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Search for Non-Nucleonic Degrees of Freedom in the Deuteron

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We propose to measure the cross-section for dual Δ photo-production from the deuteron ($\gamma d \rightarrow \Delta^{++}\Delta^{-}$) at large transverse momentum. It has been shown that a dramatic increase in the cross-section ratio of the dual Δ photo-production to the deuteron photo-disintegration, is a clear signature of a rigorous prediction of QCD namely: at short distances the deuteron wavefunction evolves into a state with 80% "hidden color." The proposed experiment would be performed in Hall C using a copper radiator to generate the bremsstrahlung photon beam which would be incident on a liquid deuterium target. The final state π^+ and p would be detected simultaneously in the SOS spectrometer in coincidence with the π^- detected in the HMS spectrometer.

PHYSICS MOTIVATION

As the simplest of nuclei, the deuteron is a natural candidate in the search for Quantum Cromodynamics (QCD) explanation of nuclear physics and for probing the transition from the nucleon-meson effective degrees of freedom to the quark-gluon degrees of freedom of QCD. Most of the successes of QCD are in the high energy regime where the quarks are almost free due to asymptotic freedom and one can use perturbative methods to perform precise calculations, however, at low energies or large distances the nucleon-meson description of the deuteron (i.e. deuteron as a bound state of a neutron and proton with the binding arising from exchange of mesons), agrees very well with experiments. In trying to map the transition between these two pictures of the nuclei, a natural question is; what happens to the nucleons inside the nucleus when they come close to each other? In QCD if the two nucleons are sufficiently close together, the quarks can reorganize and mix into a six-quark state which must be a color singlet [1]. However unlike the individual nucleons where the 3 quarks are in an unique color singlet state, the six quarks can form five different color singlet states. Only one out of the five color singlet states (or 20%) is nucleonic in nature. Thus at short distances, the deuteron state evolves into this combination of possibilities which has 80% probablility of being non-nucleonic [2], these states are sometimes also referred to as states with "hidden color". This 80% "hidden color" in the deuteron wavefunction is a rigorous prediction of QCD. At large distances the usual proton-neutron singlet combination is the dominant color configuration but at short distances all five color singlet states have equal weight and thus the deuteron wavefunction evolves into a 80% non-nucleonic ("hidden color") state. This argument can also be used to show that QCD requires the nucleon-nucleon force to be repulsive at short distances (with the nucleon-nucleon channel being one channel in a coupled channel system)[3]. As the nucleons approach each other the system must do work to change the six-quark state from nucleonic to a dominantly non-nucleonic state.

In our quest for signatures of QCD in nuclei, a search for phenomena which are indicators of these hidden color states is invaluable. The hidden color states of the deuteron can manifest as Δ^{++}(uuu)Δ^{-}(ddd) and other quantum fluctuations of the deuteron [4]. These dual hadron components become more and more important as one probes the deuteron at short distances, such

as via exclusive reactions at large transverse momentum, p_T. Therefore, the ratio;

$$\frac{\frac{d\sigma}{dt}(\gamma d \to \Delta^{++}\Delta^{-})}{\frac{d\sigma}{dt}(\gamma d \to np)}$$

should increase dramatically with increasing p_T. Over the past few years, all three halls at JLab have produced extensive data on the photo-disintegration of the deuteron [5]. Thus a clean measurement of the photo-production of dual Δ resonances ($\Delta^{++}\Delta^{-}$) on the deuteron at large C.M. angles, as a function of energy would be very helpful in confirming this unique prediction of QCD. An onset of the predicted large increase in the dual Δ states would be a clear indication of QCD in the deuteron.

THE PROPOSED MEASUREMENT

We propose to use the Hall C spectrometers SOS and HMS to measure the cross-section of the process $\gamma d \to \Delta^{++}\Delta^{-}$ at 90^0 C.M. angle at 3 different photon energies ranging from 2 to 4 GeV. In this experiment we will measure the decay products of the Δ resonances. The Δ^{++} will decay into a π^+ and a proton, both of which will be detected simultaneously in one spectrometer, namely the SOS. The Δ^{-} will decay into a π^{-} and a neutron, and in this case the π^{-} will be detected in the HMS in coincidence with the π^+ and proton. Thus this is a triple coincidence experiment using 2 spectrometers. This technique has been shown to work in a previous proposal PR-01-101, where existing data on the electroproduction of Λ hyperon from protons was used to show that it is possible to detect the decay products of the Λ (π^+ and proton) simultaneously in the same spectrometer (2 -track events) with very high efficiency.

Monte-Carlo simulation

We have performed a Monte Carlo simulation of the experiment to select the optimal kinematics for this triple coincidence experiment. This simulation also allows us to simulate various background processes which may be detected in the spectrometers along with the desired signal. The Monte Carlo simulation included the typical resolutions of the spectrometers, it also includes multiple scattering and energy loss of the particles as they traverses through the spectrometer, but it did not have a detailed model of the spectrometer optics. We chose kinematics such that both the π^+ and the proton from the Δ^{++} decay would fall within the acceptance of the SOS spectrometer. Several possible background processes were also simulated, these include; $\gamma + p \to \pi^+\pi^-p$ (here the Fermi motion of the proton inside the deuteron was included in the simulation), $\gamma + p \to \Delta^{++}\pi^-$, $\gamma + p$ (including Fermi motion)$\to \rho^0 p$ and ρ^0 decaying to π^+, π^- and $\gamma + D \to \pi^+\pi^-pn$. Among these only the last process contributes to the background for the kinematics chosen for this experiment. We were able to find just one measurement of this process in the literature, which was performed at SLAC using a 4.5 GeV photon beam [6]. However, only the total cross-section is quoted, thus we are unable to have a correct estimate of the cross-section for this background process at this time. If we assume a 2:1 cross-section ratio between the background process and the dual Δ production, we get an invariant mass spectrum as shown in Fig. 1 (at $E_\gamma = 2$ GeV).

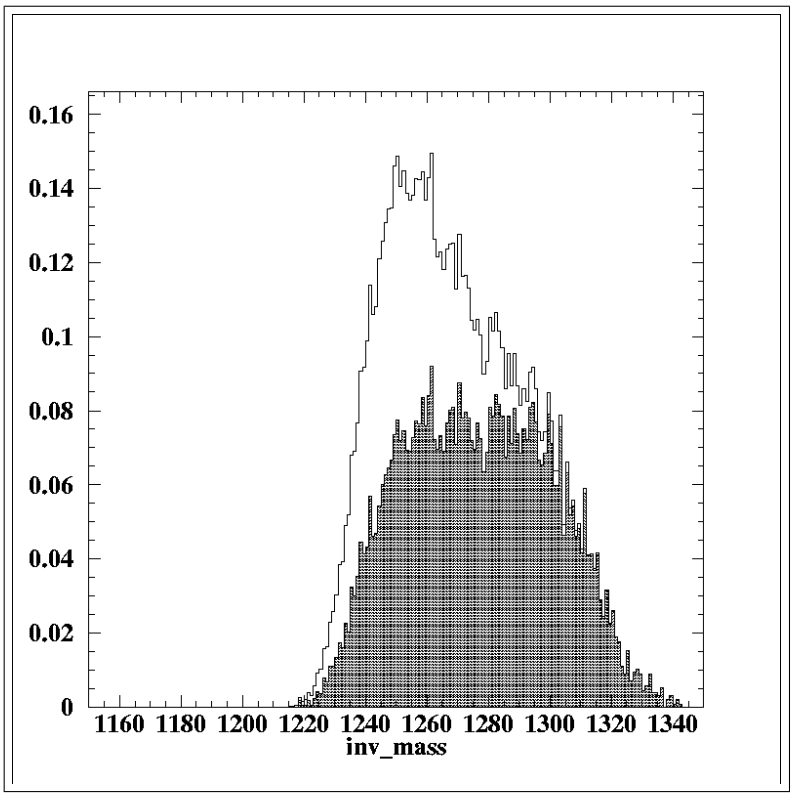

Fig. 1., The invariant mass spectra for the π^+p system for dual Δ and direct production process. Here the direct production is assumed to have a cross-section twice as large as the dual Δ production.

THE EXPERIMENT

The experiment would involve using a 50 μA CW electron beam incident on the Hall-C radiator (6% Cu) to produce a bremsrtahlung photon beam which is then incident on the Hall-C liquid Deuterium target. The π^+ and proton from the Δ^{++} decay will be detected simultaneously in the SOS while the π^- from the Δ^- decay will be detected in the HMS spectrometer. The photon energy can be reconstructed from the momentum and angle of the 3 detected particles. We will use a 100 MeV bin about 25 MeV below the photon endpoint for the production events. Restricting the kinematics to the highest photon energies helps eliminate several background processes. The missing mass and invariant mass spectra will be used to select the desired dual Δ production events. The cross-section can be extracted for these events with the aid of the Hall C Monte Carlo simulation. We will also collect data with the radiator removed from the beam, which will enable us to subtract the electroproduction background. The extracted cross-section along with the already available deuteron photo disintegration results at similar photon energies will be used to form a ratio as a function of energy.

Kinematic

The proposed kinematics are shown in table I

TABLE I: Table of kinematics for the $d(\gamma, \pi^+\pi^-p)n$ reaction at pion C.M. angle of 90°. The photon energy listed is 75 MeV less than the electron beam energy.

E_{beam}	E_γ	$\sqrt{s}$	$\theta_{(\pi^+/p)}$ (lab)	$P_{(\pi^+/p)}$	θ_{π^-}	P_{π^-}
GeV	GeV	GeV	deg	GeV/c	deg	GeV/c
2.0	1.925	3.277	46.5	0.65	46.5	0.65
3.0	2.925	3.807	44.0	1.0	44.0	1.0
4.0	3.925	4.271	39.5	1.3	39.5	1.3

RATE ESTIMATE AND BEAM TIME REQUEST

The rates for this experiment were estimated based on the analysis of g10 data from Hall-B, in that data we were able to show $\gamma d \rightarrow \Delta^{++}\Delta^-$ events by reconstructing the invariant mass vs the missing mass of the π^+, p system (for all π^+, π^-, p events) is shown in Fig. 2. These Δ^{++}, Δ^- events were seen in a 100 MeV photon energy bin around $E_\gamma = 1$ GeV and were centered around C.M. angle of 40 degrees. We were able to fit the missing mass spectrum to a resonance + background form as shown in Fig. 3. After subtracting the background we had an approximate count of desired events. Using the known luminosity and the C.M. angular distribution we estimated the event rate at E_γ =1 GeV. Assuming a similar C.M. angle dependence as the deuteron photo-disintegration and using the s^{-11} scaling assumption, we then estimated the rates at 90 degree C.M. angle and at $E_\gamma = 2$, 3 and 4 GeV. We then estimated the rates for Hall C and Hall A and found the Hall C rates to be more than a factor of 2 higher. The beam time estimate shown are for a 3%, 5% and 8% (stat uncertainty only) measurement at 2, 3 and 4 GeV respectively. The estimated beam time requirement is shown in Table II. However, if there is a dramatic enhancement in the dual Δ production cross-section at the highest energies, as predicted, the beam time requirements would also reduce dramatically. The beam time estimate shown in Table II is assuming there is no enhancement.

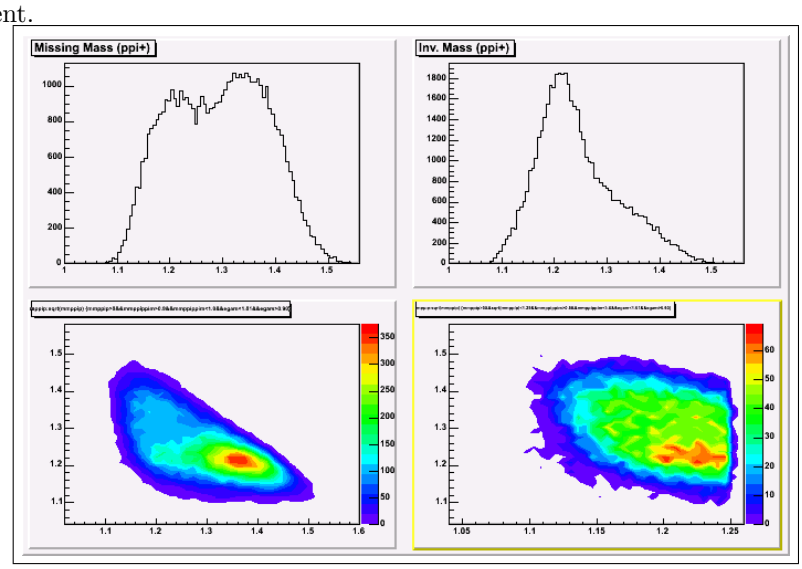

Fig. 2., The missing mass, invariant mass spectra for the π^+p system for all $\pi^-\pi^+p$ events. The lower panels show the 2-dimensional histograms of missing mass vs invariant mass, the lower right panel is a zoomed in version of lower left.

E_{beam}	$\sqrt{s}$	# of events	Radiator IN	Radiator OUT	Total
GeV	GeV		hrs	hrs	hrs
2.0	3.277	1000	10	3	13
3.0	3.807	400	90	30	120
4.0	4.271	150	330	100	430

TABLE II: Table of estimated beam time requirements

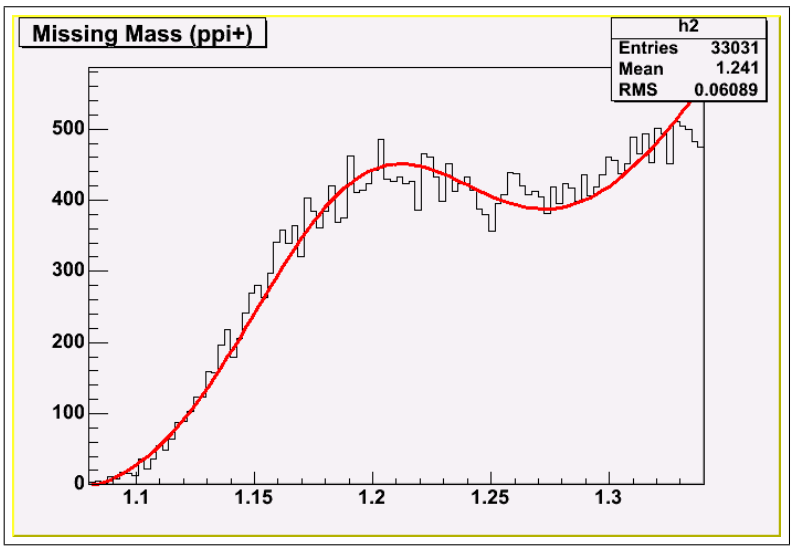

Fig. 3, Fit to the missing mass spectrum to determine the signal+background.

EXPECTED RESULTS AND UNRESOLVED ISSUES

The deuteron photodisintegration cross-section has been shown to obey the s^{-11} scaling [5] at the photon energies used in the proposed experiment. The dual Δ production cross-section is also expected to show the same scaling behavior, thus the ratio is expected to reach a constant at high transverse momentum, p_T. Brodsky *et al.* have estimated this ratio to be of the order of 0.1 to 1 at $\theta_{CM} = 90^0$ and $p_T \sim 2$ GeV/c [7]. At the highest photon energy proposed in this letter, p_T is ~ 2 GeV/c and thus we expect to have several order of magnitude enhancement in the cross-section compared to the cross-section at the lower energies. Such an enhancement would allow us to easily extend these measurements to the highest photon energies available at JLab and would also dramatically cut down the beam requirement for the experiment as proposed. This would be an exploratory measurement and if the results turn out to be promising more detailed measurements would become feasible.

One of the issues which we cannot address at this point is the contribution to the dual Δ events from final state production of Δs. We expect to get some theoretical guidance on this and other open issues and hope to address them before a full proposal is submitted.

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