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# Hyperon–Nucleon Scattering*

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## Abstract

The Nijmegen soft-core potential model is discussed in the context of modern views in strong interactions. The $NN$-version of this model is compared with some other, so-called realistic $NN$-potentials. A nice feature of this potential model is that it can easily be extended to the $YN$-channels using SU(3). It will be shown that the $YN$-version of this model gives a high quality fit to the existing experimental $YN$-data. Not only the scattering data are described very well, but also the capture ratio at rest is very good, and the $F/(F+D)$ ratio $\alpha_{PS}$ for the $PV$-coupling of the pseudoscalar mesons used in this model, could be kept in perfect agreement with the value from the weak interactions. Finally the reaction $\overline{p}p \to \overline{\Lambda}\Lambda$ will be discussed.

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## I. INTRODUCTION

When one wants to construct a meson-theoretical hyperon-nucleon potential, then it is of course clear that such a potential should fit all the availabe YN-data. When this is the only restriction placed on the potential, then it is not too difficult to construct such a potential, because of the freedom one has in the different coupling constants. A better way to proceed is to make a potential model that fits all available baryon-baryon ($BB$) and baryon-antibaryon ($B\overline{B}$) data. Especially the abundant and accurate $NN$-data contain a lot of information.

In this talk we will discuss the Nijmegen soft-core $BB + \overline{B}B$ potential model, which is based on Regge trajectory exchange. The $NN$-version [1] of this potential stems from 1978 and gave then (and also now) a very good fit to the data. The coupling constants and ideas used in the construction of this potential are in accordance with the low energy $\pi N$-data, the soft pion theorems, and the concept of duality. We will review here the theoretical background and the main results of the $YN$-potential of this model. A first version [2] was already presented at the 1986 meeting at Komaba in Japan.

We would like to point out that the same potential model has also been used in our latest fits to $\overline{N}N$-scattering [3] and in the description [4] of the reaction $\overline{p}p \rightarrow \overline{\Lambda}\Lambda$. These $\overline{B}B$-reactions can all be described very well with the help of this potential.

## II. ABOUT REGGE POLES

In Fig. 1 we give a graph of the total ($\sigma_T$) and of the elastic ($\sigma_{el}$) $pp$-cross sections as a function of the lab momentum $p_L$.

Two important regions can be distinguished:

1. The potential region: $p_L < 1\ GeV/c$. In this region a potential description gives a very good representation of the data. Most potential models are fitted to the $NN$-data with $T_L < 350\ MeV$. Because the inelasticities due to pion production are still very small at that energy, most potential models work reasonably up to say $T_L \approx 450\ MeV$. Note that $p_L = 1\ GeV/c$ corresponds to $T_L = 433\ MeV$.

2. The Regge region: $p_L > 2\ GeV/c$. In this region the Regge trajectory exchange picture gives a good representation of the data. The Pomeron is a very important ingredient of the Regge picture. Even at momenta as low as $p_L = 2\ GeV/c$ the Pomeron is the most dominant feature. It is therefore very curious, that most meson-theoretical potentials totally neglect this important exchange.

When one looks at the Regge pole models for high energy scattering [6,7] then one sees that the most important trajectories are the Pomeron trajectory $P$; the tensor trajectories, which contain the $A_2$, $f$, and $f'$; and the vector trajectories, with the $\rho$, $\omega$, and $\phi$.

The Pomeron was always a theoretical puzzle, but with the advent of QCD it was realized [8] that the Pomeron corresponds to multi-gluon exchange. To demonstrate the importance of this Pomeron we used the parameters of the 1966 model of Barger and Olsson [7]. At $p_L = 2\ GeV/c$ this model gives $\sigma_T = 45$ mb and $\sigma_{el} \approx 20$ mb in fair agreement with the data. However, when we leave out the Pomeron and keep the same parameters for the other trajectories, then the predictions change drastically, *e.g.* we obtain $\sigma_{el} \approx 2.3$ mb .

In high energy physics the Regge picture has been very successful and has given stimulans to many new ideas, like duality and strings.

This Regge picture makes extensive use of the analyticity properties of the amplitudes. This description can analytically be continued from higher energies $p_L > 2\ GeV/c$ to lower energies $p_L < 1\ GeV/c$. This was done *e.g.* by Jones and Khuri [9] in the early sixties. In 1965 Chew [10] applied it to the Pomeron. In bootstrap studies of the $\pi\pi$-system, it was found that the inclusion of the Pomeron is necessary [6].

The analytic continuation in the $NN$-system was done the first time [11] by Th.A. Rijken in 1975 and extended [12] in 1985 to all $BB$-channels. The result of these calculations can be summarized [13] as follows:

> Each exchanged trajectory will give rise to the one-boson-exchange (OBE) potential (with exponential form factors) corresponding to the lowest $J$ of the trajectory.

For example the pion-trajectory will contribute the one-pion-exchange potential (OPEP)

$$V_\pi(k^2) = -\frac{f^2}{m^2}\, e^{-k^2/\Lambda^2}\, \frac{(\underline{\sigma}_1 \cdot \underline{k})(\underline{\sigma}_2 \cdot \underline{k})}{k^2 + m^2} \ .$$

Somewhat curious trajectories are the Pomeron and the tensor trajectories. The main contributions from these trajectories come from $J = 0$. For example the Pomeron trajectory gives rise to a repulsive Gaussian central potential and will give also contributions to the spin-orbit and quadratic spin-orbit potential. The contribution of the Pomeron to the central potential looks like [1]

$$V_p(k^2) \approx \frac{g_p^2}{M^2}\, e^{-k^2/4m_p^2} \ ,$$

where the coupling constant $g_p^2$ and the effective mass $m_p$ can be obtained from high energy fits. It was very gratifying that in our 1978 fit [1] to the $NN$-data, where we kept $g_p^2$ and $m_p$ as parameters in the fit, we obtained values for these parameters in excellent agreement with the values obtained in the high-energy fits [1,13]. To demonstrate the importance of the Pomeron exchange potential we plot in Fig. 2 the contribution of the Pomeron and tensor-trajectories (dotted curve) to the $^1S_0$ Nijmegen potential (solid curve).

## III. THE NIJMEGEN SOFT-CORE $NN$-POTENTIAL

Using the ideas explained before, we constructed in 1978 a OBE-potential for $NN$ with exponential form factors [1]. Another important feature of this potential is, that we use the exchange of <u>all</u> members of a nonet (when this exchange is allowed) and do not take in advance the standpoint that certain exchanges may be neglected. We use the exchange of the following complete nonets:

$J^P = 0^-$: $\pi$; $\eta$, $\eta'$; $K$, $J^P = 0^+$: $\delta$; $\varepsilon$, $S^*$; $\kappa$,
$J^P = 1^-$: $\rho$; $\omega$, $\phi$; $K^*$, $J^P = 2^+$: $A_2$; $f$, $f'$; $K^{**}$, and the Pomeron.

Making use of SU(3), which is not a very important constraint yet in $NN$, we needed in total only 13 free parameters. These parameters are 11 coupling constants, the effective mass $m_p$ of the Pomeron, and one cut-off parameter $\Lambda$ (the same for all mesons) in the exponential form factor. These 13 parameters were searched to obtain a good fit to the 1969 Livermore phase shift analysis [14] of MacGregor, Arndt, and Wright. This phase shift analysis was based on a total of 1128 $np$ and $pp$ data and we obtained a fit corresponding to a $\chi^2$/datapoint = 2.09.

At present we are doing in Nijmegen $NN$-phase shift analyses [15]. As we have essentially finished our phase shift analyses of the $pp$-data up to $T_L = 350\ MeV$ we can compare potentials with the presently available $pp$-data using our $\chi^2$-surface [16]. Our final dataset contains 1383 $pp$-data.

| Potential | | ref. | $\chi^2$ /datapoint | |
|---|---|---|---|---|
| | | | 0–350 | 205–350 |
| Hamada-Johnston | (1962) | [17] | 10.76 | 3.10 |
| Reid soft core | (1968) | [18] | 3.11 | 2.50 |
| Nijmegen soft core | (1978) | [1] | 1.97 | 1.84 |
| parametrized Paris | (1980) | [19] | 4.93 | 2.56 |
| Argonne $v14$ | (1984) | [20] | 824. | 2.75 |
| static Bonn (OBEPR) | (1987) | [21] | 641. | 9.60 |
| new potential | (1988) | [22] | 1.14 | 1.21 |
| single energy PSA | (1988) | [23] | 0.97 | 1.02 |

TABLE I. **Comparison of different potentials with the *pp*-data.** Given is the $\chi^2$/datapoint for the different potentials in the energy regions $0 - 350\ MeV$ and $205 - 350\ MeV$.

In Table I we give the $\chi^2$/dpt for several of the well-known $NN$-potentials. We do this for all the data from 0 to 350 $MeV$, but also for the subset of data from 205–350 $MeV$. The reason for the 2nd choice is, that some of the potentials do not fit very well the very low energy $pp$-data, because they are fitted to the $np$-scattering length. This effect should have no big influence anymore above $T_L \approx 10\ MeV$, but to be sure we use as lower value $T_L = 205\ MeV$. For comparison we give the $\chi^2$/dpt obtained in the single energy Nijmegen phase shift analysis (PSA) [23]. Presumably every potential model will do worse than this PSA. We also give the present values for a new potential [22] we are constructing. This is a Reid-like potential based on the Nijmegen (1978) $NN$-potential. It is clear that after 10 years the Nijmegen (1978) $NN$-potential is still doing very well. Surprising is the fact that such a recent potential as the Bonn potential (1987) scores much worse than the old-fashioned Hamada-Johnston potential (1962).

In Fig. 3 we compare some of the Nijmegen (1978) potentials with the parametrized Paris (1980) potentials. Some curious features show up.

First of all we note that most potentials agree rather well for $r \gtrsim 1$ fm (except the $^3P$-central potential). The most surprising fact is the tail of the spin-orbit potential. In the Paris potential this must come from their $2\pi$-exchange and their $\omega$-exchange. In the

Nijmegen potential the main contributions are the OBE-contributions from $\varepsilon$, $\omega$, $\rho$, and $P$. There is marvellous agreement, even down to 0.5 fm, despite the different formalisms to come to this potential. The main difference between both potentials shows up in the inner region $r < 0.5$ fm . The Paris potentials change here very fast, indicating significant high momentum components in these potentials [24]. The central potentials become very strongly attractive ($\sim 2\ GeV$) near $r = 0$. The Nijmegen potentials have a much smoother behavior, with not such strong high momentum components.

## IV. CONSISTENCY OF THE MODEL

Important for any model is to what extent the present knowledge and theoretical concepts are incorporated into the model. In this respect, we make here briefly several remarks on the Nijmegen soft-core model.

Because of the compositeness of the mesons in QCD, the proper description of the meson-exchange forces is in principle in terms of Regge trajectories. This is strongly supported by the large $N$-expansion in QCD [25]. It is also clear in the Bethe-Salpeter equation approach to the $Q\overline{Q}$-system, which for any reasonable interaction leads to Regge poles. The Nijmegen model accepts the Regge-like nature of the mesons as the starting point in the derivation of the potentials. We also accept the Pomeron as a relevant physical object in the low energy domain. In low energy pion-nucleon and kaon-nucleon scattering the presence of the Pomeron has been convincingly demonstrated using finite-energy-sumrules (FESR) [26]. (It appeared that the background amplitude, which remains after the subtraction of the baryon resonances, is directly related to the Pomeron.)

In duality [27] the Pomeron is clearly an indispensible ingredient. Also the Pomeron has a natural place in QCD. In fact its physical nature can be understood as a two-gluon (or multi-gluon) effect [8]. We accept the duality between meson-exchanges and baryon resonances. This means for example, that $t$-channel Regge-exchanges, which couple to two pions, like the $\varepsilon$, $\rho$, and $f$, are equivalent with taking into account, in an average sense, the $s$-channel resonances $\Delta$, etc. This implies that if one takes the coupling of the $NN$-channels to the $N\Delta$-channels into account and one includes at the same time the full strength of $\varepsilon$, $\rho$, $f$, etc. exchange, then one should be aware of the double counting issue. If one uses $\varepsilon$-, $\rho$-exchange and $\Delta$-intermediate states with the physical coupling constants, then one is liable to some form of double counting in the duality sense. One can try to correct for this by reducing the physical coupling constants. This might lead then to problems when an SU(3)-generalization is needed from $NN$ to $YN$ [2].

In the present soft-core model, and also in our previous models D and F [28], which are meant for baryon-baryon scattering well below the $\Delta$ production-threshold, we have chosen to include only OBE-contributions to the potentials.

Another important question, which can be posed to any $NN$-potential model, is whether the contributing exchanges and their couplings are consistent with low energy $s$-wave pion-nucleon scattering and the soft-pion theorems [29].

Let us look for example at the $s$-wave $\pi N$-scattering lengths $a_0^+$ and $a_0^-$. Experimentally [30] $a_0^+ \approx 0$ and $a_0^- \approx 0.1\mu^{-1}$. In the literature the values for $a_0^+$ range from $-0.01\mu^{-1}$ to $0.01\mu^{-1}$ and for $a_0^-$ from $0.09\mu^{-1}$ to $0.10\mu^{-1}$. When one takes pseudovector (PV) coupling for the pion to the nucleon and when one includes only $\rho$-exchange [31], then everything seems OK. In BA one obtains $a_0^+ \approx -0.01\mu^{-1}$ and $a_0^- \approx 0.09\mu^{-1}$. But then one looks also at $\varepsilon$-exchange (some people call this the $\sigma$-meson). This exchange contributes to $a_0^+$ about $0.5\mu^{-1}$ and to $a_0^-$ nothing. Now one is in difficulties.

The inclusion of the Pomeron contribution improves this situation significantly, because there is a very substantial cancellation between the $\varepsilon$- and Pomeron-exchange contribution. The Pomeron might very well contribute to $a_0^+$ about $-0.5\ \mu^{-1}$. The margin here is actually $-(0.25-0.75)\ \mu^{-1}$, which is mainly due to the uncertainty in the low energy $P\pi\pi$-coupling. Obviously there is no contribution to $a_0^-$.

We conclude that the Nijmegen soft-core OBE-model is quite natural in QCD, and is consistent with the high-energy scattering models and with the soft-pion theorems for low energy $s$-wave pion-nucleon scattering.

## V. EXTENSION OF THE MODEL TO THE $YN$-CHANNELS

The extension of the Nijmegen (1978) $NN$-potential model to the $YN$-channels makes extensively use of SU(3) in order to reduce the number of parameters.

The coupling of a meson nonet to a baryon nonet is dependent on 4 parameters. These are: the mixing angle $\theta$, the singlet and octet coupling constants $g_1$ and $g_8$ and $\alpha = F/(F+D)$ ratio.

For the pseudoscalar $0^-$-nonet we use PV-coupling. The $\eta-\eta'$ mixing angle $\theta_{PS} = -23^o$ follows from the Gell-Mann-Okubo quadratic mass formula. We use the value $\alpha_{PS} = 0.355$ as determined in the weak decays [30]. The coupling constants $f_1$ and $f_8$ are determined by the $NN$-data. For this nonet we do not need to introduce any new parameter.

For the vector $1^-$-nonet we use as mixing angle $\theta_V = 37.5^o$, which follows from the quadratic GMO-mass formula. Ideal mixing means
$\omega = (u\overline{u} + d\overline{d})/\sqrt{2}$ and $\phi = s\overline{s}$ and gives $\theta_V = 35.3^o$.
Using the idea of universal coupling of the vector mesons, as formulated by Sakurai [31], we take $\alpha_E = 1$. For the Pauli coupling we take $\alpha_M = 0.275$ from relativistic SU(6) as formulated by Sakita and Wali [32]. The remaining coupling constants $f_1$, $f_8$, $g_1$, and $g_8$ are determined in the fit to the $NN$-data. Thus also here we do not need to introduce any new parameters.

For the scalar $0^+$-nonet the situation is different. The non-strange mesons are $\varepsilon$, $S^*$, and $\delta$. When these mesons are $Q\overline{Q}$ bound states then ideal mixing would give $\theta_S = 54.7^o = 90^o - \theta_V$. When these mesons are $Q^2\overline{Q}^2$ states, then ideal mixing would give $\theta_S = \theta_V = 35.3^o$.

In the $YN$-potentials we use $\theta_S$ as a parameter in the fit. We obtain $\theta_S = 40.91^o$. The coupling constants $g_1$, $g_8$, and $\alpha_S$ are determined again from the $NN$-data. The scalar mesons supply us thus with only 1 parameter.

For the Pomeron and tensor nonet exchange we fitted in $NN$ two parameters. The situation is here somewhat different than in the other cases. Using SU(3) we need only one extra parameter $\psi$, which measures for example the SU(3) character of the Pomeron. Here $\psi = 0$ would mean that the Pomeron is an SU(3) singlet. In the fit to the $YN$-data we obtained $\psi = 15^o$.

| | $^1S_0$ | $^3S_1 + {}^3D_1$ |
|---|---|---|
| $NN$ | 964.52 | 964. |
| $\Sigma^+ p$ | 964. | 1200. |
| $\Lambda N + \Sigma N$ | 820. | 1270.5 |

TABLE II. The cut-off parameters $\Lambda$ in $MeV$ used for the different states and channels.

This discussion shows that we have only two free parameters to fit in $YN$. These two are insufficient to give a good fit to the $YN$-data. Therefore we use the cut-off parameter $\Lambda$ for the fine-tuning. In Table II we give the values used for this parameter.

In Fig. 4 we show the fits obtained with this potential to the available $YN$-data. A very difficult number to fit is the capture ratio at rest for the reaction $\Sigma^- p \to \Sigma^0 n$ or $\Lambda n$

$$r_R = \frac{\Sigma^o}{\Sigma^o + \Lambda^o} \ .$$

Experimentally [33] one finds $r_R = 0.468 \pm 0.010$. The model gives $r_R \ = \ 0.469$. We fitted 35 data with 5 parameters. The expected $\chi^2_{\rm min} = 30$. In the fit we get $\chi^2_{\rm min} = 15$. The errors are not really statistical, so this $\chi^2$ does not mean too much. The low value shows, however, that the fit seems reasonable.

The predicted scattering lengths and effective ranges are then for

$$\begin{aligned} \Sigma^+ p \ {}^1S_0\!: \ a_0 &= -3.35 \text{ fm} \ \text{ and } r_0 = \ \ 3.46 \text{ fm} \\ {}^3S_1\!: \ a_1 &= \ \ 0.46 \text{ fm} \ \text{ and } r_1 = -6.96 \text{ fm} \ . \end{aligned}$$

For the low-energy $\Lambda N$ system we find

$$\begin{aligned} \Lambda p \ {}^1S_0\!: \ a_0 &= -2.73 \text{ fm} \ \text{ and } r_0 = 2.87 \text{ fm} \\ {}^3S_1\!: \ a_1 &= -1.48 \text{ fm} \ \text{ and } r_1 = 3.04 \text{ fm} \\ \Lambda n \ {}^1S_0\!: \ a_0 &= -2.86 \text{ fm} \ \text{ and } r_0 = 2.91 \text{ fm} \\ {}^3S_1\!: \ a_1 &= -1.24 \text{ fm} \ \text{ and } r_1 = 3.33 \text{ fm} \end{aligned}$$

When we neglect the breaking of charge symmetry we get

$$\begin{aligned} \Lambda N \ {}^1S_0\!: \ a_0 &= -2.78 \text{ fm} \ \text{ and } r_0 = 2.88 \text{ fm} \\ {}^3S_1\!: \ a_1 &= -1.41 \text{ fm} \ \text{ and } r_1 = 3.11 \text{ fm} \end{aligned}$$

Note that in the present YN-model for $\Lambda p$ we have clearly that $|a_s| > |a_t|$, whereas the Nijmegen hard core models D and F [28] have $a_s \sim a_t$. Repercussions of this on for example the $\Lambda$-binding energies $B_\Lambda$ in hypernuclei will be interesting. Preliminary results of recent calculations by Carlson and Gibson [38] show that, for the $A = 4$-systems, the difference

$B_\Lambda(0^+) - B_\Lambda(1^+) = 1.1\ MeV$, which is about the experimental value. However, for both cases there seems to be not enough attraction.

## VI. THE REACTION $\overline{P}P \rightarrow \overline{\Lambda}\Lambda$

We have also applied this Nijmegen potential model in descriptions of the various $\overline{B}B$ reactions, like the elastic $\overline{p}p \rightarrow \overline{p}p$, the charge exchange $\overline{p}p \rightarrow \overline{n}n$, and the strangeness exchange $\overline{p}p \rightarrow \overline{\Lambda}\Lambda$ reactions.

We use a $P$-matrix or boundary condition model, where we parametrize the $P$-matrix at $b = 1$ fm and for $r > 1$ fm we take the Nijmegen potential. Excellent fits [3] have been obtained for the elastic and charge exchange reactions. Let us here say something about the strangeness exchange reaction [4]. Many different groups [39] have studied this reaction with various models. Our model gives also here a very good fit to the available data [40].

In Fig. 5 a we show our fit at $p_L = 1546.2\ MeV/c$ to the 20 $d\sigma/d\Omega$ data with $\chi^2/N_d = 1.2$ and in Fig. 5 b to the 14 polarization data with $\chi^2/N_d = 1.0$. In Fig. 5 c and d, we compare at $p_L = 1445.35\ MeV/c$ corresponding to $\varepsilon = 3.62\ MeV$. The 10 $d\sigma/d\Omega$ data we fit here with $\chi^2/N_d = 1.1$ and the 10 $P(\theta)$ data with $\chi^2/N_d = 0.6$

Very interesting are the very low energy data [41], just above the $\overline{\Lambda}\Lambda$-threshold. The cm-energy of the final $\Lambda\overline{\Lambda}$ state we call $\varepsilon$. We note that at low energies (even at $\varepsilon = 0.66\ MeV$) the $P$-waves are not negligible. How is this possible? The reason is that the annihilation in the final $\Lambda\overline{\Lambda}$-channel has a **very strong** influence on the reaction rate. It suppresses enormously the $S$-waves and only weakly the $P$-waves. At $\varepsilon = 0.66\ MeV$ 15% of the cross sections goes to a $P$-final state and at $\varepsilon = 3.62\ MeV$ this is already 40%.

Important in this reaction are the coherent tensor forces due to the exchange of $K$ and $K^*$. Both these exchanges are necessary to get a very good fit to the data. These strong tensor forces are responsible for large transition amplitudes between the ${}^3L(\overline{N}N)$ states and ${}^3L(\overline{\Lambda}\Lambda)$ states where

$$ {}^3L(\overline{\Lambda}\Lambda) = {}^3L(\overline{N}N) - 2 \ . $$

Important transitions are therefore

$$ {}^3D_1(\overline{N}N) \rightarrow {}^3S_1(\overline{\Lambda}\Lambda) \quad \text{and} \quad {}^3F_2(\overline{N}N) \rightarrow {}^3P_2(\overline{\Lambda}\Lambda) \ . $$

At $\varepsilon = 0.66\ MeV$ they contribute 69% and 1.5% to the total cross section and at $\varepsilon = 3.62\ MeV$ their contributions are 51% and 12.3%.


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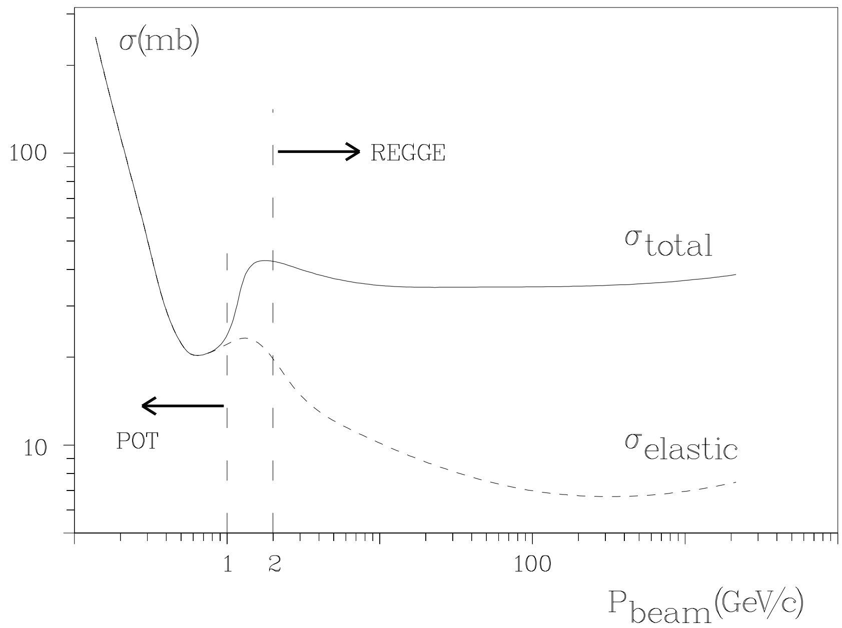


FIG. 1. The total and the elastic $pp$-cross sections as a function of $p_{\rm lab}$ [5]. The potential region and the Regge region are indicated.

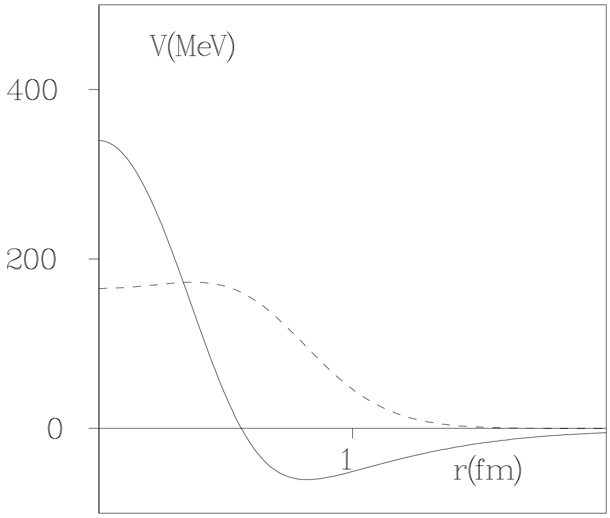


FIG. 2. The Nijmegen soft-core potential [1] for the $^1S_0$-state (solid curve) and the contribution of the Pomeron and tensor trajectories (dashed curve) to this potential.

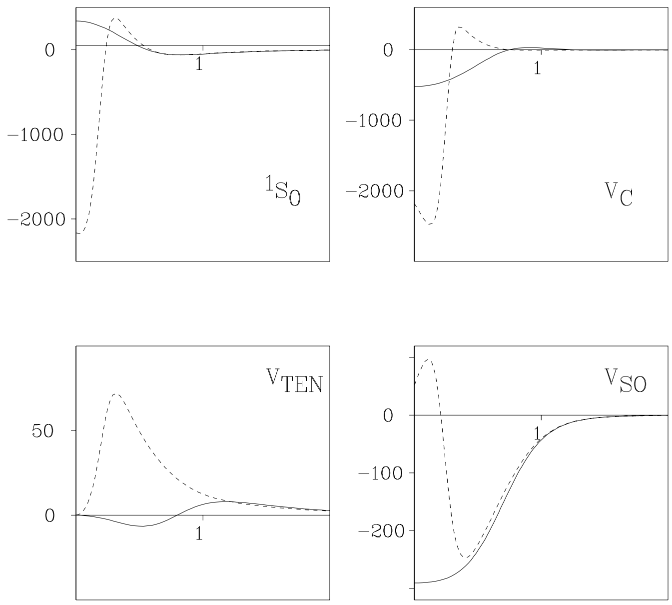


FIG. 3. The Nijmegen (1978) soft-core potential [1] (solid curves) and the parametrized Paris (1980) potential [19] (dashed curves), for the $^1S_0$- and $^3P$-states in $MeV$, as a function of the distance $r$ in fm.

FIG. 4. The cross sections in mb for the various reactions as a function of the laboratory momentum in $MeV/c$. The experimental $\Lambda p$-data are from Refs. [34] and [35]. The elastic $\Sigma^+p$-data are from Ref. [36] and the inelastic $\Sigma^-p$-data are from Ref. [37].

FIG. 5. Cross sections and polarizations for the reaction $\overline{p}p \rightarrow \overline{\Lambda}\Lambda$ at $p_L = 1546.2$ $MeV/c$ (a and b) and at $p_L = 1445.35$ $MeV/c$ (c and d).