$$T_{\rm YN} = \sum_{\rm Y'} \int {\rm d}\boldsymbol{r} \Psi^{(-)\dagger}_{\rm YY'}(\boldsymbol{r}) e^{{\rm i}\boldsymbol{q}_{\rm Y'}\cdot\boldsymbol{r}} (a_{\rm Y'} + {\rm i}\boldsymbol{b}_{\rm Y'}\cdot\sigma)\Phi_d(\boldsymbol{r}) \tag{1}$$

where Φ_d is the deuteron wave function, here taken to be the Reid soft-core, $a_{\rm Y}$, $\boldsymbol{b}_{\rm Y}$ are the elementary KY virtual photoproduction amplitudes and $\Psi_{\rm YY'}$ are the coupled-channels final-state wave functions describing the elastic and inelastic scattering processes YN $\to$ Y$'$N$'$. The sum over Y$'$ is for the three channels Y$'$N$'$ = Λn, Σ^0n and Σ^-p, and $\boldsymbol{q}_{\rm Y}$ is

$$\boldsymbol{q}_{\rm Y} = \frac{m_n}{m_n + m_{\rm Y}}\boldsymbol{P} - \frac{1}{2}\boldsymbol{P}_d \tag{2}$$

where m_n, $m_{\rm Y}$ are the neutron and Y hyperon masses and $\boldsymbol{P}_d$, $\boldsymbol{P}$ are the deuteron and YN total three-momentum, respectively.

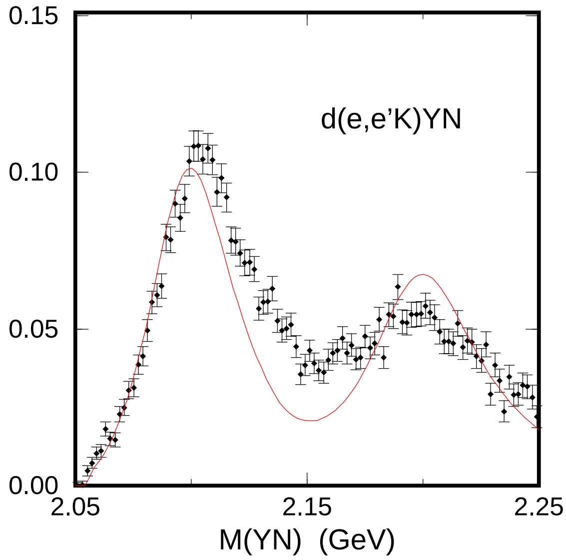


Fig. 3. Theory and data for d(e,e'K$^+$)YN.

The results from applying this model to the recent JLAB measurements of d(e,e'K$^+$)Λn, Σ^0n,Σ^-p, experiment E91-016 [2], are shown in Fig. 3 for electron beam energy 3.245 GeV, $Q^2 = 0.376$ GeV^2 and kaon lab angle (relative to the virtual photon) 1.5°. Because only the electron and the kaon are detected in Hall C, this is an inclusive measurement. Hence, to properly compare with theory, the calculated exclusive cross section has been integrated over the unobserved final-state Λ angles and plotted as a function of the YN invariant mass. The curve corresponds to the coupling constants determined by an older phenomenological anlysis [13] of elementary KΛ production. The KΣ coupling constants were generated using SU(3).

Although less accurate, this entire set of coupling constants is the consistent choice for this calculation which uses a d(e,e'K^+)YN code that currently only permits elementary KY amplitudes without baryon resonances (i.e. just Born terms). Interestingly, the predictions are in reasonable agreement with data for both peaks corresponding to Λ and Σ quasi-elastic production. The Σ peak includes the sum of the d(e,e'K^+)Σ^0n and d(e,e'K^+)Σ^-p inclusive cross sections. Considering that the curves are predictions (again, no parameters were adjusted), the results appear to confirm the simple quasi-elastic mechanism in which one of the target nucleons in the deuteron is a spectator. Further, final-state interaction effects are quite small as the use of plane waves in place of $\Psi_{\mathrm{YY}'}$ (no YN interaction) produces essentially the same quasi-elastic peak cross sections. Thus, the deuteron provides a good neutron target for extracting the n(e,e'K)Y cross sections. Such work is in process as well as a more thorough re-analysis using the improved elementary amplitudes [6] discussed in the previous section.

4. *Photoproducton of glueballs*

A profound consequence of QCD is that colored gluons can in principle combine to form color-singlet bound states with quarks (hybrid mesons) or without (glueballs). Investigating such states affords a direct test of the standard model. Lattice gauge results [14–16] indicate the lightest glueball states begin at 1.7 GeV. A recent constituent QCD Hamiltonian approach [3–5] has confirmed this result and is the only method to reproduce the lattice "measurements". This theoretical effective Hamiltonian method utilizes the QCD Coulomb-gauge Hamiltonian, regularized by cut-offs, and implements renormalization by a similarity transformation. Confinement is provided by a linear potential, and a BCS rotation is also performed from the current (low to zero mass) partons to a constituent quasi-particle basis. A variational calculation to minimize the ground state (vacuum) determines the BCS angle (gap equation). The resulting constituent quasi-particle quark and gluon masses and condensates are in good agreement with QCD sum-rules and lattice calculations. The method rigorously incorporates chiral symmetry, realized in the Nambu-Goldstone, yet manifests spontaneous chiral-symmetry breaking. The glueball states are then generated from this BCS vacuum by a Tamm-Dancoff and, for comparison, RPA calculation. The analysis was restricted to two explicit quasi-particle gluons, each having a dynamical mass about 1 GeV. The resulting gluonia spectrum (bars) is presented in Fig. 4 and is in very good agreement with three different "quenched" lattice simulations (boxes: dark [14], light [15], open [16]).

Experimental evidence is accumulating that some of these states exist but appear to mix with conventional mesons in this mass region having the same quantum numbers. It would seem appropriate to perform further searches at JLAB, especially when the proposed 12 GeV beam energy upgrade and additional meson detecting facilities become available. Depending on energy and quantum number selection rules, there are several mechanisms for electromagnetically producing these glueballs. In particular, Regge theory yields an energy dependence of s^a with $a = 1, 1/2$

and 0 for Pomeron, ρ and π t channel exchanges, respectively. Accordingly, a 12 GeV electron beam will facilitate energy "tuning" to optimize a specific exchange

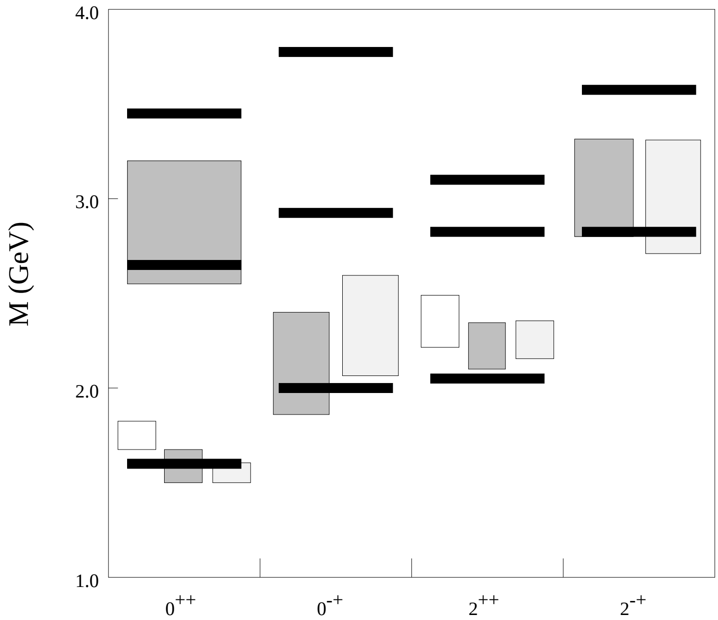


Fig. 4. Lattice gauge and QCD Hamiltonian model glueball spectra.

mechanism. Further, the complications from s-channel baryon resonance production can be mitigated by focusing upon large s and small t. Because the low-lying glueball spectrum has C parity equal $+1$, only t channel formation by vector-meson exchange is possible since C parity conservation excludes diffractive and π meson exchange production. Invoking vector-meson dominance, ρ and ω exchange should then be the dominant processes (ϕ exchange is OZI suppressed). Hence, the only quantities for estimating production of a $C = +1$ glueball G are two coupling vertices: $\rho\rho G$ and $\omega\omega G$ (isospin conservation precludes $\rho\omega G$), but implementing universality reduces this to one coupling. This coupling can be directly obtained from the roughly 50 MeV inferred [17] width for the ground state 0^{++} decay to $\rho\rho$. Predictions for glueball production rates based upon this model will soon be reported [18].

5. *Summary*

The significant findings in this paper are comparisons of the model calculations with the new JLAB kaon electroproduction data. Overall, the theoretical predictions were found to be in a reasonable agreement for both the elementary $K\Lambda$ process and YN production from the deuteron. However, further study is necessary to fully understand the elementary L/T separated cross sections. Also of future interest will be polarization measurements in Hall B, possible through the Λ self-analyzing weak decay. While new reaction data will enhance and constrain hadronic models, the possibility of extracting hyperon electromagnetic form-factors and perhaps even coupling constants provides even more significance for models at the quark level. Regarding production from the deuteron, a separate analysis of the two YN inclusive measurements, d(e,e'K^+)Σ^0n and d(e,e'K^+)Σ^-p is next in order which should provide new important information about the elementary n(e,e'K^+)Σ^- process.

Longer term, the anticipated JLAB beam energy upgrade will afford exciting glueball searches. Because mixing of these states with conventional mesons is expected to be substantial, future theoretical work should also focus upon decay mechanism to facilitate identification. Exotic states having quantum numbers forbidden for systems of quarks should also command intense scrutiny.

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References

1) G. Niculescu et al., Phys. Rev. Lett. **81** (1998) 1805; E93-018 Collaboration (O. K. Baker spokesperson);

2) J. Reinhold, E91-016 Collaboration (B. Zeidman spokesperson);

3) A. Szczepaniak, E. S. Swanson, C.-R. Ji and S. R. Cotanch, Phys. Rev. Lett. **76** (1996) 2011;

4) S. R. Cotanch, A. Szczepaniak, E. S. Swanson and C.-R. Ji, Quark *Confinement and the Hadron Spectrum* Vol. II, eds. N. Brambilla and G. M. Prosperi, World Scientific (1997) p. 342;

5) S. R. Cotanch, A. Szczepaniak, E. S. Swanson and C.-R. Ji, Nucl. Phys. A **631** (1993) 640;

6) R. A. Williams, C.-R. Ji and S. R. Cotanch, Phys. Rev. D **41** (1978) 1449; Phys. Rev. C **43** (1991) 452; *ibid.* **46** (1992) 1617; *ibid.* **48** (1993) 1318;

7) C. J. Bebek et al., Phys. Rev. D **17** (1978) 1693;

8) C. J. Bebek *et al.*, Phys. Rev. D **15** (1978) 3082;

9) F. Llanes and S. R. Cotanch, to be published;

10) S. R. Cotanch, Nucl. Phys. A **450**, (1986) 419;

11) S. S. Hsiao and S. R. Cotanch, *Proc. Int. Conf. on Medium and High Energy Nuclear Physics*, Taipei, Taiwan, World Scientific (1988) p. 368;

12) N. M. Nagels, T. A. Rijken and J. J. de Swart, Phys. Rev. D **15** (1977) 2547;

13) R. A. Adelseck et al., Phys. Rev. C **32** (1985) 1681;

14) UKQCD Collaboration. G. S. Bali et al., Phys. Lett. B **309** (1993) 378; Report No. hep-lat/9304012;

15) H. Chen, J. Sexton, A. Vaccarino and D. Weingarten, Nucl. Phys. (Proc. Suppl.) **22** (1994) 357; Report No. hep-lat/9401020;

16) M. Teper, Report No. OUTP-95-06P;

17) L. Burakovsky and P. Page, Report No. hep-lat/9807400;

18) A. Afanasev and S. R. Cotanch, to be published.

ELEKTROMAGNETSKA TVORBA HIPERONA I GLUONSKE LOPTE

Opisuje se analiza novih mjerenja elektrotvorbe kaona na protonskim i deuteronskim metama u Jefferson Lab. Uspoređuju se ishodi računa zasnovani na kvantnoj hadrodinamici s razdvojenim eksperimentalnim uzdužnim i poprečnim udarnim presjecima za elementarnu tvorbu $\mathrm{K}\Lambda$. Nalazi se također nesuglasje mjerenih podataka s predviđanjima modela za inkluzivna mjerenja d(e,e'K^+)YN s YN = Λn, Σ^0n i Σ^-p. Opća je ocjena da se mjerenja s protonskom i s deuteronskom metom dobro opisuju. Raspravlja se također tvorba gluonskih lopti, koja će biti moguća s predviđenom povećanom energijom snopa u Jefferson Lab, u svezi s ishodima računa s QCD Hamiltonovom funkcijom za niskoenergijski spektar gluonija.