HOW LARGE IS THE σ-NUCLEON-$N^*(1440)$ COUPLING CONSTANT? *

Madeleine Soyeur

Département d'Astrophysique, de Physique des Particules,
de Physique Nucléaire et de l'Instrumentation Associée
Service de Physique Nucléaire
Commissariat à l'Energie Atomique/Saclay
F-91191 Gif-sur-Yvette Cedex, France

(Received July 8, 1998)

The experimental information presently available on the σ-nucleon-N*(1440) coupling constant is briefly discussed and the large uncertainty in this quantity is emphasized. We show that measurements of the associate photoproduction of a vector meson (ρ- or ω-meson) and of the Roper resonance off proton targets near threshold could provide direct information on the strength of the scalar–isoscalar excitation of the $N^*(1440)$ and hence on the magnitude of the $\sigma NN^*(1440)$ coupling.

PACS numbers: 13.60.–r, 14.20.Gk, 12.40.Vv

1. Introduction

The Roper resonance, the $N^*(1440)$, is the first excited state of the nucleon. It has the same quantum numbers as the nucleon, spin $1/2$, isospin $1/2$ and positive parity. It is therefore expected that the $N^*(1440)$ will be excited by the action of a scalar–isoscalar field on the nucleon. In effective hadronic field theories, the strength of this excitation will be characterized by the $\sigma NN^*(1440)$ coupling. We address the question of the magnitude of this coupling.

The value of $g_{\sigma NN^*}$, the $\sigma NN^*(1440)$ coupling constant, and the expression describing the associated form factor are of interest for various issues. As a consequence of its rather low excitation energy, the $N^*(1440)$ resonance can play a role as virtual intermediate state in nuclear dynamics. For example, a repulsive three-nucleon interaction can be generated by the

* Presented at the NATO Advanced Research Workshop, Cracow, Poland, May 26–30, 1998.

π- and σ-exchange (or by the π- and ω-exchange) components of the nucleon-nucleon interaction with an intermediate $N^*(1440)$ [1]. The magnitude of this interaction is directly determined by the values of $g_{\sigma NN^*}$ and $g_{\omega NN^*}$. The decay vertices of the Roper resonance are also important to understand the very nature of the resonance. The low excitation energy, the positive parity and the large width of the $N^*(1440)$ are very hard to accommodate in the framework of constituent quark models based on harmonic confining potentials. This led to the introduction of anharmonic interactions [2] or of collective excitations, such as breathing modes of bag surfaces [3, 4]. Implementing chiral symmetry in quark models has been shown to help in understanding the energy of the Roper resonance: chiral boson exchange interactions can produce the correct ordering of positive and negative parity states in the baryon spectrum, in particular the observed mass difference between the $N^*_{1/2^-}(1535)$ and the $N^*_{1/2^+}(1440)$ [5]. The partial decay widths of the $N^*(1440)$ are stringent tests of these models. Finally, a recent coupled-channel calculation for pion–nucleon scattering, involving πN, $\pi\Delta$ and σN channels, indicates that the Roper resonance could be explained as a dynamical effect [6]. The σN channel plays a particularly important role in this interpretation.

In Section 2, we review briefly the available experimental data on the $\sigma NN^*(1440)$ vertex and show the large uncertainty associated with the corresponding coupling constant, $g_{\sigma NN^*}$. Section 3 is devoted to a presentation of a new approach to study the strength of the $\sigma NN^*(1440)$ coupling, the associate photoproduction of a vector meson (ρ- or ω-meson) and of the Roper resonance off proton targets near threshold. These processes are computed in the meson-exchange model of Ref. [7]. We conclude in Section 4.

2. The σ-nucleon-$N^*(1440)$ coupling

In the Particle Data Group [8], the $N^*(1440)$ has a width of (350 ± 100) MeV. It has three observed strong decay channels: $N\pi(60 \div 70\%)$, $\Delta\pi(20 \div 30\%)$ and $N(\pi\pi)_{I=S=0}$ $(5 \div 10\%)$.

The effective σ degree of freedom describes the propagation of two pions in the scalar-isoscalar channel. The $g_{\sigma NN^*}$ coupling constant is therefore related to the partial decay width of the $N^*(1440)$ in the $N(\pi\pi)_{I=S=0}$ channel. This relation is not simple because it depends explicitly on the σ mass, which is a model-dependent quantity. We describe the $\sigma NN^*(1440)$ coupling by the interaction Lagrangian,

$$\mathcal{L}_{\sigma NN^*} = g_{\sigma NN^*}\, \overline{\Psi}_{N^*}\, \sigma\, \Psi_N + \text{h.c.}\,, \tag{1}$$

and use the prescription of Ref. [1] for the σ mass. Taking $\Gamma[N^*(1440) \to N(\pi\pi)_{I=S=0}] = 35$ MeV, one gets $g^2_{\sigma NN^*}/4\pi \simeq 0.1$ [1]. We shall also need the $\pi N N^*(1440)$ coupling. We use the pseudoscalar form,

$$\mathcal{L}_{\pi N N^*} = -ig_{\pi N N^*}\,\overline{\Psi}_{N^*}\,\gamma_5\,\vec{\pi}\,\vec{\tau}\,\Psi_N + \text{h.c.}\,. \tag{2}$$

Taking $\Gamma[N^*(1440) \rightarrow N\pi] = 210$ MeV, one obtains $g^{\,2}_{\pi N N^*}/4\pi = 9.6$.

An effective value for $g_{\sigma N N^*}$ has also been derived recently from data [9] on the excitation of the Roper resonance in the inelastic scattering of α particles off proton targets [10]. The reaction $\alpha + p \rightarrow \alpha + X$ is studied for incident α particles of 4.2 GeV. Missing energy spectra are measured at small angles (0.8, 2.0, 3.2 and 4.1°) [9]. The dominant processes contributing to the reaction are found to be the excitation of the Δ resonance in the projectile (followed by the emission of a pion) and the excitation of the Roper resonance in the target. The latter process is described by the exchange of a σ-meson between the incident α particle and the proton target [10]. In order to reproduce the missing energy spectrum at 0.8°, the $\sigma N N^*(1440)$ coupling constant has to be quite large. The value corresponding to the best fit is $g^2_{\sigma N N^*}/4\pi = 1.33$ with a form factor $F_{\sigma N N^*} = (\Lambda^2_\sigma - m^2_\sigma)/(\Lambda^2_\sigma - q^2)$, where $\Lambda_\sigma = 1.7$ GeV [10]. Clearly, the $\sigma N N^*(1440)$ coupling needed in this case is much stronger than inferred from the partial decay width of the $N^*(1440)$ in the $N(\pi\pi)_{I=S=0}$ channel. As remarked by the authors of Ref. [10], their σ-exchange interaction could simulate other exchanges of isoscalar character. It could also be that the strength observed in the missing energy spectrum around the position of the Roper resonance, after subtraction of the Δ background, should not be attributed entirely to the $N^*(1440)$. The analysis of more exclusive experiments is in progress. Preliminary data on the $p(d,d')N^*$ reaction at incident deuteron energies of 2.3 GeV, where the excitation of the $\Delta(1232)$ and of the $N^*(1440)$ are separated by the detection of the decay proton, seem to indicate that the excitation of the Roper resonance predicted using the parameters of Ref. [10] is larger than the observed cross-section [11]. The value used for $g^2_{\pi N N^*}/4\pi$ in these analyses is 5.5.

In the next section, we will discuss the associate photoproduction of a vector meson and of the Roper resonance off proton targets, using both sets of coupling constants, the weak $\sigma N N^*(1440)$ coupling derived from the partial decay width of the $N^*(1440)$ in the $N(\pi\pi)_{I=S=0}$ channel and the strong $\sigma N N^*(1440)$ coupling needed to reproduce the missing mass spectrum measured for the $\alpha + p \rightarrow \alpha + X$ reaction.

3. The $\gamma\, p \rightarrow \omega\, N^*(1440)$ and $\gamma\, p \rightarrow \rho^0\, N^*(1440)$ reactions

The presently available data on the photoproduction of ω- and ρ^0-mesons off proton targets near threshold ($E_\gamma \leq 2$ GeV) can be described at low momentum transfers ($|\, q^2 \,| \leq 0.5 \div 0.6$ GeV^2) by a simple one-meson exchange model [7]. Charge conjugation invariance forbids the exchange of vector mesons in this approximation. The cross section for the $\gamma\, p \to \omega\, p$ and $\gamma\, p \to \rho^0\, p$ reactions comes therefore entirely from π- and σ-exchanges. The $\gamma\, p \to \omega\, p$ cross section can be understood as coming entirely from π-exchange while the $\gamma\, p \to \rho^0\, p$ reaction is dominated by σ-exchange [7]. At higher energies, typically for $E_\gamma > 2.5$ GeV (*i.e.* ~ 1.5 GeV above threshold), these cross sections develop a large diffractive component. The Roper resonance having the same quantum numbers as the nucleon, one can try to use a similar model to describe the $\gamma\, p \to \omega\, N^*(1440)$ and $\gamma\, p \to \rho^0\, N^*(1440)$ reactions close to threshold and at low q^2. The $\gamma\, p \to \rho^0\, N^*(1440)$ cross section in this kinematic regime would therefore be a very good measure of the strength of the $\sigma N N^*(1440)$ coupling while the $\gamma\, p \to \omega\, N^*(1440)$ reaction would provide constraints on the π-exchange contribution.

The one-boson exchange contributions to the $\gamma\, p \to \omega\, N^*(1440)$ and $\gamma\, p \to \rho^0\, N^*(1440)$ reactions in the Vector Dominance Model are shown in Figs 1 and 2 respectively.

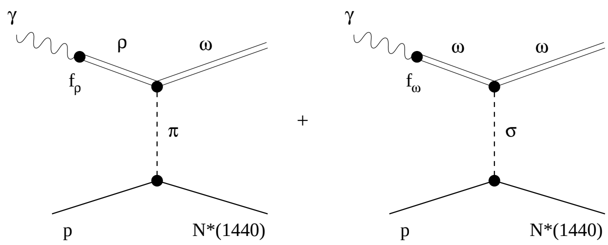

Fig. 1. Diagrams contributing to the $\gamma\, p \to \omega\, N^*(1440)$ cross section in the one-boson exchange model

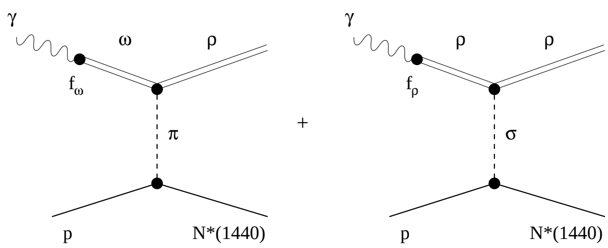

Fig. 2. Diagrams contributing to the $\gamma\, p \to \rho^0\, N^*(1440)$ cross section in the one-boson exchange model

We consider first the $\gamma\, p \to \omega\, N^*(1440)$ process ($E_\gamma^{\rm threshold} = 2.16$ GeV) and follow closely the discussion of Ref. [7]. We expect the σ-exchange diagram to be completely negligible. It was already very small in the case of the $\gamma\, p \to \omega\, p$ reaction because the $\omega\sigma\gamma$ coupling is much weaker than the

$\omega\pi\gamma$ coupling [7]. In the case of the associate excitation of the $N^*(1440)$, the $\sigma NN^*(1440)$ coupling is also much smaller than the σNN coupling ($g^2_{\sigma NN^*}/4\pi = 0.1 \div 1.33$ and $g^2_{\sigma NN}/4\pi \simeq 8$) while the $\pi NN^*(1440)$ and πNN couplings are comparable ($\mathrm{g}^{\,2}_{\pi NN^*}/4\pi = 9.6$ and $\mathrm{g}^{\,2}_{\pi NN}/4\pi = 14$). We calculate therefore the differential cross section $\mathrm{d}\sigma/\mathrm{dq}^2$ for the $\gamma\, p \to \omega\, N^*(1440)$ reaction assuming π-exchange only. We describe the $\omega\pi\gamma$ coupling as in Ref. [7] and use for the $\pi NN^*(1440)$ vertex the coupling constant $\mathrm{g}^{\,2}_{\pi NN^*}/4\pi = 9.6$ and the form factor

$$F_{\,\pi NN^*} = \frac{\Lambda_\pi^2 - m_\pi^2}{\Lambda_\pi^2 - q^2}\,,$$

where $\Lambda_\pi = 0.7$ GeV. The result for $E_\gamma = 2.5$ GeV is shown in Fig. 3. The expected domain of validity of the model is seen to be quite limited: the lowest value of $\mid q^2 \mid$ at this energy (corresponding to $\theta = 0°$) is 0.36 GeV^2 and the cutoff values restrict the applicability of the one-pion exchange model to $q^2 \leq 0.5 \div 0.6$ GeV^2.

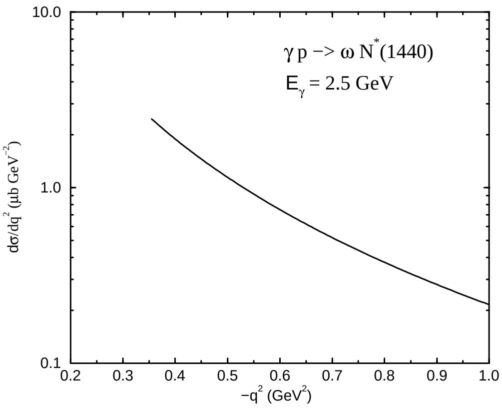

Fig. 3. Differential cross section for the $\gamma\, p \to \omega\, N^*(1440)$ cross section in the one-pion exchange model

We turn now to the $\gamma\, p \to \rho^0\, N^*(1440)$ reaction. We calculate in this case both the π- and σ-exchange contributions shown in Fig. 2 for $E_\gamma = 2.5$ GeV. We describe the $\rho^0\pi^0\gamma$ and of the $\rho^0\sigma\gamma$ vertices as in Ref. [7] and we use the two sets of coupling constants discussed in Section 2 for the πNN^* and σNN^* vertices. The result obtained with the weak $\sigma NN^*(1440)$ coupling ($g^2_{\sigma NN^*}/4\pi = 0.1$, $g^2_{\pi NN^*}/4\pi = 9.6$, $\Lambda_\sigma = 1$ GeV, $\Lambda_\pi = 0.7$ GeV) is displayed in Fig. 4. If we take instead the strong $\sigma NN^*(1440)$ coupling ($g^2_{\sigma NN^*}/4\pi = 1.33$, $g^2_{\pi NN^*}/4pi = 5.5$, $\Lambda_\sigma = 1.7$ GeV, $\Lambda_\pi = 0.7$ GeV), we obtain the differential cross section shown in Fig. 5. It is an order of magnitude larger than with the weak $\sigma NN^*(1440)$ coupling and completely dominated by the σ-exchange.

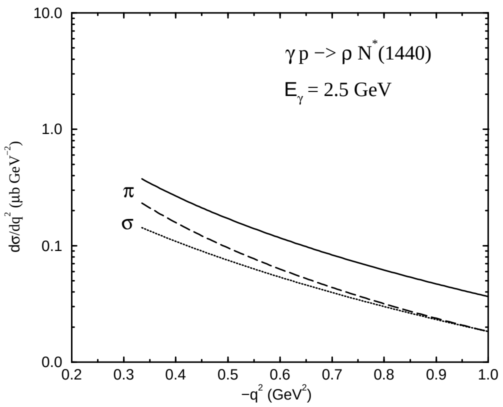

Fig. 4. Differential cross section for the $\gamma p \to \rho^0 N^*(1440)$ cross section in the $(\pi + \sigma)$-exchange model using the weak $\sigma NN^*(1440)$ coupling (see text).

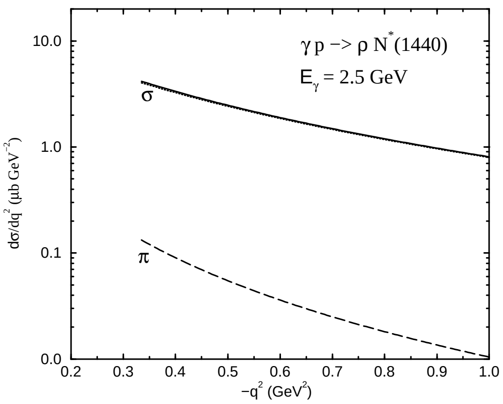

Fig. 5. Differential cross section for the $\gamma p \to \rho^0 N^*(1440)$ cross section in the $(\pi + \sigma)$-exchange model using the strong $\sigma NN^*(1440)$ coupling (see text).

4. Conclusion

We have shown that the combined study of the $\gamma p \to \omega N^*(1440)$ and $\gamma p \to \rho^0 N^*(1440)$ reactions close to threshold, and at low q^2, could be of interest to provide constraints on the $\pi NN^*(1440)$ and $\sigma NN^*(1440)$ couplings. A more detailed discussion of these processes and of their energy dependence will be published elsewhere [12].

The author is very much indebted to Berthold Schoch who suggested the work presented in this paper in relation with an experimental project at the Bonn ELSA Facility. She also acknowledges very helpful discussions with Marcel Morlet and Dan Olaf Riska.

REFERENCES

[1] S.A. Coon, M.T. Peña, D.O. Riska, *Phys. Rev.* **C52**, 2925 (1995).
[2] N. Isgur, G. Karl, *Phys. Rev.* **D19**, 2653 (1979).
[3] T.A. DeGrand, C. Rebbi, *Phys. Rev.* **D17**, 2358 (1978).
[4] G.E. Brown, J.W. Durso, M.B. Johnson, *Nucl. Phys.* **A397**, 447 (1983).
[5] L.Ya. Glozman, D.O. Riska, *Phys. Rep.* **268**, 263 (1996).
[6] C.Schütz *et al., Phys. Rev.* **C57**, 1464 (1998).
[7] B. Friman, M. Soyeur, *Nucl. Phys.* **A600**, 477 (1996).
[8] Review of Particle Properties, *Phys. Rev.* **D54**, 1 (1996).
[9] H.P. Morsch *et al., Phys. Rev. Lett.* **69**, 1336 (1992).
[10] S. Hirenzaki, P. Fernández de Córdoba, E. Oset, *Phys. Rev.* **C53**, 277 (1996).
[11] S. Hirenzaki *et al.*, in preparation.
[12] M. Soyeur, in preparation.