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A Method to Unambiguously Determine the Parity of the Θ^+ Pentaquark

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With the recent discovery of the $\Theta(1540)$ pentaquark, the question of its parity is paramount since this will constrain the correct description of its internal structure. We show that the measurement of the spin singlet and triplet cross sections for the reaction $\vec{p}\vec{p} \to \Sigma^+\Theta^+$ will unambiguously determine the parity of the Θ^+.

The recent discovery of the Θ^+ baryon[1)–3)] has been associated with a tremendous amount of theoretical activity.[4)] For the present there is no consensus within the theoretical community as to the parity of this exotic state, with roughly half of the calculations/models on either side of the mirror. For example, the original prediction of the Θ^+ in the chiral soliton model[5)] predicted that the Θ^+ (called the Z^+ in that paper) is part of an anti-decuplet, with all members having spin and parity $J^\pi = \frac{1}{2}^+$. On the other hand, lattice gauge calculations[6)] suggest that the Θ^+ has $J^\pi = \frac{1}{2}^-$. Since the parity reflects internal dynamics of the Θ^+, it is absolutely crucial to further theoretical progress that the parity be determined experimentally, as soon as possible and without ambiguity.

A number of proposals have been made so far,[7)] but all of them involve considerable experimental challenge as well as an understanding of the reaction mechanism. There is good reason why this is so difficult. Suppose that a sample of 100% polarized Θ^+ particles could be prepared at rest in the laboratory. Even under this ideal condition, the decay angular distribution of this strongly-decaying particle gives information only on the spin, and not the parity, unless the polarization of the final-state nucleon is measured (this is a simple consequence of symmetry of the magnetic substates of the system).[*)] Even if the difficult experimental task of measuring the final nucleon polarization is accomplished for the small Θ^+ cross section, the polarization of the Θ^+ depends on the density matrix elements of the reaction mechanism. It would be much more desirable to have a method that is independent of the details of the production mechanism.

A classic, well-known example of parity determination is the case of the pion,

[*)] In fact, the angular distribution of the kaon from a polarised $\Theta^+(J_z = J)$ is proportional to $(\sin\theta)^{2J-1}$ regardless of the parity.

which involved the decay of pionic deuterium.[8] There the Fermi statistics of the two nucleons and the threshold kinematics played an essential role. Here we consider an analogous reaction, namely Θ^+ production from two protons in the threshold region. We will briefly explain how this process can provide an unambiguous determination of the parity of the Θ^+. For the purposes of our analysis we assume that the Θ^+ has spin-1/2, but it is trivial to show that the argument generalises to spin-3/2. We consider the process

$$\vec{p} + \vec{p} \to \Sigma^+ + \Theta^+ \,, \tag{1}$$

at and just above threshold. If the final centre of mass momentum is k, a final state with $L = 1$ is suppressed in production rate with respect to $L = 0$ by a factor $(kR)^2$, with R a characteristic distance of order one fermi. If one is within a few MeV of threshold the suppression is one to two orders of magnitude. Thus one can be sure that the final state has $L = 0$. (The energy dependence of the production cross section in the region just above threshold will, in any case, provide an unambiguous check of this assumption.) The total spin of the Σ^+ and the Θ^+ is $S = 0$ or 1. Thus the total angular momentum and parity of the final state must be 0^+ or 1^+ if the parity of the Θ^+ is positive and 0^- or 1^- if the parity of the Θ^+ is negative. Since the total angular momentum and parity are conserved in strong interactions these values will also be the total angular momentum and parity of the initial state.

We note that the isospin of the initial pp state is $I = 1$ and the Pauli exclusion principle then implies that if the initial pp orbital angular momentum is even the initial spin must be $S = 0$, while if it is odd the initial spin must be $S = 1$. This leads to the following possibilities:

- **Parity of Θ^+ positive:** In this case, the spins of the protons should be anti-alligned. Then the initial pp state must be $^1S_0$.
- **Parity of Θ^+ negative:** In this case, the spins of the protons should be alligned. Then the initial pp state must be $^3P_0$ or $^3P_1$ (for $J = 0$ and 1, respectively).

No other possibilities exist.

Clearly a measurement with polarised proton beam and target which observes the reaction (1) near threshold enables one to determine whether the production occurs for the spin singlet or triplet state of the initial protons. If it is the former the Θ^+ **must** have positive parity, while if the latter it **must** have negative parity. We stress that this conclusion relies only on the conservation of total angular momentum, parity and isospin in the strong interaction and is totally independent of any particular reaction mechanism.

Assuming that the width of the Θ^+ is of the order an MeV or more, one would expect the total cross section for the reaction (1) to be in the range 0.1 to 1.0 μb at beam energies a few tens of MeV above the reaction threshold.[9] Near threshold, the cross section will be lower, perhaps by one or two orders of magnitude. In addition, the requirement of a polarized beam and a polarized target could reduce the luminosity of the measurement, making it still more difficult. However, near-threshold measurements are now routinely done with polarized beam and target[10] that were considered extremely difficult in the previous years. Considering the overwhelming theoretical importance of determining the parity of the Θ^+, experimentalists have a strong motivation to use their ingenuity and overcome the difficulties of such a measurement. We expect that it is within the the capabilities of facilities such as COSY at Jülich, and it is important that this measurement be carried out as soon as possible.

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1) T. Nakano et al. [LEPS Collaboration], Phys. Rev. Lett. **91** (2003), 012002; hep-ex/0301020.
2) V. V. Barmin et al. [DIANA Collaboration], Phys. Atom. Nucl. **66** (2003), 1715 [Yadern. Fiz. **66** (2003), 1763]; hep-ex/0304040.
3) S. Stepanyan et al. [CLAS Collaboration], hep-ex/0307018.
4) Recent activities are found on the web page of the Pentaquark workshop at JLab, November (2003): `http://www.jlab.org/intralab/calendar/archive03/pentaquark/`
5) D. Diakonov, V. Petrov and M. Polyakov, Z. Phys. A **359** (1997), 305.
6) F. Csikor, Z. Fodor, S. D. Katz and T. G. Kovacs, hep-lat/0309090.
Shoichi Sasaki, hep-lat/0310014.
7) T. Hyodo, A. Hosaka and E. Oset, nucl-th/0307105; Phys. Lett. B, to appear.
S. I. Nam, A. Hosaka and H.-Ch. Kim, hep-ph/0308313; Phys. Lett. B, to appear.
Y. Oh, H. Kim and S. H. Lee, hep-ph/0310019.
Q. Zhao, hep-ph/0310350.
K. Nakayama and K. Tsushima, hep-ph/0311112.
8) W. K. Panofsky, R. L. Aamodt and J. Hadley, Phys. Rev. **81** (1951), 565.
9) W. Eyrich, private communications.
M. V. Polyakov, A. Sibirtsev, K. Tsushima, W. Cassing and K. Goeke, Eur. Phys. J. A **9** (2000), 115; nucl-th/9909048.
10) H. O. Meyer et al., Phys. Rev. C **63** (2001), 064002.