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Proposal Title
SEARCH FOR JPC = 1-+ EXOTIC MESONS IN THE ELECTROPRODUCTION REACTIONS USING CLAS DETECTOR AT CEBAF.

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SEARCH FOR $J^{PC} = 1^{-+}$ EXOTIC MESONS
IN THE ELECTROPRODUCTION REACTIONS
USING CLAS DETECTOR AT CEBAF *

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ABSTRACT

This experiment will search for $J^{PC} = 1^{-+}$, $J^{PG} = 1^{--}$ exotic hybrids in electroproduction in the mass range up to $\approx 2$ GeV by detection of the $\eta \pi$, and $\eta' \pi$, pseudoscalar meson decay products. The signature for the exotic will be obtained from the measurement of the angular distributions of the reconstructed pseudoscalar mesons. There have been indications of these hybrids in hadronic production. Using estimates of the electroproduction cross section and the exotic hybrid branching fraction into $\eta \pi$ we expect $\sim 10000$ reconstructed hybrids in a 30 day running period with a $6 \text{ GeV}^{-}$ e$^{-}$ beam.

*Proposal for PAC9
1. Introduction

The gluon, the QCD gauge boson, carries color charge. It can have a component characterizing it as a force and a component characterizing it as a constituent particle\(^1\). It can thus act as a particle and experience a binding force to quarks arising from additional gluons interconnecting to the quarks. One thus expects a class of hadrons, hybrid mesons, comprised of a valence gluon bound to quarks, \(gq\). (In addition, there are expectations for the existence of a glueball meson consisting of a gluon loop, \(gg\) and for existence of hybrid baryons \(gqqq\)). QCD models have made a variety of predictions of the masses, widths, and decays of hybrid \(gqq\).\(^2,3,4,5,6\) Although evidence for gluons has been found in jet measurements and in deep inelastic scattering, an unambiguous signal of constituent glue has not been observed. The discovery of hybrids would be a strong confirmation of QCD and important for understanding the non-perturbative structure of hadrons.

A subset of the \(J^{PC} / J^{PG}\) hybrid exotics, has a simple detection signature. A bound system consisting of only a fermion - antifermion pair, i.e., a \(q\bar{q}\) system, lacks some members of its \(J \geq 1\) positive naturality (i.e., \(J^P = 1^-, 2^+, 3^-, \) etc) states. For a neutral meson, states with \(P \neq C\) will be lacking. These states have "exotic" quantum numbers and must have a constituent boson in addition to a \(q\bar{q}\) pair, i.e., the state is a hybrid. For a charged meson of isospin \(I\), states with \(G = (-1)^I P\) will be exotic.

The detection of a state with the exotic quantum quantum numbers \(J^{PC} = 1^{--}\) or \(J^{PG} = 1^{--}\), denoted by \(\hat{X}\), then unambiguously indicates a hybrid. Although nonexotic hybrids (i.e., hybrids with conventional quantum numbers) exist, disentangling them from \(q\bar{q}\) states with the same quantum numbers is difficult. Furthermore, nonexotic hybrid - \(q\bar{q}\) mixing may be appreciable.

In experimentally detecting exotic hybrids, the additive quantum number \(C/G\) is determined by final state particle identification. A determination of \(J\) and \(P\) from the meson's angular decay distribution pattern, \(W\), can then yield the existence of a \(J^{PC/G}\) hybrid exotic.

Most of the searches for exotics have used hadronic production, i.e., \(\pi^- p\) and \(p\bar{p}\) reactions characteristically yielding high statistics data. \(J/\psi\) decays have been studied, but with considerably lower statistics. \(e^+ e^-\) reactions have been used to search for exotic production via a \(2\gamma\) process, although exotic production cross sections are not expected to differ with that for hadronic production\(^7\).

Since a charged pion and a photon in a relative \(P\) wave (\(l = 1\)) can couple to the \(J^{PG} = 1^{--}\) exotic quantum numbers, electromagnetic production of these exotics by \(t\)-channel pion exchange may be competitive with hadronic production. Several experiments have investigated coherent nuclear production from incident charged \(\pi\) in the intense coulombic field of a high \(Z\) nucleus (Primakoff - like production). Experimental results for Primakoff production have been inconclusive.
2. Theoretical Predictions and Existing Data

Theory

Predictions have been made for hybrids in several different QCD models and have been presented in hadron spectroscopy workshop proceedings and reviews. All models in general predict $J^{PC}=1^{++}$ and $J^{PG}=1^{--}$ hybrids with masses at or below $2.0 GeV$. Widths in the range $\Gamma \sim 50 \rightarrow 200 MeV$ are favored. The predicted decay modes are uncertain. In some models, gluonic excitation does not transfer its spin to the final state mesons' relative orbital angular momentum and hybrid decay to two mesons with quark S-waves does not occur. However, other models predict such decay. It occurs through such effects as spurious bag CM motion, or through the sequential decay of the exotic hybrid into a nonexotic hybrid and then into a conventional meson via mixing. The nonexotic hybrid is mixed with a conventional meson which appears in the final state. In this description the $\pi\eta(\eta')$ have small constituent gluonic components. In general $Br_{\pi\pi} \sim 0.1$ and $Br_{\pi\pi}/Br_{\eta\pi} \sim 1/3$ is predicted.

Existing Data

Several experiments have examined the decay angular distribution in the $\pi\eta(\eta')$ final states in hadronic production in order to detect $J^{PC}=1^{++}$ and $J^{PG}=1^{--}$ exotic hybrid states. Although their results have not been conclusive, there is general indication of the existence of these states. (The subscript on a decay partial wave value indicates the naturality of a $t$-channel exchange in the limit $s \rightarrow \infty$, 0, -- indicates negative naturality, + is positive).

a) GAMS Experiment (CERN)

The reaction

$$\pi^- p \rightarrow \bar{X}^0 n; \bar{X}^0 \rightarrow \pi^0 \eta$$

was studied at the CERN SPS with a 100 GeV/c negative pion beam using the GAMS-4000 lead-glass hadoscopic calorimeter. The mass range $1.2 \leq m_{\bar{X}} \leq 1.6$ GeV was examined. Partial wave analysis (PWA) of this data shows a clear $a_2(1320)$ $D_0$ wave in the $\eta \pi^0$ system and a resonant structure in the $P_0$-wave at a mass 1.4 GeV (Fig.1a). Forward-backward asymmetry of the decay angular distribution in the Gottfried-Jackson frame of the $\eta \pi^0$ system was observed (Fig.1b). This is indicative of interfering D and P waves. The resonance was ascribed to a $\rho(1405)$ exotic. Questions, however, have arisen about the analysis (see Sec.4).

b) KEK Experiment

Forward-backward decay asymmetry in $\bar{X}^- \rightarrow \pi^- \eta$ has also been seen in the
reaction
\[ \pi^- p \rightarrow \hat{X}^- n; \hat{X}^- \rightarrow \pi^- \eta \]
at 6.3 GeV/c beam momentum (Fig.2a). PWA, as in GAMS, showed a clear D-wave of the \( a_2(1320) \) and a resonant structure in the P-wave (Fig.2b). \( m_{\hat{X}^-} \approx 1.32 \text{ GeV} \); obtained by a Breit-Wigner fit to the \( P_+ \)-wave. (This is 0.1 GeV less than that obtained by GAMS.

c) Fermilab Experiment E272 \(^{17,18,19}\)
A Primakoff production experiment has been carried out at Fermilab using a 202.5 GeV energy \( \pi^+ \) beam interacting with heavy nuclear targets (\( Pb, Cu \)). The measured reactions were:
\[ \pi^+ A \rightarrow \hat{X}^+ A; \hat{X}^+ \rightarrow \rho \pi^+; \eta \pi^+; D(1285)\pi^+ \]
The data showed that neither \( \rho^0 \pi^+ \) nor \( \eta \pi^+ \) are likely to be major decay modes of a hybrid with a mass below 1.5 GeV and width larger than 20 MeV. Upper limits of \( Br(\hat{X}^+ \rightarrow \rho \pi^+) \) of a few percent and \( \Gamma(\hat{X}^+ \rightarrow \gamma \pi^+) \cdot Br(\hat{X}^+ \rightarrow \eta \pi^+) \approx 15 - 25 \text{keV} \) (Fig.3a,b) were obtained in the experiment\(^{20}\). The \( D(1285) \) \( \pi^+ \) data indicated a relatively narrow structure at 1.6 GeV (Fig.3c). However \( J^P \) of this mode has not been determined.

d) VES Experiment (IHEP) \(^{21}\)
Possible \( \hat{X}^- \) decays to \( \eta \pi^- \) and \( \eta' \pi^- \) systems were studied in a high-statistics experiment at the IHEP VES setup using a \( \pi^- \) beam at momentum \( p_{\pi^-} = 37 \text{GeV} \) on a beryllium target. The reactions studied were:
\[ \pi^- N \rightarrow \hat{X}^- N; \hat{X}^- \rightarrow \pi^- \eta(\eta') \]
Partial-wave analysis were done for both reactions.
In the \( \eta \pi^- \) system the \( a_2^{-}(1320) \) \( D_+ \) wave was dominant. A \( P_+ \) wave with exotic quantum numbers appeared as a small, broad bump at mass \( M_{\pi^-} \approx 1.4 \text{ GeV} \) (see Fig.4a).
In the \( \eta' \pi^- \) system the intensity of the \( D_+ \) wave was small (branching ratio \( Br(a_2 \rightarrow \eta' \pi) \leq 0.01 \)). The largest wave in this system was \( P_+ \) (Fig.4b).
The intensity of \( P_+ \) waves in the both systems is shown in Fig.5. The authors\(^{21}\) conclude that the \( q\bar{q}g \) system could be the main component of \( P_+ \) wave. The relative strengths are consistent with a valence gluon hybrid, \( q\bar{q}g \), with \( J^{PC} = 1^{--} \) predicted by Close and Lipkin\(^ {19}\).

e) Photoproduction Experiments \(^{22,23}\)
Photoproduction data of hybrids is sparse. There are two reported experiments on photoproduction of hybrids that are not necessarily \( J^{PC} \) exotics. Final state meson systems other than \( \pi \eta \) (\( \eta' \)) were observed. There are no reported electroproduction experiments.
The first experiment was diffractive photoproduction of $b_1\pi$ system\textsuperscript{22}. There were two resonant structures for $m_{b_1\pi} \geq 1.5 \text{ GeV}$, Fig.6. The first structure was interpreted as the $\omega_2(1670)$. The second had a centroid mass of 1.8 $\text{ GeV}$ and a width $\leq 0.3 \text{ GeV}$. It was interpreted as a gluonic hybrid.

The second experiment was photoproduction of an isovector $\rho\pi$ meson system\textsuperscript{23}. A resonant structure was observed at an invariant mass of $(\rho\pi) 1.775 \text{ GeV}(\text{Fig.7a})$. The structure can not be interpreted as a $\pi_2(1670)$ due to significant mass shift ($\sim 100 \text{ MeV}$) and dominant $\rho\pi$ coupling (Fig.7b). The angular distribution of the decay in the Gottfried-Jackson frame was consistent with $J^P = 1^-; 2^-; 3^+$. 

3. Proposed Experiment

The experiment we propose is electroproduction of $\hat{X}$, with isospin 1, $J^{PC} = 1^{-+}$ and $J^{PG} = 1^{--}$ exotic hybrid from a hydrogen target. In electromagnetic production hybrids may be produced via vertices that do not exist in hadroproduction. Electroproduction allows measurements of couplings to polarization states not accessible with either a pion or real photon beam. Furthermore transition form factors can be measured. Electroproduction is the complement to the above Primakoff production method. The photon is now incident on the pionic field of a nucleon. The lack of a large nuclear coulombic field is compensated by a high incident flux of virtual photons.

We propose to use the CLAS to search for exotic hybrids in the $\pi^+\eta(\eta')$ and $\pi^0\eta(\eta')$ decay channels at $E_e = 6 \text{ GeV}$ beam energy. Reactions to be studied are:

$$ ep \rightarrow e'\hat{x}^+ n; \hat{x}^+ \rightarrow \pi^+\eta(\eta') $$ \hspace{2cm} (1)

$$ ep \rightarrow e'\hat{x}^0 p; \hat{x}^0 \rightarrow \pi^0\eta(\eta') $$ \hspace{2cm} (2)

where $\hat{x}^{(\delta)}$ are the charged/neutral $J^{PC} = 1^{-+} / J^{PG} = 1^{--}$ exotic hybrid mesons. One photon exchange diagram of reactions (1) and (2) are presented in Fig.8. Measurements will be done in the hadronic mass range $W \geq 2.6 \text{ GeV}$ and $Q^2 \geq 0.7(\text{GeV}/c)^2$. These final state mesons $\pi, \eta, \eta'$ will insure the desired G / C parity of the decaying meson.

The ability of the Hall B CLAS spectrometer to detect multiparticle final states will allow determination of the $J$ and $P$ from the angular distribution, $W(\theta, \phi, \Phi)$ of the pseudoscalar decay. Here $\theta$ is the decay polar angle, $\phi$ is the angle between the decay and hadron CMS planes and $\Phi$ is the angle between electron and hadron CMS planes (see Fig.9).

$W(\theta, \phi, \Phi)$ uniquely determines $J$ and $P$ since the relative orbital angular momentum of the two pseudoscalar mesons, characterizing $W(\theta, \phi, \Phi)$, equals $J$. The equality would not exist if the mesons had non-zero spin. $W(\theta, \phi, \Phi)$ also determines the polarization of the hybrid meson, i.e., the measurement is polarization "self analyzing". A second scattering measurement is not needed.
The polarization will indicate the electroproduction mechanism. For example if electroproduction is predominately by $t$-channel exchange of a spinless particle, e.g., a pion, the polarization determined by evaluating $W(\theta, \phi, \Phi)$ in the Gottfried-Jackson frame$^{24}$ will be that of the incident virtual photon as seen in this frame.

The C/G, J, P measurement will then identify a $J^{PC} = 1^{-+}$ or $J^{PG} = 1^{--}$ exotic.

Under some conditions, additional information can be obtained from the dependence of $W(\theta, \phi, \Phi)$ on the $m_{\pi\eta^{'}}$ invariant mass. This occurs when a electroproduced meson, M, has a mass lying nearby $m_{\pi}$. If M decays into the same final states into which the X decays, the electroproduction amplitudes for X relative to those of M can be obtained from the interference terms in $W(\theta, \phi, \Phi)$ (see Sec.8.2). An example in the mass region 1.2 - 1.4 GeV is the $a_2(1320)$ meson which has a $\approx 15\%$ branching ratio into $\eta \pi$. Additional measurements of $W(\theta, \phi, \Phi)$ at the $a_2(1320)$ mass centroid yield amplitudes characteristic of direct $a_2(1320)$ electroproduction. These can then be used with those obtained in the interference mass region to obtain absolute X production amplitudes.

4. Production Mechanism and Decay Analysis

The predominant electromagnetic production mechanisms of $J^{PG} = 1^{--}$ states can be estimated for forward scattering by using values of allowed hadronic couplings and VMD.

Electromagnetic production of positive $J^{PG} = 1^{--}$ mesons will proceed via the diagrams in Fig.10a. In our experiment we expect forward production of positive $J^{PG} = 1^{--}$ (also $a_2(1320)$) to proceed predominantly via $\pi^+$ exchange because of the large $\pi NN$ coupling.

Electromagnetic production of neutral $J^{PG} = 1^{--}$ mesons can go only through the C-odd exchanges of $\omega$ and $\rho$ (see diagrams Fig.10b). The left diagram in Fig.10b is dominant at small momenta transfers because:

(a) the coupling constant $g_{\omega \pi}$ is larger than $g_{\rho \pi}$: $g_{\omega \pi} \approx 4 \cdot g_{\omega \pi}$
(b) the coupling constant $g_{\rho \gamma}$ is larger than $g_{\omega \gamma}$: $g_{\rho \gamma} \approx 3 \cdot g_{\omega \gamma}$.

Since spin nonflip $g_{\omega \pi}$ is much larger then spin flip $g_{\omega \pi}$, in the forward direction the $X$ polarization equals that of the virtual photon. Production of neutral $J^{PC} = 1^{-+}$ system is dominated at small momentum transfer by spin-nonflip natural parity exchange (NPE).

In the analysis of the GAMS experiment $\pi^- p \rightarrow \pi^0 \eta n$, the exotic state $J^{PC} = 1^{-+}$ appears in the amplitude $P_0$, i.e. its production mechanism corresponds to unnatural parity exchange (UPE). At the same time, at the energies used in the experiment (100 GeV) the main contribution is expected to be $\rho$-exchange i.e. natural parity exchange (NPE). This was confirmed in the KEK$^{18}$ and VES$^{21}$ experiments, where in the reaction $\pi^- p \rightarrow \pi^- \eta (\eta')$ an exotic appears in the $P_+$ amplitude (NPE).
For this reason the results of the partial wave analysis of data from $^{15}$ are doubtful.

Decay analysis is simplified by the spins of the final states. These zero spins will uniquely determine the $J$ and $P$ of the exotic by measurement of the decay angular distribution, $W(\theta, \phi, \Phi)$.

Determination of $W(\theta, \phi, \Phi)$ will be done in an appropriate Lorentz frame. As noted previously, if pion t-channel exchange is predominant, the Gottfried - Jackson frame greatly simplifies analysis. Full analysis of cross section dependence from density matrices for electroproduction of spin one particles are given in Ref. $^{26,27,28}$. Calculations of the expected sensitivities to the production amplitudes in electroproduction are in progress. Estimates of the sensitivities in the photoproduction can be found in Appendix A.

5. Kinematics

The kinematics of the proposed experiment is based on the expected exotic's mass range ($m_\chi \approx 1.2 \, GeV \rightarrow 2.0 \, GeV$).

A 6 GeV beam energy is required to cover the masses of interest.

In Fig. 11a obtainable ranges of $W$ and $Q^2$ are shown. The CLAS magnetic field was set at 1/2 nominal value in order to detect the range of the scattered electrons, bending inwards the toward the beam axis. Lowering the magnetic field has little effect on the resolution of reconstructed mass and angles which is dominated by the electromagnetic calorimeter resolution for the final states photons.

The $\hat{X}$ mass range necessitates $W \geq 2.6 \, GeV$; the maximum value of $W$ is 3.1 GeV. The $\hat{X}$ mass range is shown in Fig. 11b. Corresponding ranges of the scattered electron energy and polar angle are shown in Fig. 11c. The $m_\chi$ dependence of $t_{\text{min}}$ is shown in Fig. 11d for the above range of $W$ ($t_{\text{min}}$ is the minimum value of 4 - momentum transfer at the hadron scattering vertex).

Low values of $t_{\text{min}}$ result in high cross section values, particularly if t - channel pion exchange predominates.

The kinematic variables $\nu, Q^2$ and $W$ will be determined by detection of the scattered electron. The four-momenta of the $\hat{X}$ will be reconstructed from the detected $\pi^+$ and reconstructed $\eta$ or $\eta'$ decay mesons in reaction (1) and from the detected proton in reaction (2).

Vertex definition will not be problem since in all proposed reactions there are at least two charged particles in the final states.
6. Acceptance Simulations

As noted above, the hybrid exotics will be studied via decay modes: \( \pi^+\eta, \pi^+\eta', \pi^0\eta \) and \( \pi^0\eta' \). Reconstruction of \( \pi^0 \) and \( \eta \) mesons will be done by detection of their two photon decay in the CLAS electromagnetic shower calorimeter. For the \( \eta \) mesons the two photon decay branch is \( Br(\eta \rightarrow \gamma\gamma) = 0.39 \). \( \eta' \) reconstruction will be by the \( \rho\gamma \) decay mode \( (Br(\eta' \rightarrow \rho\gamma) = 0.3) \). The final detected particles in the reactions (1) and (2) are:

\[
\begin{align*}
(1) & \quad \hat{X}^+ \Rightarrow \pi^+\eta : e^+ \pi^+ \gamma \gamma \\
& \quad \hat{X}^+ \Rightarrow \pi^+\eta' : e^+ \pi^+ \pi^+ \pi^- \gamma \\
(2) & \quad \hat{X}^0 \Rightarrow \pi^0\eta : e^+ p \gamma \gamma \gamma \\
& \quad \hat{X}^0 \Rightarrow \pi^0\eta' : e^+ p \pi^+ \pi^- \gamma \gamma
\end{align*}
\]

Event simulation and reconstruction in the CLAS was performed using the SDA program\textsuperscript{29}. The CLAS electromagnetic calorimeter \( \gamma \) response was simulated by use of the GEANT\textsuperscript{30} and EGI\textsuperscript{31} codes. The resulting \( \gamma \) response was parameterized and incorporated into the SDA simulations.

An event generator was written to simulate \( t \)-channel photo- and electroproduction from a proton target. The \( t \) behavior of the cross section and decay angular correlation, \( W(\theta, \phi, \Phi) \), was determined.

Events were generated as functions of \( W \), (hadron vertex cm energy), \( Q^2 \), (\( \gamma \) invariant mass squared), \( \Phi \) (electron - hadron plane angle), \( m_\chi, t \), and \( \Omega_{GJ} \), (spherical angle of decay mesons in the Gottfried-Jackson frame).

Calculations of acceptances and resolutions for each of the four final states were made at \( W = 3.0 \text{ GeV} \) and \( Q^2 = 1.0 \text{ (GeV/c)}^2 \), the average minimum \( Q^2 \) for \( W = 2.6 \rightarrow 3.1 \text{ GeV} \), at \( 6 \text{ GeV} \) beam energy and for \( 1/2 \) magnetic field.

A typical CLAS event pattern for a \( ep \Rightarrow p\pi^+\gamma\gamma \) reaction is shown in Fig.12.

Acceptances for the reactions (1) are shown in Fig.13 and 14. Similar results were obtained for the reaction (2). The acceptances vary smoothly with \( m_\chi, t \), and \( \Omega_{GJ} \). There are no gaps in \( \Omega_{GJ} \), important in partial wave analysis. The acceptance for the \( \pi^+\eta \) final state, \( A_{\pi^+\eta} \approx 11\% \). Acceptances for the other final states were:

\[
A_{\pi^+\eta'} \approx 4\%; \quad A_{\pi^0\eta} \approx 4.5\%; \quad \text{and} \quad A_{\pi^0\eta'} \approx 1\%.
\]

In this calculations, \( 3\sigma \) cuts were used on all three reconstructed masses (\( \sigma_{\pi^0} = 17 \text{ MeV}, \sigma_{\eta} = 35 \text{ MeV} \) and \( \sigma_{\eta'} = 20 \text{ MeV} \)).

Two photon invariant mass distributions, \( m_{\gamma\gamma} \), for \( \pi^0 \) (dashed histogram) and \( \eta \) (solid histogram) are shown in Fig.15a. Reconstructed mass of \( \eta' \) is shown in Fig.15b.

In reactions (1) the outgoing neutron is not detected. To suppress background, discussed later, a cut was made on the neutron missing mass. This eliminated semi-inclusive \( \pi\eta(\eta') \) final states accompanied by high multiplicity.

The simulated mass, \( t \), \( \Omega_{GJ} \) and \( \phi \) resolutions for \( \hat{X}^+ \) are shown in Fig.16 and 17.

For the neutral \( \hat{X}^0 \) reactions in (2), we use the proton information for mass and \( t \).
reconstruction. It significantly improves the resolution (see Fig.18). Distributions for $\theta_{GJ}$ and $\phi$ remain the same.

7. Cross Section and Counting Rate

There is no reported data on electromagnetic production of the $J^{PC} = 1^{-+}$ hybrid. However $a_2(1320)$ ($J^{PC} = 2^{++}$) photoproduction data and measured upper limits to Primakoff nuclear $J^{PC} = 1^{-+}$ hybrid production exist. From these the estimated photoproduction cross section $\sigma_X = 0.9 \ [m]b$ (see Appendix B).

The estimated $X$ photoproduction cross section can be extended to electroproduction (see Appendix B):

\[
\frac{d^2\sigma_{ep \rightarrow X+n}}{dQ^2dW} = \Gamma_e \cdot F_\rho \cdot \sigma_X
\]

where $\Gamma_e$ is the Mott cross section and $F_\rho$ is a factor based upon $\gamma \rightarrow \rho$ VMD conversion.

For $W = 3.0 \ GeV$ and $Q^2 = 1.0 \ (GeV/c)^2$, $\Gamma_e \cdot F_\rho = 3 \cdot 10^{-4}$. This yields a cross section is $\approx 2.7 \cdot 10^{-4} \ mu b \cdot (GeV/c)^{-3}$.

For comparison, the inclusive (ee') cross section at $Q^2 = 1.0 (GeV/c)^2$ and $W = 3.0 \ GeV$ is $3 \cdot 10^{-2} \ mu b \cdot (GeV/c)^{-3}$.

Table 1 shows the estimated count rates for $\Delta W = 0.6 \ GeV$ and $\Delta Q^2 = 0.5 \ (GeV/c)^2$ and 30 days running period with $E_e = 6 \ GeV$ electron beam on hydrogen target at total luminosity $L = 10^{34} \ cm^{-2} \ sec^{-1}$.

<table>
<thead>
<tr>
<th>Process</th>
<th>Decay Modes and Br. Ratios</th>
<th>Acc.</th>
<th>Counts</th>
</tr>
</thead>
<tbody>
<tr>
<td>$ep \rightarrow e'X^+$</td>
<td>$X \rightarrow \eta \pi^+$</td>
<td>0.1</td>
<td>$\eta \rightarrow \gamma \gamma$</td>
</tr>
<tr>
<td>$ep \rightarrow e'X^+$</td>
<td>$X \rightarrow \eta' \pi^+$</td>
<td>0.3 : 1.4*</td>
<td>$\eta' \rightarrow \pi^+ \pi^- \gamma$</td>
</tr>
<tr>
<td>$ep \rightarrow e'a_2^+n$</td>
<td>$a_2^+ \rightarrow \eta \pi^+$</td>
<td>0.15 :</td>
<td>$\eta \rightarrow \gamma \gamma$</td>
</tr>
</tbody>
</table>

\* Using $Br(X^+ \rightarrow \pi \eta') = 3 \cdot Br(X^+ \rightarrow \pi \eta)$ and phase space factor for $\eta'$ of 1.4.

8. Background

Coherent and incoherent background for $X$ identification will arise from multiparticle final state events. For example, in the electromagnetic shower calorimeter one
photon from each $\pi^0$ in a $\pi^+\pi^0\pi^0$ final state can be confused with a $\pi^+\eta \to \pi^+\gamma\gamma$ final state. This incoherent background, as shown below, can be minimized by narrow kinematic cuts.

8.1. Incoherent Background

Incoherent background was estimated for the final states in reaction (1) using CELEG code\textsuperscript{32} as an event generator. The program includes baryon resonances up to $\sim 2.5 GeV$ in mass. In the deep inelastic region CELEG uses the Lund Monte-Carlo program LEPTO\textsuperscript{33}. The relatively large value of $W (W \geq 2.6 \text{ GeV})$ needed for this experiment results in background arising predominately from the deep inelastic scattering region rather than the resonance region.

A total of $2 \cdot 10^5 \, ep$ interactions were generated in the range of $W = 2.5 \to 3.1 \text{ GeV}$ and $Q^2 \geq 0.7 (\text{GeV/c})^2$. The ratio of differential cross sections for reaction $ep \to e'X^+$ and $ee'$ is $\approx 10^{-2}$ (see Sec.7). After simulation of the CLAS detector efficiency for these events the final states were reconstructed. The two photon invariant mass spectrum from final states that have $e'\pi^+\gamma\gamma$ tracks, (total 461 events) is shown in Fig.19a. Clearly seen two $m_{\gamma\gamma}$ mass peaks corresponding to $\pi^0$ (401 events) and $\eta$ (34 events). These events were contained within 3-$\sigma$ cuts. When an additional 3-$\sigma_{M_n}$ cut was made on the missing recoil neutron mass only two events resulted under $\eta$ peak (Fig.19b), the suppression is $\zeta \approx 10^{-5}$. Using the branching ratios and CLAS acceptances, the resulting ratio of $ep \to e'X^+$ to background count rates is $\approx 25\%$.

A similar estimation for the $\pi^+\eta'$ final state of (1) resulted in an upper limit for background contribution of $< 20\%$.

8.2. Coherent Background

Coherent background arises from production of conventional mesons that decay to the specific final states in (1) and (2). However only a limited number of them, i.e., those with natural spatial and C parity, (i.e., $J^{PC} = 0^{++}$, $1^{--}$, $2^{++}$),... decay to $\pi\eta$ or $\pi\eta'$ final states. The decay angular distribution partial wave analysis that is necessary for the $J^{PC} = 1^{--}$ exotics will permit additional identification of these conventional mesons (see end of Sec.3).

Among the well known mesons in the mass range $m_M \geq 1.3 \text{ GeV}$ only the $2^{++}$ $a_2(1320)$ has a large relative with and branching ratio to $\pi\eta$ (see Appendix B).

There are no known mesons with significant branching ratio to the $\pi\eta'$ final state. ($\text{Br}(a_2(1320) \to \pi\eta') < \% 3^4$).

Hence the $a_2(1320)$ appears to be the only other meson in this mass range having the final states of reactions (1) and (2). In previous experiments with $\pi$ beams (see Sec.2) the signature of exotics was found in accompaniment with the $a_2^{13,16,21}$. In the Table 1. we show the estimated rate for $a_2^+(1320)$ electroproduction under the
same kinematic conditions and decay meson systems as the exotic production. The estimated statistics will allow reliable analysis to determine the hybrid and $a_2(1320)$ meson properties.

9. Summary

The quark model allows the existence of hybrids, hadrons having a constituent gluon in addition to the constituent quarks. Hybrid mesons can have exotic $J^{PC}$ or $J^{PG}$ quantum numbers, unequal to those of a $q\bar{q}$ pair. Such mesons offer a unique signal of hybrids. A variety of hadronic, $e^+e^-$, Primakoff production, pion induced production in a nuclear coulombic field, and $J/\psi$ decay experiments have ambiguous indications of hybrids. Two photoproduction experiments, detecting $b_1\pi$ and $\rho\pi$ decay channels, yielded similar results. Electroproduction experiments have not been reported.

This experiment will search for a $\hat{X}^0$, $J^{PC} = 1^{-+}$, $J^{PG} = 1^{--}$ exotic hybrid meson in electroproduction using the Hall B CLAS detector. The mass range of $\hat{X}^{+0}$ will be up to $\approx 2$ GeV. The hybrid will be unambiguously reconstructed through the $\eta\pi^{+0}$ and $\eta'\pi^{+0}$ decay channels. In addition the zero spins of the decay channel mesons permit unique determination of the $J$ and $P$ of the exotic hybrid by measurement of the decay angular distribution, $W(\theta, \phi, \Phi)$. The polarization of the hybrid and hence the electroproduction helicity amplitudes can additionally be determined from $W(\theta, \phi, \Phi)$, giving a powerful tool in determining the production mechanism.

A thirty day run time period is requested at a beam energy of 6 GeV. Based upon a cross section upper limit obtained from charged $X$ Primakoff production data and the assumption of predominance of pion $t$-channel exchange for $\hat{X}^+$ production, the number of reconstructed events is expected to be $\approx 5,000 - 10,000$. (CLAS acceptance efficiencies for the final states are $\approx 5 \rightarrow 10\%$). The background count rate is expected to be in order of 1/4 of the signal. The electromagnetic production cross section of $\hat{X}^0$ cannot be estimated due to lack of data relating to diagrams having $\hat{X}^0$ vertices not violating C parity.

Because of the relatively large value of $W$ used in the search, $W \leq 3$ GeV, the CLAS magnetic field will set at half its nominal value in order to optimize acceptance of the outgoing $e^-$. Trigger requirements are an electron with one positive track. Target will be high pressure hydrogen gas.
10. Appendix A: Sensitivity to Photoproduction Amplitudes

Sensitivities to \( \bar{X} \) production amplitudes obtained from \( W(\theta, \phi, \Phi) \) measurements and characteristic of a 30 day run were estimated, (see Table 1). Photoproduction was chosen as illustrative. The \( \bar{X} \) was assumed to lie above and interfere with the \( a_2 \). Equal widths were assumed for both mesons. The mass bin chosen for the decaying mesons was the lower quarter of the \( \bar{X} \) mass distribution. It was positioned to overlap the upper quarter of the \( a_2 \) mass distribution. There were thus \( \approx 5,000 \) analyzed events in the mass bin. The resulting phase angle between the \( \bar{X} \) and the \( a_2 \) was \( \approx 160^\circ \) and was approximately constant. Assuming pion t - channel exchange results in the T matrix being diagonal in helicities. The decay angular distribution in the Gottfried Jackson frame is then:

\[
W(\theta) \sim 5 \sin^2 \theta \cos^2 \theta + |a_T|^2 \sin^2 \theta + 2\sqrt{3} \sin^2 \theta \cos \theta \Re(a_T)
\]

where \( a_T \) is the (complex) transverse amplitude of the \( \bar{X} \) relative to the transverse \( a_2 \). \( \Re(a_T) \) is the real part of \( a_T \). \( a_T \) was chosen = 0.3, resulting in a \( \bar{X} \) cross section 1/10 that of the \( a_2 \).

A least squares fit was made to a simulation of the above decay angular distribution for the 5,000 events in the mass bin (4500 \( a_2 \), 500 \( \bar{X} \)). This is \( \approx 1/5 \) the estimated yield of \( \bar{X}^+ \rightarrow \pi^+\eta \) given in Table 1. The width of the mass bin was chosen such that 1/4 of the Breit-Wigner distribution of each resonance was included. The resulting relative errors in the measured values of \( |a_T| \) and \( \frac{\Re(a_T)}{|a_T|} \) were 6 % and 3 % respectively.

The front-back asymmetry is, from the above expression for \( W(\theta, \phi, \Phi) \):

\[
\frac{3 \sqrt{3} \Re(a_T)}{5 + |a_T|^2}
\]

For the amplitude values chosen above, the value of the asymmetry is \( \approx 40 \% \) with relative error \( \approx 3 \% \).

Even though there may be substantial amplitude for \( \bar{X} \) production, asymmetry measurements may be small in regions where \( a_T \) is mostly imaginary. Asymmetry measurements can, however, obtain \( \Im(a_T) \) from the photon transverse - transverse interference parts in polarized real photoproduction and electroproduction.

11. Appendix B:

Photo and Electroproduction Cross Sections

Assuming that the electromagnetic production of both the hybrid \( \bar{X} \) (\( J^{PC} = 1^{-+} \)) and \( a_2 \) is by \( \pi \) t-channel exchange, upper limits to \( J^{PC} = 1^{-+} \) hybrid photoproduction
cross section can be estimated by using radiative decay widths and the $a_2$ photopro-duction cross section\textsuperscript{38}:

$$
\sigma_\gamma^\gamma = \frac{3}{5} \cdot \frac{\Gamma(\hat{X} \to \gamma \pi)}{\Gamma(a_2 \to \gamma \pi)} \cdot \sigma_\gamma^2
$$  \hspace{1cm} (1)

The assumption of $\pi$ t-channel exchange in $a_2(1320)$ photoproduction is based upon measurements\textsuperscript{35} indicating the predominance of this diagram. For $\hat{X}$ photoproduction, as mentioned earlier, Primakoff production is thought to be dominated by a similar t channel exchange with $\gamma \leftrightarrow \pi$. The values of the $\gamma$ and $\pi$ propagators are approximately equal since $m_\gamma^2 \approx m_\pi^2 = 0$. Upper vertex form factor differences are negligible. The lower vertex, $\pi N N$, is obviously the same for both $a_2$ and $\hat{X}$ production. Eq.\textsuperscript{(10)} is calculated for charged $a_2^\pm$ and ($\rho^+ = \hat{X}^+$) hybrid states.

The radiative width of the $a_2$ is known\textsuperscript{34}:

$$
\Gamma(a_2 \to \gamma \pi) \approx 300 \text{ keV}
$$  \hspace{1cm} (2)

An upper limit of 20 keV is used for $\Gamma(\hat{X} \to \gamma \pi) \cdot Br(\hat{X} \to \eta \pi)$ (see Fig.4b). It is based\textsuperscript{20} upon the measured $\hat{X} \to \rho \pi$ decay angular distribution in $\hat{X}$ Primakoff production in the $m_\pi$ range of $\sim 1.1 \to 1.5$ GeV. Assuming reasonable 10% branching ratio for $\hat{X} \to \eta \pi$ we will have

$$
\Gamma(\hat{X} \to \gamma \pi) \approx 200 \text{ keV}
$$  \hspace{1cm} (3)

Note that for counting rate the value of $Br(\hat{X} \to \eta \pi)$ is not important.

The photoproduction cross section $\sigma_\gamma^\gamma$ is obtained from the measurements of reaction $\gamma p = n a_2^+ = n \rho^0 \pi^+ = n \pi^+ \pi^+ \pi^- \bar{\rho}$ in the energy range $E_\gamma = 3.7 \to 4.7$ GeV corresponding to the energy range of this proposal. It was measured:

$$
\sigma_{a_2^+ \to \rho^0 \pi^+} \approx 0.8 \mu b
$$

After scaling by the known\textsuperscript{34} branching ratios $Br(a_2^+ \to \rho^0 \pi^+) = 0.35$ the $\gamma p \to a_2^+ n$ photoproduction total cross section was determined:

$$
\sigma_{\gamma p \to a_2^+ n} = 2.3 \mu b
$$  \hspace{1cm} (4)

Then using the values (2), (3) and (4) in equation (1):

$$
\sigma_{\gamma p \to \hat{X}^+ n} \leq 0.9 \mu b
$$  \hspace{1cm} (5)

The estimated $\hat{X}$ photoproduction cross section can be extended to electropro-duction by expressing $\sigma_{\gamma p \to \hat{X}^+ n}$ in terms of its longitudinal and transverse components $\sigma_L$ and $\sigma_T$:

$$
\frac{d^2 \sigma_{\gamma p \to \hat{X}^+ n}}{dQ^2 dW} = \Gamma_e \cdot (\sigma_T + \epsilon \sigma_L)
$$  \hspace{1cm} (6)
where $\Gamma_\varepsilon$ is the Mott cross section, i.e., flux of transverse virtual photons

$$\Gamma_\varepsilon = \frac{\alpha}{4\pi} \cdot \frac{W^2 - m^2}{m^2 E^2} \cdot \frac{W}{Q^2} \cdot \frac{1}{1 - \varepsilon}$$

(7)

$\varepsilon$ is the virtual photon polarization parameter

$$\varepsilon = \left(1 + \frac{2Q^2 + \nu^2}{4EE' - Q^2}\right)^{-1}$$

(8)

and $E$, $E'$ and $m$ are initial and scattered electron energies and the proton mass, respectively and $\nu = E - E'$.

The VMD formalism can be used to approximate $\sigma_T$ and $\sigma_L$. We use the Sakurai model$^{36}$. It is a convenient hadronically based approximation in which the incident virtual photon is converted to a vector meson (VM) which has the same quantum numbers as the $\gamma V$ (vector meson dominance, VMD). The transverse and longitudinal cross sections are:

$$\sigma_T = \left(\frac{e}{f_{VM}}\right)^2 \left(\frac{m_p^2}{m_p^2 + Q^2}\right)^2 \cdot \sigma_{VM \rho \rightarrow X+n}^T$$

(9)

$$\sigma_L = \left(\frac{e}{f_{VM}}\right)^2 \left(\frac{m_p^2}{m_p^2 + Q^2}\right)^2 \frac{Q^2}{m_p^2} \cdot (1 - x)^2 \cdot \xi(Q^2, \nu) \cdot \sigma_{VM \rho \rightarrow X+n}^T$$

(10)

The factor $\left(\frac{e}{f_{\rho}}\right)^2 \frac{m_p^2}{m_p^2 + Q^2}$ describes the VMD process $\gamma \rightarrow \rho$; the denominator on the right is the (off shell) $\rho$ propagator; the other terms describes the $\gamma \rho$ vertex$^{37}$. $\frac{Q^2}{m_p^2}$ is the longitudinal component of a relativistic spin 1 state in the Lorentz gauge; see, e.g., Ref. $^{38}$, $x = \frac{Q^2}{2m_\rho}$ the Bjorken scaling variable, $m_\rho$ is the $\rho$ mass. $\xi(Q^2, \nu)$ scales this model to the data. Vector meson electroproduction measurements in the $Q^2$ range of this proposal are best describes $\xi(Q^2, \nu) \approx 0.5$ $^{39}$.

Inserting the expressions for $\sigma_T$ and $\sigma_L$ into (15) and expressing the VM cross sections in terms of photoproduction, i.e.,

$$\sigma_{VM \rho \rightarrow X+n}^T = \left(\frac{e}{f_{VM}}\right)^{-2} \sigma_{\gamma \rho \rightarrow X+n}$$

(11)

we obtain the electroproduction cross section:

$$\frac{d^2\sigma_{\gamma p \rightarrow X+n}}{dQ^2 dW} = \Gamma_\varepsilon \cdot F_\rho \cdot \sigma_{\gamma \rho}$$

(12)

where

$$F_\rho = \left(\frac{e}{f_{\rho}}\right)^2 \left(\frac{m_p^2}{m_p^2 + Q^2}\right)^2 \cdot \left(1 + \frac{Q^2}{2m_p^2} (1 - x)^2\right)$$

(13)
29. B. Niczyporuk, CLAS simulation program SDA, private communication.
30. GEANT, CERN Library
32. CELEG Event Generator, CLAS-NOTE-89-0004
39. D. Cassel et al, Phys. Rev. D24, p. 2787 (1981), Fig.19
Figure 1: GAMS experiment: (a) - intensity distribution of the $P_0$ wave. (b) - dependance of forward-backward asymmetry in the GJ frame on invariant mass of $\eta \pi^0$ system.

Figure 2: KEK experiment: (a) - Observed forward-backward asymmetry in the GJ frame. (b) - Intensity distributions of partial waves.
Figure 3: Estimated upper limits for the branching ratios and radiative widths for $\rho^0\pi^+$ - (a) and $\eta\pi^+$ - (b) final states in Primakoff production. (c) - observed peak in the $\pi^+D$ system.
Figure 4: Results of the VES experiment. Partial wave intensity distribution in the (a) $\eta\pi$ and (b) $\eta'\pi$ decay meson systems.

Figure 5: Matrix element squared of the $P_+$ wave in the $\eta\pi^-$ – o and $\eta'\pi^-$ – o systems.
Figure 6: Yields of the reaction $\gamma p \rightarrow \pi^+\pi^-\pi^+\pi^-\pi^0p$ as a function of $\omega \pi \pi$ mass. o o o - contribution of $\omega_3$, .... - contribution of another resonance.

Figure 7: Distribution of events in the reaction $\gamma p \rightarrow p\pi^+n \rightarrow n\pi^+\pi^+\pi^-$ as a function of $M(3\pi)$ (a). The $\pi^+\pi^-$ spectrum for events with $1.7 \leq M(3\pi) \leq 1.9GeV$ (b).
\( q = (k - k') \)
\( W = (q + p_p)^2 = 2.6 \text{GeV} - 3.1 \text{GeV} \)
\( Q^2 = -q^2 > 0.7 (\text{GeV}/c)^2 \).

Figure 8: One photon exchange diagram for meson electroproduction. \( k, k' \) and \( q \) are four-momenta of primary and scattered electrons and virtual photon, \( p_p, p_N \) and \( p_X \) are four-momenta of target proton, recoil nucleon and produced meson, respectively.

Figure 9: Electron scattering, hadron CMS (XYZ) and decay (\( x'z' \)) planes are shown. \( \Phi \) is the angle between the electron and the hadron planes, \( \theta \) is the polar angle of decay particle in the rest frame of decayed meson, \( \phi \) is the angle between decay and \( x'z' \) planes.
Figure 10: Diagrams corresponding to the production of exotic mesons in the reactions
\( \gamma^* p \rightarrow \bar{X} N \): (a) - \( \bar{X}^+ \rightarrow \pi^+ \eta(\eta') \), (b) - \( \bar{X}^0 \rightarrow \pi^0 \eta(\eta') \)
Figure 11: Simulation of kinematics for the reaction $ep \rightarrow e'XN$ at a beam energy 6 GeV and 1/2 strength magnetic field. (a) - $Q^2$, $W$ range accepted by CLAS, (b) - $M_x$ acceptance for $W > 2.6$ GeV, (c) - scattered electron energy and polar angle distribution, (d) - minimum $t$ v.s. measured hybrid mass for $W > 2.6$ GeV.
Figure 12: Simulated $e^p \rightarrow e^\prime \pi^+ \gamma \gamma$ event in the CLAS detector: The tracks are labelled: 1 - electron, 2 - neutron, 3 - $\pi^+$, 4,5 - photons.
Figure 13: Dependence of CLAS acceptance for the $e'\pi^+\gamma\gamma$ final state: (a) - on invariant mass of $\pi^+\gamma\gamma$ system, (b) - on transfer momenta $t$, (c) and (d) - on polar and azimuthal angels in the GJ frame.
Figure 14: The same as in Fig. 13 for the final state $e'\pi^+\pi^+\pi^-\gamma$. 
Figure 15: (a) - mass spectrum of reconstructed $\pi^0$ ($\sigma_{\pi^0} = 17\text{MeV}$) and $\eta$ ($\sigma_\eta = 35\text{MeV}$) from $2\gamma$ events, (b) - reconstructed $\eta'$ ($\sigma_{\eta'} = 20\text{MeV}$) from $\pi^+\pi^-\gamma$ events.
Figure 16: Simulated $M_\chi$, $t$, $\theta_{GJ}$ and $\phi_{GJ}$ resolutions (a), (b), (c) and (d) respectively) for the process $\hat{X} \rightarrow \pi^+\eta$. 
Figure 17: The same as in Fig.16 for the process $\hat{X} \to \pi^+\eta'$. 
Figure 18: Resolutions of reconstructed $M_{\bar{X}}$ and $t$ in the reaction $ep \rightarrow e'p\bar{X}^0$ from the detected proton.
Figure 19: Reconstructed invariant mass spectrum of two photons detected by the electromagnetic shower calorimeter from simulated $e'\pi^+\gamma\gamma$ events.

Figure 20: Reconstructed missing mass spectrum of neutrons in the reactions $ep \rightarrow e'\pi^+\gamma\gamma$ - (a) and $ep \rightarrow e'\pi^+\pi^+\pi^-\gamma$ - (b).
HAZARD IDENTIFICATION CHECKLIST

CEBAF Proposal No. ___________________________  Date: ________________

Check all items for which there is an anticipated need.

<table>
<thead>
<tr>
<th>Cryogenics</th>
<th>Electrical Equipment</th>
<th>Radioactive/Hazardous Materials</th>
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Other: ________________
BEAM REQUIREMENTS LIST

List all combinations of anticipated targets and beam conditions required to execute the experiment. (This list will form the primary basis for the Radiation Safety Assessment Document (RSAD) calculations that must be performed for each experiment.)

<table>
<thead>
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<th>Condition #</th>
<th>Beam Energy (MeV)</th>
<th>Beam Current (μA)</th>
<th>Polarisation and Other Special Requirements (e.g., time structure)</th>
<th>Target Material (use multiple rows for complex targets — e.g., w/ windows)</th>
<th>Target Material Thickness (mg/cm²)</th>
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The beam energies, $E_{\text{Beam}}$, available are: $E_{\text{Beam}} = N \times E_{\text{Linac}}$ where $N = 1, 2, 3, 4, \text{ or } 5$. For 1995, $E_{\text{Linac}} = 800$ MeV, i.e., available $E_{\text{Beam}}$ 800, 1600, 2400, 3200, and 4000 MeV. Starting in 1995, in an evolutionary way (and not necessarily in the order given) the following additional values of $E_{\text{Linac}}$ will become available: $E_{\text{Linac}} = 400, 500, 600, 700, 900, 1000, 1100, \text{ and } 1200$ MeV. The sequence and timing of the available resultant energies, $E_{\text{Beam}}$, will be determined by physics priorities and technical capabilities.
LAB RESOURCES REQUIREMENTS LIST

CEBAF Proposal No.: ___________________   Date: ___________________

(For CEBAF User Liaison Office use only)

List below significant resources — both equipment and human — that you are requesting from CEBAF in support of mounting and executing the proposed experiment. Do not include items that will be routinely supplied to all running experiments, such as the base equipment for the hall and technical support for routine operation, installation, and maintenance.

Major Installations (either your equip. or new equip. requested from CEBAF)

________________________________________________________________________

________________________________________________________________________

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New Support Structures:

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________________________________________________________________________

Data Acquisition/Reduction

Computing Resources:

________________________________________________________________________

________________________________________________________________________

New Software:

________________________________________________________________________

________________________________________________________________________

Major Equipment

Magnets

________________________________________________________________________

Power Supplies

________________________________________________________________________

Targets

________________________________________________________________________

Detectors

________________________________________________________________________

Electronics

________________________________________________________________________

Computer Hardware

________________________________________________________________________

Other

________________________________________________________________________

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Other

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