Spin and parity measurement of the $\Lambda(1405)$ baryon

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A determination of the spin and parity of the $\Lambda(1405)$ is presented using photoproduction data from the CLAS detector at Jefferson Lab. The reaction $\gamma + p \rightarrow K^+ + \Lambda(1405)$ is analyzed in the decay channel $\Lambda(1405) \rightarrow \Sigma^0 + \pi^-$, where the decay distribution to $\Sigma^0\pi^-$ and the variation of the $\Sigma^+$ polarization with respect to the $\Lambda(1405)$ polarization direction determines the parity. The $\Lambda(1405)$ is produced, in the energy range $2.55 < W < 2.85$ GeV and for $0.6 < \cos\theta_{\gamma p}^{\Lambda(1405)} < 0.9$, with polarization $P = 0.45 \pm 0.02$ (stat) $\pm 0.07$ (syst). The analysis shows that the decays are in $S$ wave, with the $\Sigma^+$ polarized such that the $\Lambda(1405)$ has spin-parity $J^P = \frac{1}{2}^-$, as expected by most theories.

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The $\Lambda(1405)$ has long been a peculiar state in the spectrum of excited hyperons. Lying just below the $N\bar{K}$ threshold, there is no universal agreement on the nature of this state. The constituent quark model for $P$-wave baryons [1], which has had success in describing the nonstrange low-mass baryons, has difficulty in computing the correct mass. More recently, the chiral unitary wave baryons [1], which has had success in describing the $Y\pi$ decays strongly into $N\bar{K}$ final states [9, 11]. A rapid falloff of the line shapes was observed [4, 5]. Only a state that couples to $\Sigma^+$, where

$$Y \rightarrow N\bar{K}$$

by $\hat{\gamma}$, which is transferred from $Y\pi$ to $Y$, called $\bar{Q}$ in Fig. 1, is related to the odd-$L$ $t_L^{\bar{M}}$. One finds that the longitudinal polarization of $Y$ along $\hat{q}$, the decay direction in the $Y^*$ rest frame, will be independent of the parity of $Y^*$, while the transverse polarization will change sign depending on the parity. Since the parity of the $Y^*$ is determined by the orbital angular momentum $L$ of the decay $Y^* \rightarrow Y\pi$, and since a measurement of $\bar{Q}$ determines $L$, the parity can be found.

\begin{equation}
I(\theta_Y) \propto 1 + \frac{3(1 - 2p)}{2p + 1} \cos^2 \theta_Y,
\end{equation}
A schematic of two polarization transfer scenarios depending on the parity of the $Y^*$ is shown in Fig. 1. In the case of spin $\frac{1}{2}$, the use of an unpolarized beam and target restricts the polarization of the $Y^*$ to be in the direction out of the production plane specified by $\vec{P} = \vec{P} \hat{z}$ in Fig. 1. It can be shown that for an $S$-wave decay ($J^P = \frac{1}{2}^-$) of $Y^* \to Y \pi$, $\vec{Q}$ is independent of $\theta_Y$ and is given as $\vec{Q} = \vec{P}$; that is, it retains the same polarization as that for the $Y^*$, so that $Q_z = P$. For a $P$-wave decay ($J^P = \frac{1}{2}^+$), it is given by

$$\vec{Q} = -\vec{P} + 2 \left(\vec{P} \cdot \hat{q}\right) \hat{q}, \quad (2)$$

so that although the magnitude is unchanged, the direction depends on $\vec{q}$. If a component measurement is made of the polarization along the original $Y^*$ polarization direction, then $Q_z = P/(2 \cos^2 \theta_Y - 1)$ so that at $\cos \theta_Y = 0$, $Q_z$ must have the opposite sign compared to $\cos \theta_Y = \pm 1$.

In all cases, the polarization of a ground state hyperon can be measured by the weak decay asymmetry in its decay distribution into a nucleon and pion. Therefore, by measuring the polarization of the $Y$ for different decay directions in the $Y^*$ rest frame, we can deduce the parity of the $Y^*$. This method requires that the original $Y^*$ be produced polarized, but beyond that, there are no further assumptions necessary to uniquely determine the spin and parity.

The setup of the CLAS experimental run g11a used in this analysis has been explained in Ref. 9, and further details are also available. Based on the results of our previous analyses [9, 10], we select kinematic ranges where the $\Lambda(1405)$ is the dominant contribution in the $\Sigma\pi$ mass range of interest. The nine bins of energy and angle we select have c.m. energies $W$ centered at 2.6, 2.7, and 2.8 GeV, and for each energy bin, the three forwardmost kaon angle bins were used. The detected particles were $K^+, p$, and $\pi^-$, with a kinematic fit applied to select events with a missing $\pi^0$.

Figure 2(a) shows the $\Sigma^+\pi^-$ invariant mass $M(\Sigma^+\pi^-)$ for these nine bins combined, where the $\Lambda(1405)$ and $\Lambda(1520)$ are seen, along with background contributions from $K^+\Sigma^0(1385)$ and $K^0\Sigma^+$ production. In the present analysis the backgrounds could not be removed event by event. Events were selected based on the $\Sigma^+\pi^-$ invariant mass range of 1.30-1.45 GeV/$c^2$, where the spectrum is dominated by the $\Lambda(1405)$. Backgrounds due to non-$\Lambda(1405)$ production were estimated in previous works, where beside the channels listed above, a $Y^*(1670)$ background was used to parametrize the higher-mass data. We estimate these backgrounds as approximately 16% total, mostly from the $\Sigma^0(1385)$.

Figure 2(b) shows a Dalitz-like plot of the $\Sigma^+\pi^-$ invariant mass $M(\Sigma^+\pi^-)$ versus the mass $M(K^+\pi^-)$, where a slight overlap of the $K^0\Sigma^+$ events (vertical band) with the $\Lambda(1405)$ and $\Lambda(1520)$ events (horizontal bands) is seen. Due to the kinematics of the reaction, the overlap is not significant and has little influence in these kinematic bins.

For each of the nine bins of $W$ and kaon angle, each spin-parity hypothesis was tested with maximum likelihood fits to the data using a MC simulation of the data that was matched to have the same $\Sigma^+\pi^-$ invariant mass distribution as the data but generated without any angular correlations. The fit functions used joint probability distributions of the $\Sigma^+\pi^-$ angular decay distribution and the $p\pi^0$ weak decay distribution. The $\Sigma^+\pi^-$ distribution was isotropic for spin $\frac{1}{2}$ and as given in Eq. (1) for spin $\frac{3}{2}$. The $p\pi^0$ weak decay distribution used $I(\theta_p) \propto 1 + \alpha_0 Q_2 \cos \theta_p$, with the polarization $Q_2$ as a fit parameter, and $\theta_p$ is the proton decay angle in the $\Sigma^+$ rest frame. Figure 3 shows sample distributions of data and MC events for $\cos \theta_{\Sigma^+}$ (our specific $\sin \theta_{\Sigma^+}$) and $\cos \theta_p$. The nonflatness of the $\cos \theta_{\Sigma^+}$ distribution reflects the CLAS acceptance, which varies significantly depending not only on $\cos \theta_{\Sigma^+}$ and $\cos \theta_p$ but also the azimuthal angles for each distribution. We see from Fig. 3 that the unweighted MC that was generated with isotropic distributions is able to reproduce the data well for the $\cos \theta_{\Sigma^+}$ distribution, lending support to the spin $\frac{3}{2}$ hypothesis. However, the $\cos \theta_p$ distribution requires a reweighting of MC events with a polarization to match the data, and it is this polarization of the data that allows a strong discrimination among the different hypotheses.

The $\frac{1}{2}^+$ hypotheses were tested but showed no significant deviation from an isotropic $\Sigma^+\pi^-$ decay distribution, and the parameter $p$ given in Eq. (1) was seen to be consistent with $\frac{1}{2}$ (unpolarized). For each separate hypothesis, each of the MC events was assigned a weight according to its fitted intensity. The resulting distribution was compared with the data to calculate a $\chi^2$ probability. The $\chi^2$ probability calculated for the $\cos \theta_p$ dis-
distribution had the most discriminating power, and the $\frac{1}{2}^-$ case consistently had the best $\chi^2$ probability. In our nine independent kinematic bins, the $\frac{1}{2}^+$ and $\frac{3}{2}^-$ hypotheses are typically ruled out by $3\sigma$ or more from the $\chi^2$ probabilities and can be excluded. The three parameters describing the $\frac{3}{2}^+$ hypothesis can conspire to exactly mimic the behavior of a $\frac{1}{2}^-$ state, so definitive exclusion based on statistical tests is impossible. Fits to the $\frac{3}{2}^+$ hypothesis had worse $\chi^2$ probabilities in all energy bins, but we also excluded it by assuming the simpler hypothesis with fewer parameters is correct.

For the cases of spin-parity $\frac{3}{2}^\pm$, the two distinct behaviors of the transferred polarization allow a simple visual illustration. Independent fits were performed in separate bins of $\cos \theta_{\Sigma^+}$. An example of the polarization $Q_z$ in the $\hat{z}$ direction for one bin of $W$ and angle is shown in Fig. 4. As a function of $\cos \theta_{\Sigma^+}$, the polarization clearly does not change sign between the extremes of $\cos \theta_{\Sigma^+} = \pm 1$ and $\cos \theta_{\Sigma^+} = 0$, as would be expected from Eq. (2). We can compute the probability of each hypothesis and while the $\frac{1}{2}^-$ hypothesis consistently gives a good $\chi^2$ probability, the $\frac{1}{2}^+$ hypothesis is ruled out in its most favorable bin by at least $3.6\sigma$ and is typically ruled out by more than $5\sigma$. With nine independent $W$ and angle bins, the $\frac{1}{2}^+$ hypothesis is overwhelmingly ruled out.

The $\Sigma^+$ polarizations using all events in each kinematic bin with the $\frac{1}{2}^-$ hypothesis are shown in Table I. Since in this situation the polarization that is measured through $\Sigma^+$ is equivalent to the polarization of the $\Lambda(1405)$ itself, the $Q_z$ values in Table I represent measurements...
of the $\Lambda(1405)$ polarization.

To ensure that the polarization we observe is not affected by the $\Sigma^0(1385)$, the range of $\Sigma^+\pi^-$ invariant mass was changed to reduce this contribution. With a range of $1.40 - 1.48$ GeV/$c^2$, we estimate the contribution of the $\Sigma^0(1385)$ as 6%, and a change in polarization of 0.06 was observed. Removal of events with the $K^+\pi^-$ invariant mass within $\pm 1\Gamma$ of the $K^{*0}$, where $\Gamma$ is the full width of the $K^{*0}$, gave a change of 0.02 in the final result.

As a final check that the CLAS detector is able to measure decay distributions without bias using this method, the polarization components along the $x$ and $y$ directions were measured. If the $\Lambda(1405)$ is a state of $\frac{1}{2}^-$, then the polarization components in the production plane should be zero. Table I shows that the measured components $Q_x$ and $Q_y$ are mostly consistent with zero within the statistical errors. Using these fits to estimate the systematic uncertainty of the analysis in measuring these polarizations accurately, we take $\pm 0.03$ as an upper limit for this systematic uncertainty. We add the upper limit polarization components in the $x$ and $y$ directions, the uncertainty due to varying the $\Sigma^{+}\pi^-\pi^0$ mass range, and the uncertainty due to the $K^{*0}$ removal in quadrature to obtain the final systematic uncertainty of $\pm 0.07$.

To summarize, our analysis indicates that the spin-parity of the $\Lambda(1405)$ is fully consistent with $J^P = \frac{1}{2}^-$, while the $\frac{1}{2}^+$ and $\frac{3}{2}^-$ combinations are strongly disfavored. The $\frac{3}{2}^+$ combination cannot, in principle, be ruled out by statistical tests, but it did not lead to better fits, and so it is rejected. The decay angular distribution is consistent with isotropy, which strongly favors spin $\frac{1}{2}$, and under this assumption, a direct measurement of the parity has been carried out for the first time. The data strongly indicate negative parity, due to the unchanging direction of the daughter $\Sigma^+$ polarization with respect to the $\Lambda(1405)$ polarization direction. Thus, this first complete experimental test of the $\frac{1}{2}^-$ hypothesis confirms most long-held expectations. As an additional outcome, the polarization of the $\Lambda(1405)$ in photoproduction has been measured to be $0.45 \pm 0.02 \text{(stat)} \pm 0.07 \text{(syst)}$ in the forward kaon angle region for $2.55 < W < 2.85$ GeV.

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| $W$ (GeV) | $\cos \theta_{K^+}^{m}$ | $Q_x$ | $Q_y$ | $Q_z = |\vec{P}|$ |
|-----------|-----------------|--------|--------|-----------------|
| 2.55–2.65 | 0.60–0.70       | $-0.06 \pm 0.06$ | $-0.02 \pm 0.06$ | $0.38 \pm 0.05$ |
| 2.55–2.65 | 0.70–0.80       | $-0.04 \pm 0.05$ | $0.01 \pm 0.05$ | $0.43 \pm 0.05$ |
| 2.55–2.65 | 0.80–0.88       | $-0.09 \pm 0.07$ | $0.06 \pm 0.07$ | $0.47 \pm 0.06$ |
| 2.65–2.75 | 0.60–0.70       | $-0.09 \pm 0.07$ | $-0.11 \pm 0.06$ | $0.36 \pm 0.07$ |
| 2.65–2.75 | 0.70–0.80       | $0.03 \pm 0.06$ | $0.08 \pm 0.06$ | $0.59 \pm 0.06$ |
| 2.65–2.75 | 0.80–0.86       | $0.14 \pm 0.09$ | $-0.01 \pm 0.09$ | $0.38 \pm 0.08$ |
| 2.75–2.85 | 0.60–0.70       | $0.05 \pm 0.08$ | $-0.11 \pm 0.08$ | $0.40 \pm 0.08$ |
| 2.75–2.85 | 0.70–0.80       | $-0.02 \pm 0.07$ | $0.08 \pm 0.07$ | $0.55 \pm 0.06$ |
| 2.75–2.85 | 0.80–0.86       | $-0.05 \pm 0.09$ | $-0.13 \pm 0.10$ | $0.48 \pm 0.09$ |
| Full range | Full range       | $-0.03 \pm 0.02$ | $0.00 \pm 0.02$ | $0.45 \pm 0.02$ |

TABLE I. Measured $\Sigma^+$ polarization components with statistical uncertainties in the $x$, $y$, and $z$ directions for each kinematic bin. The $z$ direction is the out-of-plane production and polarization direction. The $y$ direction is the initial-state proton axis, and the $x$ direction is $\hat{y} \times \hat{z}$.