THE ROLE OF THE ROPER RESONANCE IN THE NUCLEAR MANY-BODY PROBLEM*

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The intention of this lecture is to review the dynamical role of the lowest excited state of the nucleon, the Roper resonance or $N^*(1440)$, in nuclear systems. We discuss first its couplings to meson–nucleon channels and, based on these couplings, its contribution to the two-body and three-body interaction respectively. The importance of the Roper resonance as baryonic excitation for particle production in relativistic heavy ion collisions is then examined, particularly in view of recent results obtained at the GSI-SIS Facility.

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1. Introduction

Nuclear systems consist of interacting nucleons whose internal degrees of freedom can manifest themselves by the excitation of baryon resonances. These resonances play a major role as intermediate states in nuclear interactions.

The contribution of the lowest-lying baryonic resonance, the $\Delta(1232)$, to a broad range of nuclear phenomena has been extensively studied [1]. This resonance ($J = 3/2,\ I = 3/2,\ P = +1$) is the dominant feature of the pion–nucleon scattering amplitude at low energy. As such, it influences strongly the creation, propagation and absorption of pions in the nuclear medium and acts as an independent degree of freedom of nuclear dynamics at energy scales of the order of a few hundred MeV.

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The next baryon resonance, the Roper resonance or $N^*(1440)$, has the same quantum numbers as the nucleon ($J = 1/2,\ I = 1/2,\ P = +1$) and is therefore regarded as its first intrinsic excitation, at an energy of about 500 MeV. The structure of this excitation appears rather complex and its properties could have profound consequences on the understanding of the baryon spectrum.

The $N^*(1440)$ is a very broad resonance, with a full width of (350 ± 100) MeV, while the neighbouring nucleon excitations [$N^*(1520)$ and $N^*(1535)$] are twice narrower [2]. The $N^*(1440)$ is not visible as a well-defined peak in the total pion–nucleon cross section. It is established as a pion–nucleon resonance in the P11 channel only through detailed partial wave analyses [3]. In contrast to the negative parity baryon resonances observed in the 1500–1700 MeV range, which can be described by constituent quark models with harmonic confining potentials [4], a proper description of the mass and positive parity of the $N^*(1440)$ requires the introduction of anharmonic interactions among quarks [5]. The positive parity of the $N^*(1440)$ and its position compared to the neighbouring negative parity states come out from $1/N_c$ expansions of the baryon mass operator [6] and from models involving chiral boson-exchange interactions among constituent quarks [7]. The Roper resonance has been considered a good candidate for a collective excitation and interpreted as a breathing mode of the nucleon in bag models [8, 9]. A recent coupled-channel calculation [10], involving the πN, $\pi\Delta$ and σN channels, suggests that the $N^*(1440)$ could be explained as a dynamical effect, without an associated genuine three-quark state.

In this lecture, we will not address further the issue of the internal structure of the Roper resonance. We consider it an independent baryon whose role in the nuclear medium is determined by its mass, width, and couplings to meson–nucleon channels. These couplings are discussed in Section 2, where we emphasize particularly the theoretical uncertainties associated with the $\sigma N N^*(1440)$ coupling and the need for data on the $\omega N N^*(1440)$ and $\rho N N^*(1440)$ couplings. The contribution of the Roper resonance to the $pp \to pp\pi^0$ reaction cross section close to threshold is presented in Section 3. Section 4 deals with the role of the $N^*(1440)$ in generating a repulsive short-range three-body interaction. The importance of the Roper resonance to understand specific aspects of particle production in relativistic heavy ion collisions is discussed in Section 5. We conclude in Section 6.

2. The couplings of the $N^*(1440)$ to meson–nucleon channels

The last edition of the Particle Data Group [2] tells us that the $N^*(1440)$ couples strongly (60–70 %) to the π-nucleon channel and significantly (5–10 %) to the σ-nucleon (more properly $(\pi\pi)^{I=0}_{S-\mathrm{wave}}$-nucleon) channel.

There are no data on its coupling to the vector meson–nucleon channels, except for an upper limit of 8% to the ρ-nucleon channel. The branching ratios to radiative final states (0.035–0.048 % for $p\gamma$ and 0.009–0.032 % for $n\gamma$) are unusually small (compared for example to the branching ratio of 0.52–0.60 % for $\Delta \to N\gamma$). The general impression one gets from these data is that the transition of the nucleon to the $N^*(1440)$ (or vice-versa) is induced mainly by scalar fields (π and σ) and very little by vector fields.

We consider first the coupling of the $N^*(1440)$ to the $N\pi$ channel. From the partial decay width of the $N^*(1440)$ into the $N\pi$ channel, $\Gamma_{N^* \to N\pi} = (228 \pm\ 82)$ MeV, we can deduce the values of the coupling constants $g_{\pi NN^*}$ and $f_{\pi NN^*}$ characterizing the strength of the πNN^* pseudoscalar coupling,

$$\mathcal{L}^{\rm int}_{\pi NN^*} = -i g_{\pi NN^*} \bar{N}^* \gamma_5 (\vec{\tau} \cdot \vec{\pi}) N + \text{h.c.}, \tag{1}$$

and of the πNN^* pseudovector coupling,

$$\mathcal{L}^{\rm int}_{\pi NN^*} = -\frac{f_{\pi NN^*}}{m_\pi} \bar{N}^* \gamma_5 \gamma_\mu \partial^\mu (\vec{\tau} \cdot \vec{\pi}) N + \text{h.c.}, \tag{2}$$

respectively. We find [11]

$$\frac{g^2_{\pi NN^*}}{4\pi} = 3.4 \pm 1.2 \tag{3}$$

and

$$\frac{f^2_{\pi NN^*}}{4\pi} = 0.011 \pm 0.004. \tag{4}$$

The relation between the $\sigma NN^*(1440)$ coupling constant and the partial decay width of the Roper resonance into the $(\pi\pi)^{I=0}_{S-\text{wave}}$-nucleon channel is model-dependent. We assume that it can be described by the process displayed in Fig. 1.

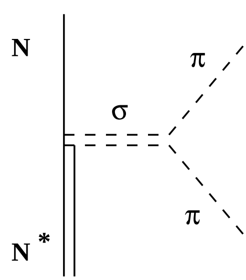

Fig. 1. Roper resonance decay into the $(\pi\pi)^{I=0}_{S-\text{wave}}$-nucleon channel through an intermediate σ-meson.

We take the σNN^* and $\sigma\pi\pi$ couplings to be of the form

$$\mathcal{L}^{\rm int}_{\sigma NN^*} = -g_{\sigma NN^*}\bar{N}^*\sigma N + \text{h.c.} \tag{5}$$

and

$$\mathcal{L}^{\rm int}_{\sigma\pi\pi} = \tfrac{1}{2}\, g_{\sigma\pi\pi}\, m^0_\sigma\, \bar{\pi}.\bar{\pi}\,\sigma, \tag{6}$$

where m^0_σ is the σ-meson mass.

The coupling constant $g_{\sigma NN^*}$ depends on the σ mass and on the width $\Gamma_{\sigma\to\pi\pi}(m^0_\sigma)$ of the σ-meson at the peak of the resonance. The σ-meson of relevance in the many-body problem is the effective degree of freedom accounting for the exchange of two uncorrelated as well as two resonating pions in the scalar–isoscalar channel. It is expected to have a mass of the order of 500–550 MeV [12] and to be a broad state. It can be shown that $g_{\sigma NN^*}$ depends weakly on the value of $\Gamma_{\sigma\to\pi\pi}(m^0_\sigma)$ but rather strongly on m^0_σ [11]. The latter effect is a consequence of the coincidence between the σ mass and the difference between the mass of the $N^*(1440)$ and of the nucleon, which determines the phase space limit for the $N^*(1440) \to N\pi\pi$ decay. Fixing $\Gamma_{\sigma\to\pi\pi}(m^0_\sigma) = 250$ MeV, we obtain for example

$$\frac{g^2_{\sigma NN^*}}{4\pi} = 0.34 \pm 0.21 \tag{7}$$

for $m^0_\sigma = 500$ MeV and

$$\frac{g^2_{\sigma NN^*}}{4\pi} = 0.56 \pm 0.35 \tag{8}$$

for $m^0_\sigma = 550$ MeV [11].

Comparing these πNN^* and σNN^* coupling constants to the corresponding values for the πNN and σNN vertices [12], we have

$$\frac{g_{\pi NN^*}}{g_{\pi NN}} \simeq \tfrac{1}{2} \tag{9}$$

and

$$\frac{g_{\sigma NN^*}}{g_{\sigma NN}} \simeq \tfrac{1}{4}. \tag{10}$$

This seems to depart somewhat from the scaling law

$$\frac{g_{\pi NN^*}}{g_{\pi NN}} = \frac{g_{\sigma NN^*}}{g_{\sigma NN}} = \frac{g_{\omega NN^*}}{g_{\omega NN}} = \frac{g_{\rho NN^*}}{g_{\rho NN}} \tag{11}$$

often used on the basis of constituent quark model arguments [13]. There are however large uncertainties.

To have more constraints on the couplings discussed above, it is useful to make meson-exchange models of simple processes in which the Roper resonance is excited and compare the coupling constants needed to understand the data on these processes to their values derived from the $N^*(1440)$ partial decay widths. One should keep in mind however the limits of such determinations: the exchanged mesons are effective degrees of freedom and meson-baryon vertices involve not only coupling constants but also form factors which may affect significantly the strength of the couplings.

Because of its scalar-isoscalar character, the α-particle appears as a particularly appropriate projectile to excite proton targets into Roper resonances. The reaction $\alpha + p \to \alpha + X$ has been studied at SATURNE with incident α particles of 4.2 GeV [14]. The dominant inelastic 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 [15]. In order to reproduce the data, the $\sigma NN^*(1440)$ coupling constant has to be larger than the value obtained in Eq. (8). The best fit is obtained for $g^{\,2}_{\sigma NN^*}/4\pi = 1.33$ with a form factor $F_{\sigma NN^*} = (\Lambda_\sigma^2 - m_\sigma^{0\,2})/(\Lambda_\sigma^2 - q^2)$, where $\Lambda_\sigma = 1.7$ GeV and $m_\sigma^0 = 550$ MeV [15]. This is illustrated in Fig. 2. As remarked by the authors, their σ-exchange interaction could simulate other exchanges of isoscalar character (ω-exchange). 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. [15] is larger than the observed cross-section [16], typically by a factor of two. If this effect could be confirmed, it would suggest that the analysis of the $p(d, d')N^*$ reaction leads to an effective value of $g_{\sigma NN^*}$ quite close to the phenomenological coupling constant given in Eq. (8) for $m_\sigma^0 = 550$ MeV. In this case also, however, there could be a contribution from ω-exchange [17].

An interesting possibility to have additional experimental constraints on the $\pi NN^*(1440)$ and $\sigma NN^*(1440)$ couplings would be to study the photoproduction of ω- and ρ-mesons off proton targets in the channel where the target proton is excited to the Roper resonance [11]. Close to threshold and at low momentum transfers, the $\gamma p \to \omega N^{*+}(1440)$ reaction cross section should be very sensitive to the $\pi NN^*(1440)$ coupling and the $\gamma p \to \rho^0 N^{*+}(1440)$ reaction cross section to the $\sigma NN^*(1440)$ coupling [11].

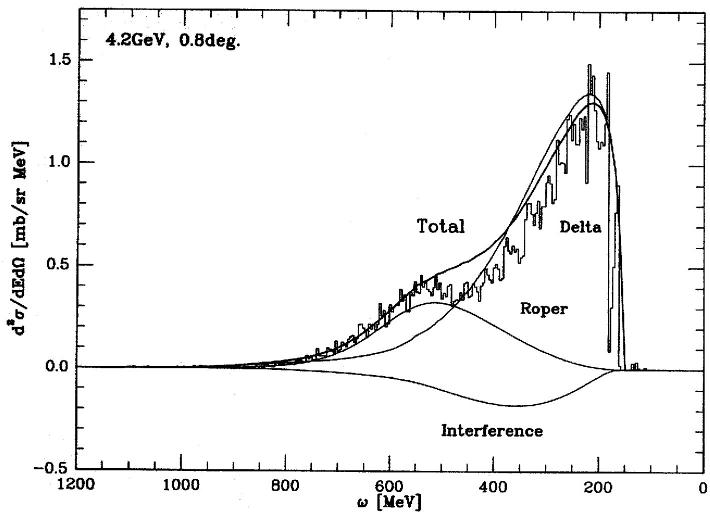

Fig. 2. Calculated cross section of the $\alpha + p \to \alpha + X$ reaction at $E_\alpha = 4.2$ GeV and $\theta = 0.8°$ as function of the energy transfer [15]. The contributions from the excitation of the Δ resonance in the projectile and of the $N^*(1440)$ in the target are shown together with their interference.

As illustrated in the next sections, major unknowns in discussing the role of the Roper resonance in the nuclear many-body problem are the strengths of the $\omega NN^*(1440)$ and $\rho NN^*(1440)$ couplings, on which there are no direct experimental data.

3. The contribution of the Roper resonance to the $pp \to pp\pi^0$ reaction close to threshold

The role of the Roper resonance in the inelastic $pp \to pp\pi^0$ channel of the nucleon–nucleon interaction has been studied recently [18]. It is a very nice process to investigate the role of intermediate baryon resonances in meson production because π^0 emission from a single proton underestimates largely the cross section and the π-exchange term is suppressed by the particular isospin structure of the reaction [19]. The main part of the $pp \to pp\pi^0$ cross section near threshold arises from the nucleon–antinucleon pair currents (or Z-graphs) [18]. The contributions from virtual intermediate resonances of isospin 1/2 provide corrections to the Z-graphs. A typical diagram, involving the excitation of the $N^*(1440)$ by σ-exchange, is shown in Fig. 3. The con-

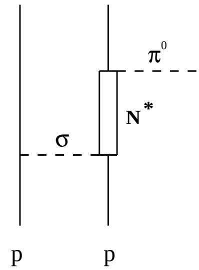

Fig. 3. σ-exchange contribution to the $pp \to pp\pi^0$ cross section involving the excitation of the $N^*(1440)$ resonance.

tribution from a virtual intermediate $N^*(1440)$ resonance is rather modest and enhances the cross section. In contrast to this behaviour, the contributions from the neighbouring $N^*(1535)$ and $N^*(1520)$ resonances apppear to reduce the cross section [18]. This effect is illustrated in Fig. 4, compared to data from Ref. [20].

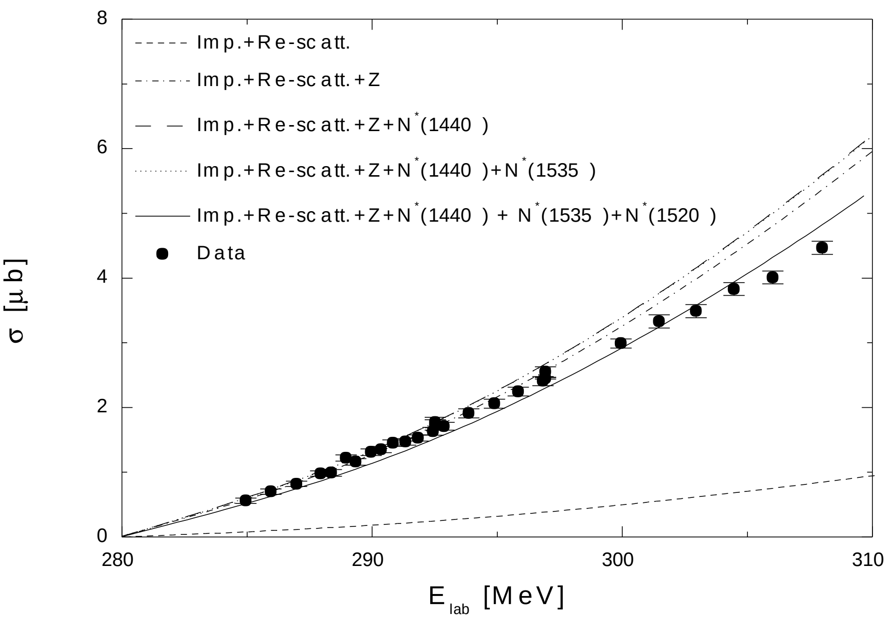

Fig. 4. Total cross section for the $pp \to pp\pi^0$ reaction near threshold (from Ref. [18]). The meaning of the different curves is explained in the figure and in the text. The data are from Ref. [20].

The reason for the smallness of the intermediate $N^*(1440)$ contribution is that the σ-exchange term depicted in Fig. 3 gets largely cancelled by the corresponding ω-exchange term [18]. The graphs are calculated assuming the relation

$$\frac{g_{\omega NN^*}}{g_{\sigma NN^*}} = \frac{g_{\omega NN}}{g_{\sigma NN}} = 1.55 \tag{12}$$

and the coupling constant

$$\frac{g^2_{\sigma NN^*}}{4\pi} = 0.1. \tag{13}$$

Using the values of $g^2_{\sigma NN^*}/4\pi$ discussed in Section 2, the contribution from the virtual $N^*(1440)$ excitation would be larger.

This discussion of the $pp \to pp\pi^0$ illustrates the need for data on the excitation of the nucleon into the $N^*(1440)$ through the ω-field. Such data are important to check or modify Eq. (12) and assess the role of the Roper resonance in nuclear processes involving short-range meson exchanges.

4. The contribution of the Roper resonance to the three-nucleon interaction

By very much the same processes as those involved in the pp$\to$ppπ^0 reaction, intermediate $N^*(1440)$ resonances can produce three-body forces [21]. Attaching a nucleon line to the pion in Fig. 3, we can generate the three-body diagram displayed in Fig. 5. Again, there is a similar graph where the exchanged σ-meson is replaced by an ω-meson.

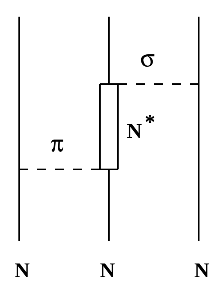

Fig. 5. $\pi\sigma$-exchange three-nucleon interaction involving the excitation of the $N^*(1440)$ resonance.

The sum of both σ- and ω-meson exchange diagrams generates a small but repulsive short-range three-nucleon interaction which is welcome in view of the slight overbinding of the triton [21]. In this case also, the three-body energies associated with the $\pi\sigma$- and $\pi\omega$-exchange diagrams have opposite sign and largely cancel. The values of $g_{\sigma NN^*}$ and $g_{\omega NN^*}$ are therefore crucial parameters in determining the exact strength of the three-nucleon interaction generated by virtual $N^*(1440)$ excitations.

5. The contribution of the Roper resonance to particle production in relativistic heavy ion collisions (E/A $\simeq$ 1–2 GeV)

In heavy ion collisions at relativistic energies ($E/A \simeq 1$–2 GeV), baryon resonances are excited during the initial stage of the reaction, when the colliding nuclei form a very dense nuclear system [22, 23]. In later stages, their interactions and decays influence strongly the production of hadrons [24, 25]. It is particularly so for the production of subthreshold particles because the internal energy stored in intrinsic baryonic excitations increases the two-body phase space of the subsequent collisions and helps in making higher mass hadrons [25].

The abundance of baryon resonances produced in relativistic heavy ion collisions depends on the impact parameter of the collision, on the energy of the projectile and on the mass of the resonance. At $E/A \simeq 1$–2 GeV, the most abundant baryon resonance is the $\Delta(1232)$. The $N^*(1440)$ abundance in ^{197}Au + ^{197}Au collisions is shown in Fig. 6 as function of time for different values of the impact parameter and beam energy [25].

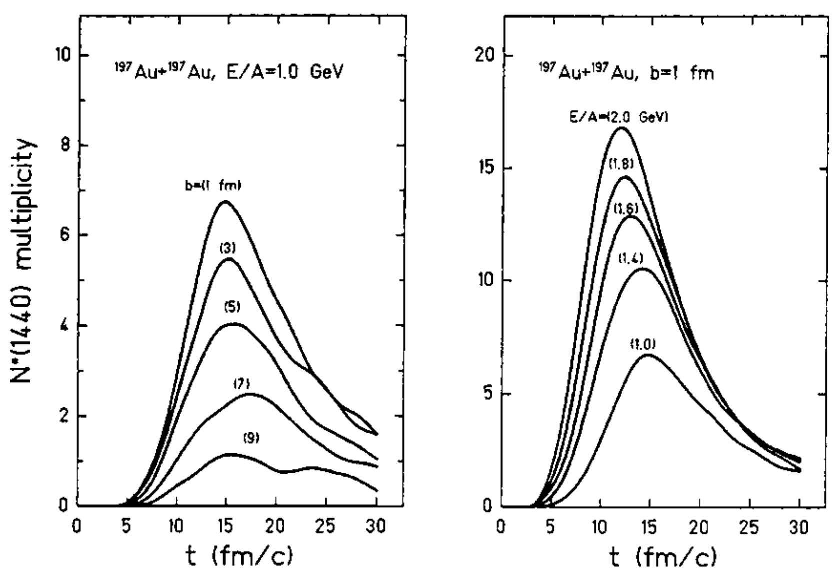

Fig. 6. Time evolution of the $N^*(1440)$ abundance in ^{197}Au + ^{197}Au collisions for different values of the impact parameter (left) and beam energy (right) [25].

It is interesting to compare the $N^*(1440)$ population displayed in Fig. 6 to the corresponding quantity for the $\Delta(1232)$. In central collisions (b=1 fm), the maximum number of $N^*(1440)$ resonances is 7 at 1 GeV per nucleon and 17 at 2 GeV per nucleon. In the same conditions, the maximum number of $\Delta(1232)$ resonances is 52 at 1 GeV per nucleon and 89 at 2 GeV per nucleon [25]. It is expected that particle production processes favoured by the excitation of high mass resonances will be very sensitive to the $N^*(1440)$ abundance and reflect the strong energy dependence of this quantity. This is illustrated in Fig. 7 for the production of antiprotons which appears dominated by intermediate $N^*(1440)$ excitation in the model of Ref. [25]. As cautioned by the authors, this calculation assumes free space properties for the baryon resonances involved and would be quite sensitive to in-medium broadenings or self-energies [25]. The results displayed in Figs. 6 and 7 should therefore be viewed as qualitative effects rather than detailed numerical predictions. Considering these uncertainties, it would be of much

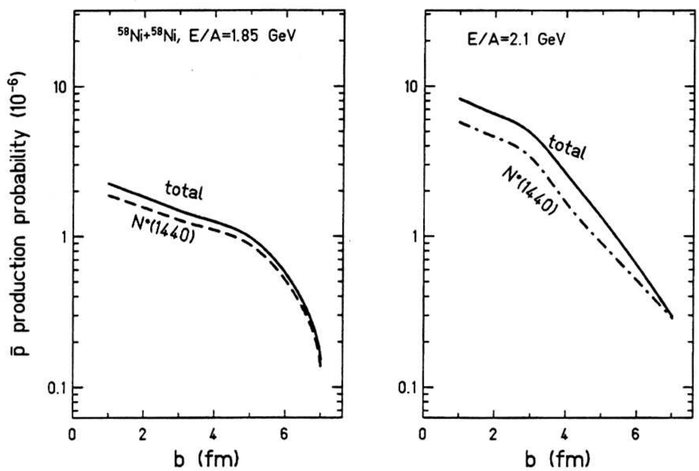

Fig. 7. Total (solid) and $N^*(1440)$ induced (dashed) antiproton production probability in ^{58}Ni + ^{58}Ni collisions at 1.85 and 2.1 GeV per nucleon [25].

interest to have an experimental signal of the excitation of the $N^*(1440)$ in relativistic heavy ion collisions. Such signal could have been seen recently in data taken by the FOPI Collaboration at GSI [26]. Four reactions were studied: ^{197}Au + ^{197}Au at 1.06 GeV per nucleon, ^{58}Ni + ^{58}Ni at 1.06, 1.45, and 1.93 GeV per nucleon. The measurement of correlated (p, π^+) and (p, π^-) pairs makes it possible to reconstruct the invariant mass spectra of the baryon resonances excited in the collision. These spectra [26] are shown in Fig. 8.

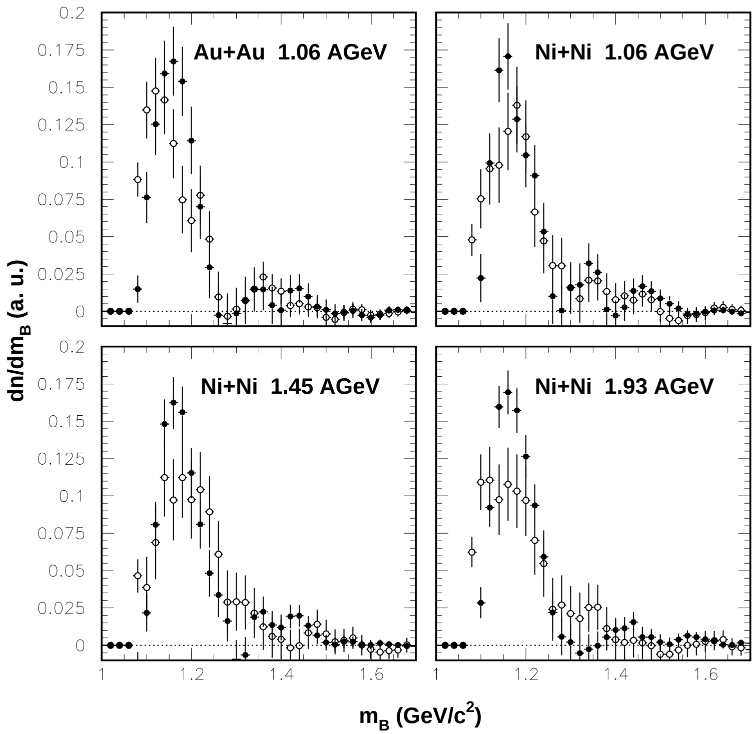

Fig. 8. The invariant mass spectra of correlated $(p,\ \pi^-)$ [open points] and $(p,\ \pi^+)$ [full points] pairs for the reactions indicated in the pictures (from Ref. [26])

The $(p,\ \pi^+)$ events come necessarily from the decay of $I = 3/2$ resonances (dominantly the $\Delta(1232)$) while the $(p,\ \pi^-)$ pairs can originate in the decay of $I = 3/2$ or $I = 1/2$ resonances. The comparison of $(p,\ \pi^+)$ and $(p,\ \pi^-)$ pair cross sections in Ni + Ni reactions (Fig. 8) indicates the presence of $I = 1/2$ resonance contributions with a mean free mass above the $\Delta(1232)$ mass. This contribution is of the order of 20 % [26]. The low-energy tail of the $N^*(1440)$ appears as the most plausible origin of this effect.

Detailed studies of the importance of the Roper resonance for particle production in relativistic heavy ion collisions ($E/A \simeq$ 1–2 GeV) require the understanding of the two elementary processes leading to its excitation, $\pi N \to N^*(1440)$ and $NN \to NN^*(1440)$. The $\pi N \to N^*(1440)$ process is constrained by the πN decay width of the $N^*(1440)$ discussed in Section 2. The $NN \to NN^*(1440)$ reaction is very poorly known, especially in the energy range needed for the interpretation of the $I = 1/2$ contribution of Ref. [26]. This problem is illustrated in Fig. 9, where the available data are plotted together with the result of the one-boson exchange model of Ref. [13]. The $\pi NN^*(1440)$ and $\sigma NN^*(1440)$ couplings used in this model differ significantly from the the values deduced in Section 2 and very low form factor cut offs (0.3–0.6 GeV) are needed to reproduce the available cross sections [13]. Data on the $NN \to NN^*(1440)$ reaction at energies appropriate to relativistic heavy ion collisions would be most useful.

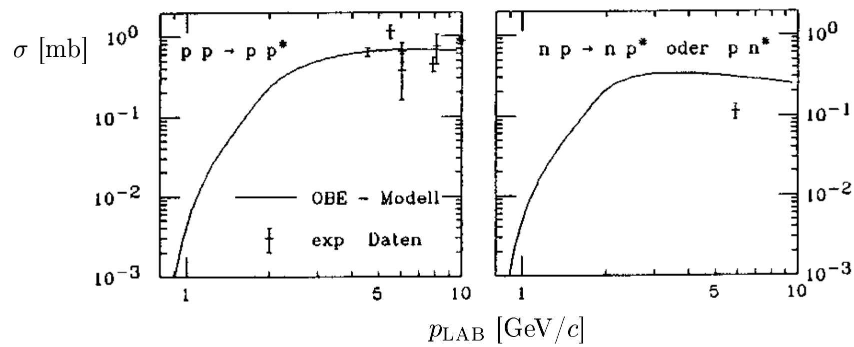

Fig. 9. $pp \to pN^{*+}(1440)$ and $np \to nN^{*+}(1440)$ cross sections compared to the one-boson exchange model of Ref. [13].

6. Conclusion

A fair conclusion of this lecture is that we have still a very poor understanding of the Roper resonance and of its role in the nuclear many-body problem. Progress on the latter issue is directly linked to the availability of new experimental data providing constraints on the couplings of the $N^*(1440)$ to the πN, σN, ωN and ρN channels. We emphasize particularly that the value of both the $\omega NN^*(1440)$ and $\rho NN^*(1440)$ coupling constants are at present completely unknown. The uncertainties associated with this problem are important because many-body diagrams involving the excitation of the Roper resonance through σ- and ω-meson exchanges appear to have opposite signs. The relative strength of the $\omega NN^*(1440)$ and $\sigma NN^*(1440)$ couplings determines therefore the net effect of the Roper resonance in the corresponding many-body processes.

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