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Electroproduction of the Roper Resonance as a Hybrid State

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Abstract

The Q^2 dependence of the helicity amplitudes for the Roper resonance as a hybrid state is presented. Our study shows that the magnitude of the transverse helicity amplitude decreases rapidly as Q^2 increases, while the longitudinal helicity amplitude vanishes for the hybrid state. This feature is quite different from the prediction of the q^3 potential quark model, in which the Roper resonance is assumed to be an orbitally excited state. The comparison with data shows that the hybrid interpretation of the Roper is favoured. Future experiments at CEBAF can provide the information needed to definitely determine the spin-flavour content of this resonance.

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1. Introduction

Recently, it has been shown[1] that there should be a gluonic partner state of the nucleon whose ratio of the magnetic moments and photoproduction helicity amplitudes is $-\frac{3}{2}$ between proton and neutron. It is possible that the Roper resonance is such a hybrid state, because the Roper resonance is predicted about $100 \sim 150$ MeV higher than the experiment data in the potential quark model. The crucial test will be the transition properties of this state, especially, the electromagnetic transition which is sensitive to the structure of wavefunctions. A hybrid state is excited in the spin-flavour space, whose $SU(6)$ spin-flavour wavefunction is orthogonal to that of the nucleon, while in the q^3 potential quark model, the Roper resonance is assumed to be the orbitally excited state, whose spin-flavour wavefunction is the same as that of the nucleon. The difference between the spin-flavour excitation and orbitally excitation for the Roper resonance will have quite different phenomenological consequences in their electromagnetic transition, specially in Q^2 dependence of the helicity amplitudes in the electroproduction. In this paper, we present our result of the Q^2 dependence of the helicity amplitudes in the electroproduction for the Roper resonance as a hybrid state and an orbitally excited three quark state. Our investigation shows that the transverse helicity amplitude for a hybrid state decreases faster than the helicity amplitude for a orbitally excited state, while the longitudinal helicity amplitude for a hybrid state vanishes in contrast to the large longitudinal helicity amplitude predicted for a orbitally excited state at small Q^2. Because of these major differences, precise data on the electroproduction of the Roper resonance will provide very important information on its spin-flavour correlation. Thus, it is quite possible that the nature of the Roper resonance can be determined in future experiments at CEBAF.

2. Transverse Transition Amplitude

The wavefunction of the nucleon with gluonic degrees of freedom can be written as[1]

$$|N\rangle = \frac{1}{\sqrt{1+2\delta^2}}\left[|N_0\rangle - \delta(|^4N_g\rangle + |^2N_g\rangle)\right], \tag{1}$$

where $|N_0\rangle$ represents the wavefunction for a three quark system, which is **56** SU(6) multiplet for protons and neutrons[2], $|^4N_g\rangle$ and $|^2N_g\rangle$ are the wavefunctions for a q^3G system with the total quark spin $\frac{3}{2}$ and $\frac{1}{2}$[3], which transform as **70** multiplet of SU(6), and the parameter δ is determined by the quark-gluon vertex. The wavefunction given by Eq. 1 preserves the success of the q^3 quark model, specially the ratio of magnetic moments between the proton and the neutron. The corresponding orthogonal state of the nucleon in the spin-flavour space is

$$|N', J=\frac{1}{2}\rangle = \sqrt{\frac{2}{(1+2\delta^2)}}\left[\delta|N_0\rangle + \frac{1}{2}\left(|^2N_g\rangle + |^4N_g\rangle\right)\right] \tag{2}$$

whose ratio of magnetic moments and the photoproduction amplitudes between the proton and the neutron is also $-\frac{3}{2}$.

The transverse helicity amplitude is given by

$$A_\lambda = 3\sqrt{\pi k}\mu_0 \langle N,\ J,\ \lambda | e_3 \left[\sigma_3^+ + 2i \left(\sigma_3 \times \frac{\mathbf{J}_3^{TE}}{\omega_g} \right)^+ \right] e^{(ikz_3)} | N,\ J = \frac{1}{2},\ \lambda - 1 \rangle, \quad (3)$$

where the first term comes from the normal quark-photon vertex and the second from the $\gamma q \to qG$ process, (see Ref. 1 for detail). Assume the spatial wavefunction in Eq. 2 has a Gaussian form, we have an explicit expression for $A^p_{\frac{1}{2}}$;

$$A^p_{\frac{1}{2}} = \frac{4\sqrt{2}}{3} \delta \sqrt{\pi k} \mu_0 e^{\left(-\frac{k^2}{6\alpha^2}\right)}, \quad (4)$$

where the parameter α^2 is determined by the harmonic oscillator potential. Furthermore, it also measures the average charge radius of the nucleon and hybrid state. Since a hybrid configuration consists of at least four particles, its charge radius should be larger than that of the nucleon, which means the parameter α is even smaller. The study[1] in the real photon limit shows that the parameters $\delta = -0.35$ and $\alpha = 0.25$ GeV give a good systematic description of the helicity amplitudes for the Roper resonance, $P_{31}(1550)$, $P_{13}(1540)$ and $P_{33}(1600)$, which are the candidates for the hybrid states.

Following the procedure of Foster and Hughes[4] and without introducing the ad hoc form factor, we extend the Eq. 4 to electroproduction, in which the photon becomes a virtual photon. In Fig. 1, we show the Q^2 dependence of $A^p_{\frac{1}{2}}$ for the Roper resonance as a hybrid state and an orbitally excited state of the nucleon in comparison with fits to experimental data. We have adopted the formalism of Koniuk and Isgur[5] for the Roper resonance as an orbitally excited state, in which the QCD configuration mixing effects has not been considered. It should be pointed out that the wavefunction of the Roper resonance in the Isgur and Karl model is particularly sensitive to the wavefunction of the nucleon; because the wavefunction of the nucleon is mixed in two harmonic oscillator shells[6], while the Roper is mixed in one shell[7], the wavefunctions of the Roper resonance and the nucleon used in the photoproduction amplitude calculation[8,9] are not orthogonal to each other, which leads to a very large photoproduction amplitude in the mixed basis given by Isgur and Karl model. This is misleading, the physical states of the Roper and the nucleon must be orthogonal to each other. In fact the calculation by Weber[10] has shown that the mixing effect will reduce the photoproduction amplitude for the Roper.

Our calculation shows that the transverse helicity amplitudes should decrease very quickly to zero as Q^2 increases. This is because a hybrid state is not orbitally excited, the corresponding helicity amplitudes will have different Q^2 dependences in the nonrelativistic limit. Generally,

$$\frac{A^p_{\frac{1}{2}}(q^3G; N=0)}{A^p_{\frac{1}{2}}(q^3; N=2)} \sim \frac{1}{k^2} \sim \frac{1}{Q^2} \quad (5)$$

where Q^2 becomes large. Therefore the $A^p_{\frac{1}{2}}$ for a hybrid state decreases faster than that for the radial excitation state as Q^2 increases. One may argue that the nonrelativistic quark model fails at large Q^2. However, in a pQCD description[11], a q^3G state is a higher configuration relative to the three quark states, therefore, the $A^p_{\frac{1}{2}}$ for a hybrid state should decrease faster than the $A^p_{\frac{1}{2}}$ for an orbitally excited three quark state at large Q^2.

3. Longitudinal Transition Amplitude

The difference in the electroproduction between a hybrid state and a radial excited state becomes more transparent when one calculates the longitudinal helicity amplitudes for these states. A longitudinal electromagnetic field is given by

$$A^L_\mu = \sqrt{\frac{4\pi}{2k_0}}\epsilon^L_\mu e^{i\mathbf{k}\cdot\mathbf{r}} \tag{6}$$

where the polarization vector ϵ^L_μ is defined as

$$\epsilon^L_\mu = \{\epsilon_0,\ 0,\ 0, \epsilon_z\} = \left\{\frac{k_z}{\sqrt{Q^2}},\ 0,\ 0,\ \frac{k_0}{\sqrt{Q^2}}\right\} \tag{7}$$

so that

$$k^\mu \cdot \epsilon_\mu = 0, \tag{8}$$

where one choses the photon momentum $\mathbf{k} = \{0,\ 0,\ k_z\}$. In the norelativistic limit, the corresponding electromagnetic interaction $H^L_{e,m}$ for a longitudinal field in three quark systems is

$$H^L_{e,m} = \sum_j \sqrt{\frac{2\pi}{k_0}} e_j \left\{\epsilon_0 e^{i\mathbf{k}\cdot\mathbf{r}_j} - \frac{\epsilon_z}{2m_q}\left[p_{z,j}e^{i\mathbf{k}\cdot\mathbf{r}_j} + e^{i\mathbf{k}\cdot\mathbf{r}_j}p_{z,j}\right]\right\}, \tag{9}$$

where e_j and m_q is the charge and mass of a valence quark. It can be shown[12] that Eq. 9 can be written as

$$H^L_{e,m} = \sum_j \sqrt{\frac{2\pi}{k_0}} e_j \left\{\epsilon_0 e^{i\mathbf{k}\cdot\mathbf{r}_j} - \frac{\epsilon_z}{k_z}\left[H, e^{i\mathbf{k}\cdot\mathbf{r}_j}\right]\right\} \tag{10}$$

where

$$H = \sum_i \frac{p_i^2}{2m_i} + \sum_{i<j} V_{ij} \tag{11}$$

is the Hamiltonian for a quark–gluon system. Therefore, the transition matrix elements are

$$\begin{aligned}\langle\Psi_f|H^L_{e,m}|\Psi_i\rangle &= \sum_j \sqrt{\frac{2\pi}{k_0}}\langle\Psi_f|e_j\left\{\epsilon_0 e^{i\mathbf{k}\cdot\mathbf{r}_j} - \frac{\epsilon_z}{k_z}\left[H, e^{i\mathbf{k}\cdot\mathbf{r}_j}\right]\right\}|\Psi_i\rangle \\ &= \sum_j \sqrt{\frac{2\pi}{k_0}}\langle\Psi_f|e_j\left\{\epsilon_0 - \frac{\epsilon_z(E_f - E_i)}{k_z}\right\}e^{i\mathbf{k}\cdot\mathbf{r}_j}|\Psi_i\rangle. \end{aligned} \tag{12}$$

For the photon transition, the energy difference between the initial and final state equals to the photon energy, that is

$$E_f - E_i = k_0 \tag{13}$$

and notice that

$$\begin{aligned}\epsilon_0 - \frac{\epsilon_z k_0}{k_z} &= \frac{1}{k_z}\left(k_z\epsilon_0 - k_0\epsilon_z\right)\\ &= \frac{1}{k_z\sqrt{Q^2}}\left(k_z^2 - k_0^2\right)\\ &= \frac{\sqrt{Q^2}}{k_z},\end{aligned} \tag{14}$$

we have

$$\langle\Psi_f|H^L_{e,m}|\Psi_i\rangle = \sum_j \sqrt{\frac{2\pi}{k_0}}\frac{\sqrt{Q^2}}{k_z}\langle\Psi_f|e_j e^{i\mathbf{k}\cdot\mathbf{r}_j}|\Psi_i\rangle. \tag{15}$$

The longitudinal helicity ampltude can be written as

$$\begin{aligned}S_{\frac{1}{2}} &= \frac{k_z}{\sqrt{Q^2}}\langle N,\ J,\ \lambda = \frac{1}{2}|H^L_{e,m}|N=0,\ J=\frac{1}{2},\lambda=\frac{1}{2}\rangle\\ &= \sum_j \sqrt{\frac{2\pi}{k_0}} 2m_q\mu_p\langle N,\ J,\ \lambda=\frac{1}{2}|q_j e^{i\mathbf{k}\cdot\mathbf{r}_j}|N=0,\ J=\frac{1}{2},\lambda=\frac{1}{2}\rangle\end{aligned} \tag{16}$$

where $\mu_p = 0.13$ Gev^{-1} is the magnetic moment of proton, $m_q = 330$ MeV is the constituent quark mass and q_j is the quark charge operator. In this approach, the current conservation for the longitudinal transition operator is automatically satisfied without further substracting procedure[13] in the electromagnetic interaction. This is generally true to any order of the $(\frac{v}{c})$ expansion[14]. Therefore, the calculation of the longitudinal helicity amplitude in the literature[9] merits reconsideration.

Note that the transition operator for the longitudinal helicity amplitude in Eq. 16 is only proportional to the charge operator in the nonrelativistic limit, it probes only the relative charge distribution between the nucleon and the excited states. Because the spin-flavour wavefunction of the Roper resonance is the same as that of the nucleon in the q^3 quark model, the corresponding longitudinal helicty amplitude is the Fourier transformation of the spatial wavefunctions of the nucleon and the radial excited state. In the harmonic oscillator basis, this gives

$$S^p_{\frac{1}{2}}(q^3) = -\frac{1}{3\sqrt{3}}\sqrt{\frac{2\pi}{k_0}}m_q\mu_p\frac{k^2}{\alpha^2}e^{-\frac{k^2}{6\alpha^2}}. \tag{17}$$

For a hybrid state, the transition operator for the process $\gamma_L q \to qG$ is

$$O^L = \frac{1}{\omega_g}\left[h^{TE}_{QCD},\ H^L_{e.m.}\right] = 0, \tag{18}$$

where[1]

$$h^{TE}_{QCD} = -\sum_j i g_s \frac{\lambda^a_i}{2} \frac{1}{2m_j} \sigma_j \cdot \mathbf{B}_g. \tag{19}$$

The reason why the operator $\mathcal{O}^L$ vanishes is because the color $\mathbf{B}_g$ is a transverse field and only couples to the transverse component of the electromagnetic field in the process $\gamma q \to qG$. This is not true if one expands the electromagnetic interaction to order $(\frac{v}{c})^2$, at which the spin-orbit and nonadditive terms[12] contribute to the longitudinal transition operator. Hence we have

$$\begin{aligned} S^p_{\frac{1}{2}}(q^3G) = {} & 6\sqrt{\frac{2\pi}{k_0}} m_q \mu_p \frac{\sqrt{2}\delta}{1+2\delta^2} \Big\{ \langle N_0 | q_3 | N_0 \rangle \\ & - \frac{1}{2} \left[\langle ^2N_g | q_3 | ^2N_g \rangle + \langle ^4N_g | q_3 | ^4N_g \rangle \right] \Big\} \langle \phi(q^3G) | e^{i\mathbf{k}\cdot\mathbf{r}_j} | \phi(q^3) \rangle \\ = {} & 0 \end{aligned} \tag{20}$$

where $\phi(q^3G)$ and $\phi(q^3)$ are the spatial wavefunctions for the hybrid state and the nucleon respectively. The physics is that the hybrid state is excited in the spin-flavour space, therefore the spin-flavour wavefunction for a hybrid state is orthogonal to the wavefunction of the nucleon. This selection rule may be broken if one expands the electromagnetic interaction to the order $(\frac{v}{c})^2$, in which the spin-orbit and the nonadditive terms should be included[14].

4. Discussion

In Fig. 2, we show the Q^2 dependence of $S^p_{\frac{1}{2}}(q^3)$ for the radial excitation state in comparison with experimental data. The $S^p_{\frac{1}{2}}(q^3)$ is significantly large at small Q^2 in contrast to the vanishing $S^p_{\frac{1}{2}}$ for a hybrid state, similar results[10] have been obtained in the relativistic constituent quark model, where the light cone formalism is used. The more significant quantity is the ratio $S^p_{\frac{1}{2}}/A^p_{\frac{1}{2}}$, where common features, such as the confinement, can be factored out, so that the remaining information can reveal the spin-flavour correlations of the resonance. For the Roper resonance, this leads to

$$\frac{S^p_{\frac{1}{2}}}{A^p_{\frac{1}{2}}} = \begin{cases} 0 & \text{for a hybrid state} \\ \frac{\sqrt{2}m_q}{k_z} & \text{for a } q^3 \text{ radial excitation state,} \end{cases} \tag{21}$$

where $\frac{\sqrt{2}m_q}{k_z} \approx 1.13$ in the real photon limit. In Fig. 3, we show the Q^2 dependence of this ratio for the Roper resonance in the q^3 quark model. The longitudinal helicity component is comparable to the transverse helicity amplitude at small Q^2. In other studies[9,10] it was found that the longitudinal amplitude is even larger than the transverse amplitude. Because this ratio vanishes for the hybrid state, more precise data for this quantity at small Q^2 are crucial in determining the spin-flavour content of the Roper resonance.

The difference between a hybrid state and a radial excitation state for the Roper resonance also has quite different consequences for the relative strength between the Roper and the resonance $P_{33}(1232)$. If the Roper is an orbitally excited state, it has been argued[15] that the resonance $P_{33}(1232)$ should die out faster than the Roper in the q^3 quark model. In Fig. 4, we shown the ratio of the transverse helicity amplitudes $A^p_{\frac{1}{2}}$ between the Roper and $P_{33}(1232)$. This ratio increases for a orbital excitation state and decreases for a hybrid state as Q^2 increases. Combining with the vanishing longitudinal helicity amplitude, this implies that the total cross section for a hybrid state should decrease faster than that for three quark baryons at small Q^2. Such a behaviour is consistent with the data of inclusive electron–proton scattering at low momentum transfer. It has been pointed out[16] that already at small Q^2 indications of the Roper excitation have disappeared from the inclusive cross section. Moreover, a recent analysis[17] of the high Q^2 behaviour of the inclusive cross section finds no indication of the excitation of the Roper, even at the highest Q^2 of 20 GeV^2. Detailed analyses of single pion production in the region of the Roper have been performed by Devenish and Lyth[18], Gerhardt[19], and Boden and Krõsen[20]. Devenish and Lyth conclude that the $P_{11}(1440)$ drops so fast with Q^2 that it is effectively absent from the fits to electroproduction data. Gerhardt, as well as Boden and Krõsen, using more detailed electroproduction data, extract quantitative values for the transition amplitudes to the Roper. Using various data sets, and different assumptions in the fit, ranges for $A^p_{1/2}(Q^2)$ and $S^p_{1/2}(Q^2)$ as shown in Fig. 1 and Fig. 2 were obtained. The systematic uncertainties, due to incomplete data sets, as well as from different theoretical assumptions, are significant, and estimated to be no smaller than $\pm 12 \cdot 10^{-3} GeV^{-1/2}$. The results, both for the transverse and for the longitudinal coupling clearly favour the interpretation of the Roper as a q^3G hybrid state. However, considering the uncertainties in the data analysis, more precise data for the exclusive process $\gamma_v p \rightarrow P_{11}(1440)$ at low and intermediate momentum transfers are needed to definitely determine the nature of the Roper resonance. In particular, pion electroproduction off polarized protons will be very sensitive to the excitation strength of the Roper[21].

Similar arguments can be made regarding the $P_{33}(1600)$. It has been shown in Ref. 1 that the $P_{33}(1600)$ should also be a hybrid state, if the Roper is a hybrid baryon, while the $P_{33}(1600)$ is a radial excitation partner in the q^3 quark model. For a orbitally excited state, the helicity amplitudes for the $P_{33}(1600)$ is suppressed in the real photon limit, but they become significant at $Q^2 = 1 \sim 2$ GeV^2 like the Roper. However, for a hybrid state, the helicity amplitudes should disappear quickly. The data on the Q^2 dependence of the helicity amplitudes for the $P_{33}(1600)$ are also very important in determining the nature of the Roper resonance and whether the gluonic degrees of freedom play an explicit role in the baryon resonance at 1.5 GeV.

Our investigation is restricted to the nonrelativistic limit, the extension to higher order relativistic correction is needed to examine whether our prediction is stable here, especially for the longitudinal helicity amplitude. It is likely that there is some configuration mixing between the hybrid state and the radial excitation state of the nucleon, which would affect the prediction presented here. This requires a more detailed investigation of the baryon spectroscopy including the gluonic degrees of freedom, which goes far beyond the present study.

In summary, our calculation shows that data on the Q^2 dependences of the helicity amplitudes of the Roper resonance are crucial in determining its spin-flavour content. The Roper resonance provides a challenge to our understanding of baryon spectroscopy; if it is indeed the orbitally excitation state of the nucleon, one has to understand why the excitation energy of the Roper is lower than that of all P-wave baryon resonances. Moreover, the rapid decrease of the transverse transition amplitude at small Q^2 has to be explained. If it is a hybrid state, the role of the gluonic degrees of freedom in baryon spectroscopy should be fully investigated. Our calculations indicate that the hybrid interpretation of the Roper is in better agreement with existing data. Planned experiments[22] at CEBAF will certainly give us a more definite answer about the nature of this state.

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Figure Caption

1. $A^p_{\frac{1}{2}}(Q^2)$ for the transition $\gamma_v p \rightarrow P_{11}$ if the Roper is a q^3 state[5] (long-dashed line), or a q^3G state (solid line), respectively. The short dashes and the dashed-dotted line represent different results of the analysis by C. Gerhardt. Note that the analysis was constraint by a photoproduction value $A^p_{\frac{1}{2}}(0) = -50 \cdot 10^{-3} GeV^{-1/2}$. The data points indicate the results of fits at fixed Q^2. Gerhardt - diamond symbols, Boden, Krõsen - cross symbols.

2. $S^p_{\frac{1}{2}}(Q^2)$ for the transition $\gamma_v p \rightarrow P_{11}(1440)$ if the Roper is a q^3 state. The short-dashed and dashed-dotted line represent different results of the analysis by C. Gerhardt. The $S^p_{\frac{1}{2}}(Q^2)$ is zero for a hybrid state. Data from Gerhardt (squares) and from Boden, Krõsen (crosses).

3. Ratio $S^p_{\frac{1}{2}}(Q^2)/A^p_{\frac{1}{2}}(Q^2)$ for the transition $\gamma_v p \rightarrow P_{11}$ if the Roper is a q^3 state. For a hybrid state, this quantity vanishes.

4. Ratio of the transverse helicity 1/2 amplitudes for $P_{11}(1440)$ and $P_{33}(1232)$ if the Roper is a q^3 state (dashed line), and if it is a q^3G state (solid line).

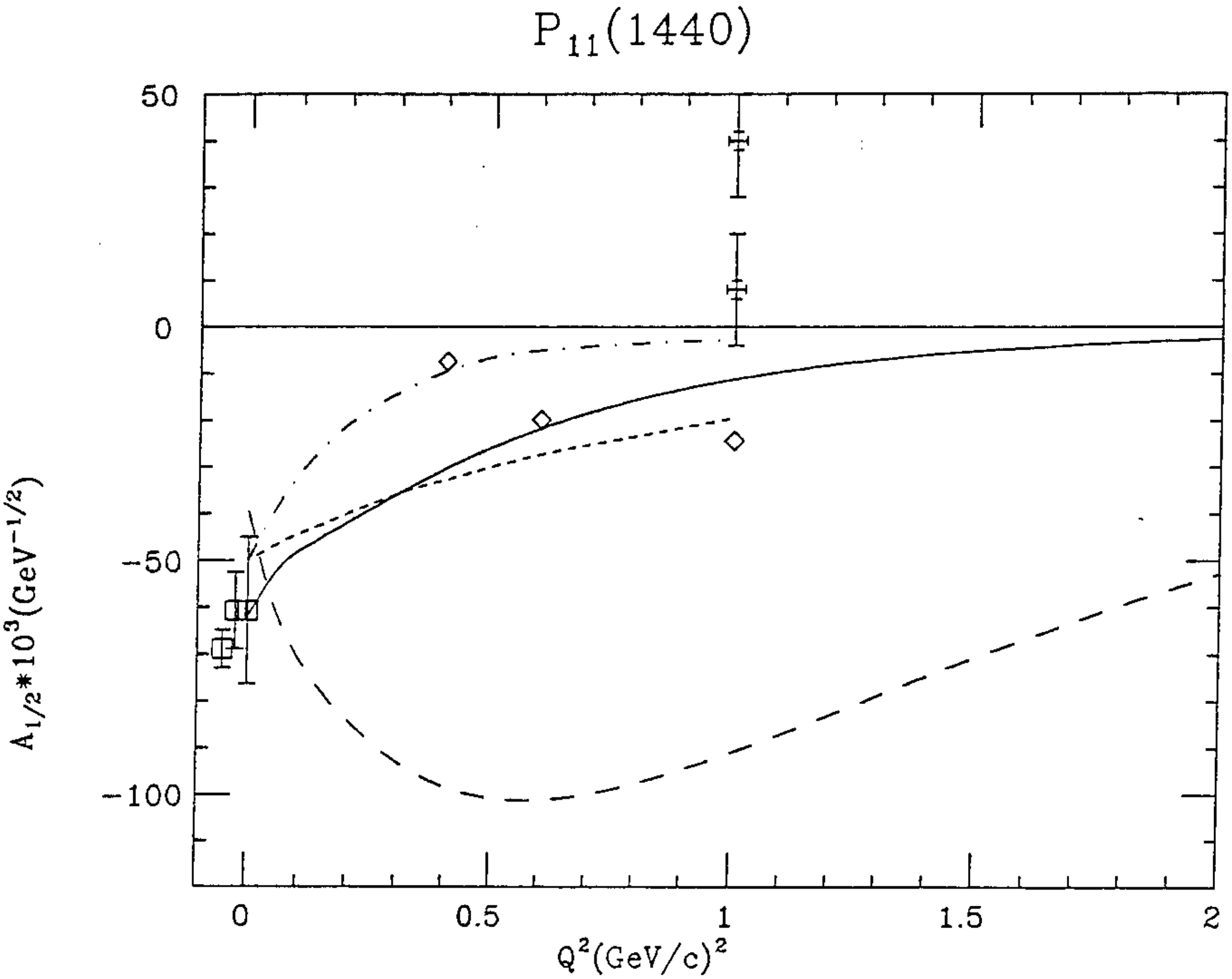

Figure 1

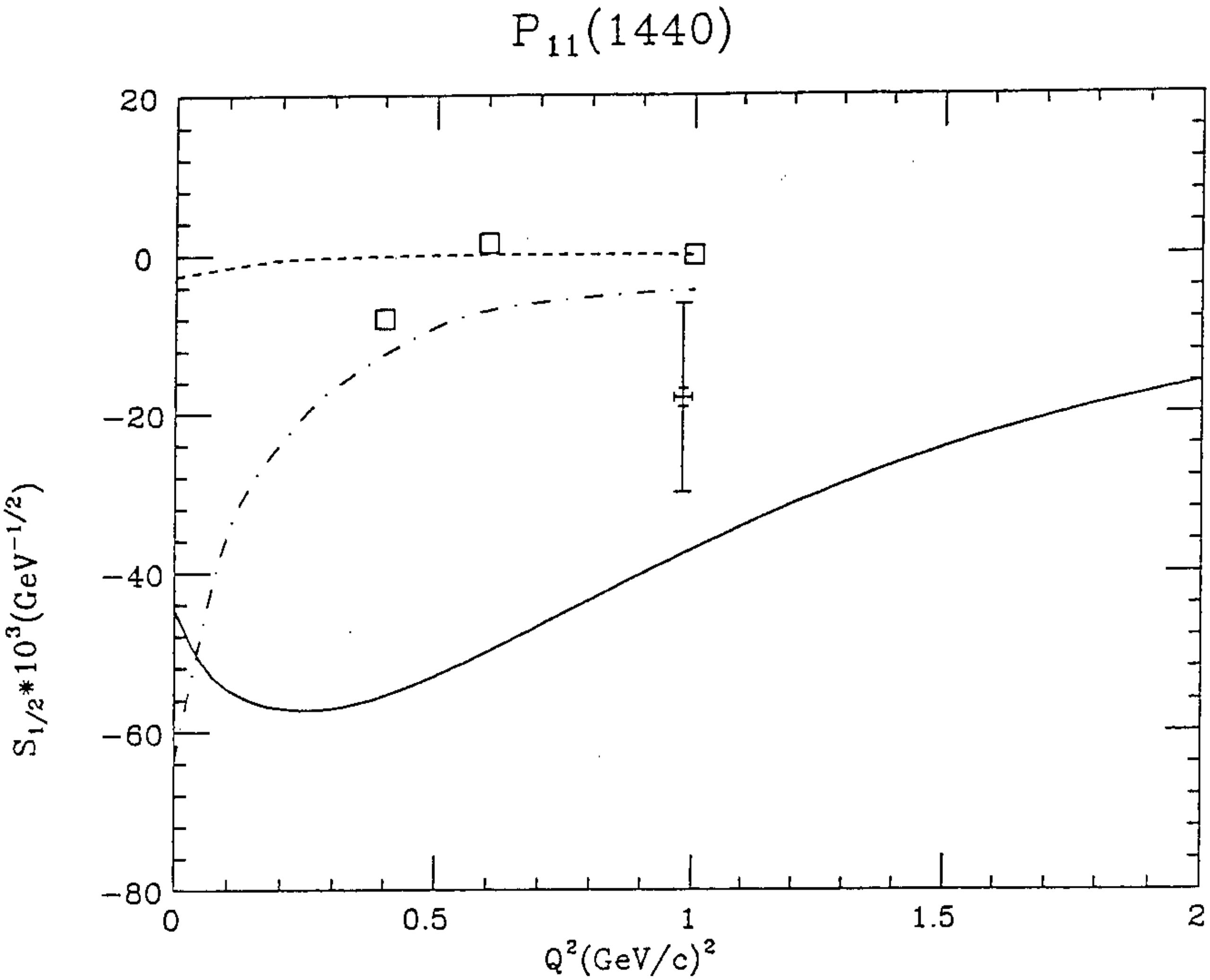

Figure 2

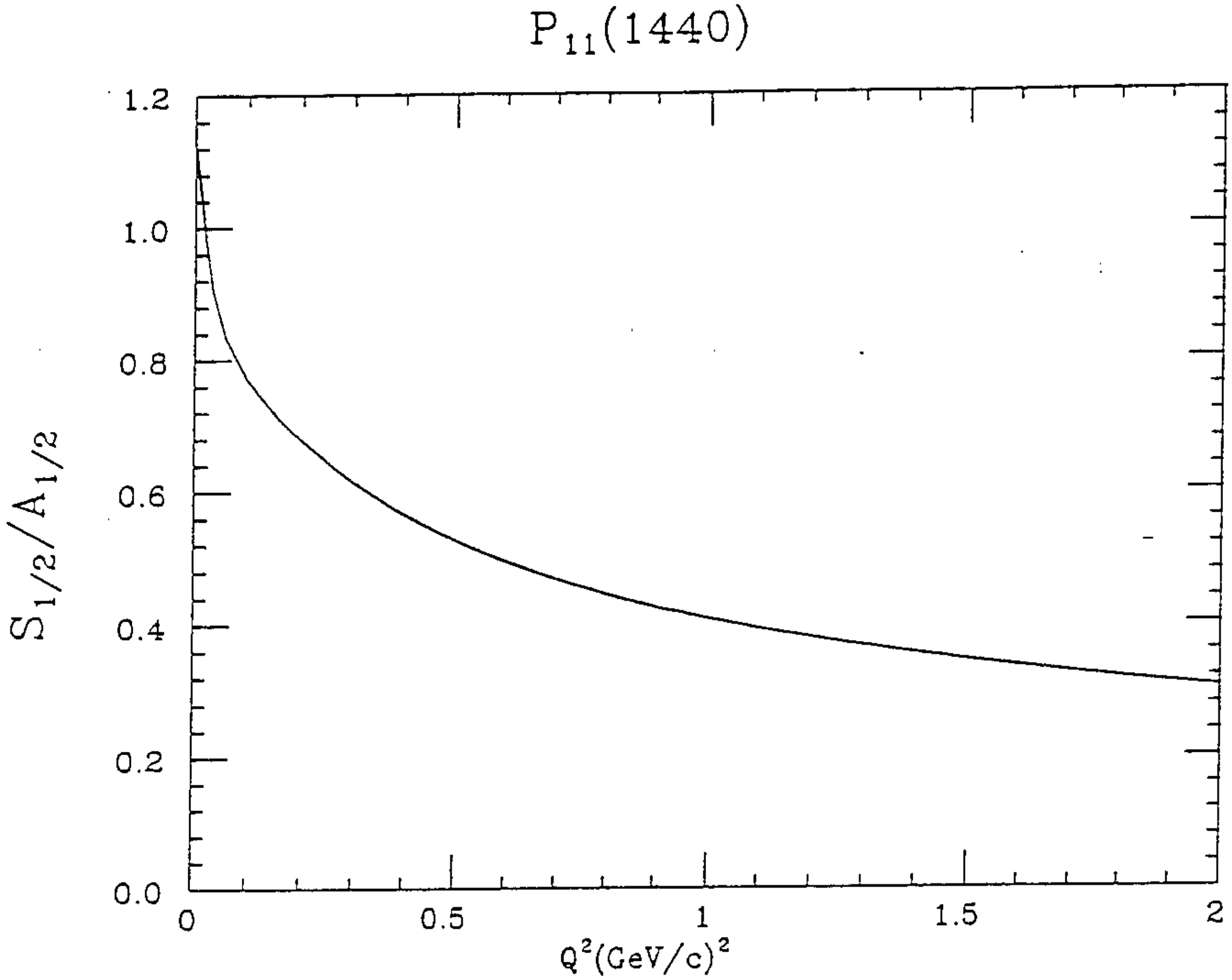

Figure 3

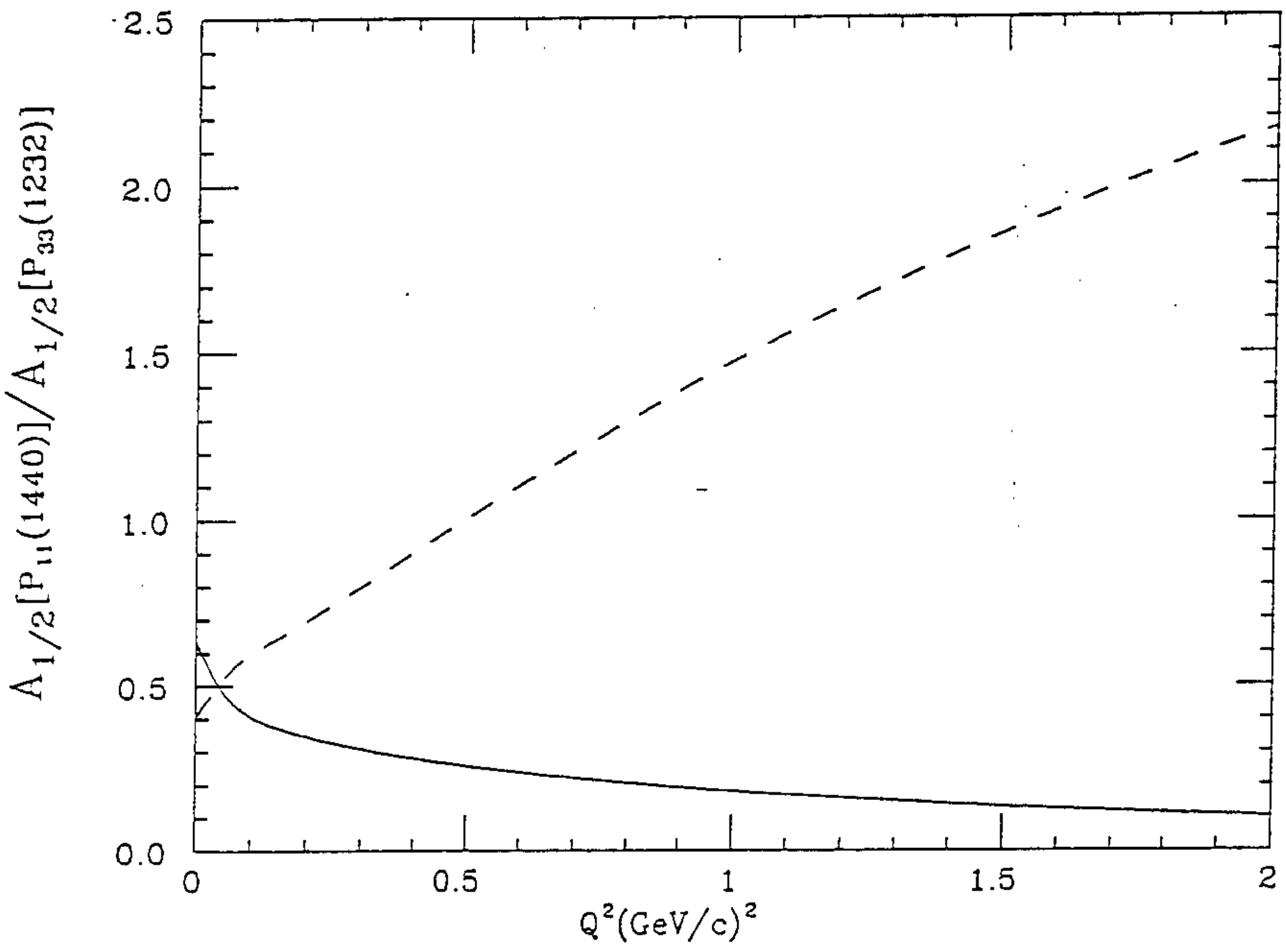

Figure 4