Introduction

A thorough understanding of the basic forces that govern the interaction of nucleons and nuclei has lain at the basis of the continuous research effort in nuclear physics over the time. Early successes are represented by Yukawa’s realization in 1935 that the strong interaction is mediated by finite range particles, later called pions. The effort has continued with the development of the effective range formalism \[1\] in the 40’s and of the pion theories in the 50’s \[2, 3, 4, 5, 6\]. A common feature of these latter models was the incapability to produce a spin-orbit term consistent with experiment \[7\]. Their failure is now understood in view of the fact that pion dynamics constrained by chiral symmetry was unknown back then. The discovery of the heavier mesons in the early 1960’s led to the development of one-boson-exchange (OBE) models \[8, 9, 10\]. Besides the one-pion-exchange diagram, the potential also collects contributions from heavier mesons, most commonly the $\rho$, $\omega$, $\eta$, $\delta$ and $\sigma$. The last is an idealization of a strong S wave $\pi\pi$ correlation observed experimentally and described as a wide mass distribution of about $600\pm250$ MeV, possibly resulting from a broad scalar meson \[11\]. This fact together with the inclusion in the potential of only tree-level meson-exchange diagrams constitute the two main deficiencies of the OBE models. One of the most sophisticated representative of this class is the non-relativistic Nijmegen potential \[12\].

The importance of the two-pion-exchange contributions to the medium-range $NN$ potential ($\approx 1.5$ fm) was already known from the 50’s. Two approaches are possible for the inclusion of such contributions: field theoretic (pursued by Partovi and Lomon \[13\] and the Bonn group \[14\]) and dispersion theory (Stony Brook \[15\] and Paris \[16, 17\] groups). For the short-range part, again, two approaches have been possible: meson theory, pursued by the Bonn group who has considered $\pi\rho$ contributions to the potential and a phenomenological approach, the short-range part of the potential being described by a soft-core term (Paris group). A reasonable description of the $NN$ scattering data base is achieved by these models with values of the $\chi^2$/data-point close to 2.0 for both the $pp$ and $np$ data. In the last decade, modern charge-dependent nucleon-nucleon potentials such as CD Bonn \[18\], Argonne V18 \[19\] and the Nijmegen I,II and Reid93 \[20\] have provided a even better description of the available elastic $NN$ scattering data, close to $\chi^2$/data-point=1.0.

In the last two decades an alternative approach for the study of strong interactions has appeared. The discovery of quantum chromodynamics (QCD) has led to the hope of setting the derivation of the nucleon-nucleon interaction on a firm basis. It has proved impossible to do so, due to the nonperturbative character of QCD in the region of interest.
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for nuclear physics. Nevertheless at energies close to 1 GeV a transition between fundamental and effective levels takes place via the spontaneous breaking of chiral symmetry which generates a set of pseudoscalar Goldstone bosons. Therefore at energies of interest for nuclear physics the appropriate degrees of freedom are mesons and hadrons, rather than quarks and gluons. The correct low-energy limit of QCD is ensured by including all possible interaction terms. The effective theory which describes the low energy regime of strong interactions is known as chiral perturbation theory [21, 22]. The implementation of such ideas for the nucleon-nucleon interaction knows a few variations: in the KSW approach [23, 24, 25] the amplitude of interest is calculated perturbatively. In a second approach, proposed by Weinberg [26, 27, 28], the effective expansion is applied at the level of the potential. A first comprehensive implementation of Weinberg’s scheme was accomplished by Ordóñez et al. [29, 30] who constructed an energy-dependent \( NN \) potential allowing a qualitative description of the experimental data. An energy-independent version of the \( NN \) potential at next-to-next-to-leading order (NNLO) in chiral perturbation theory has been constructed by Epelbaum et al. [31, 32] using the method of unitary transformations. In the last few years the \( NN \) potential has been determined up to \( N^3LO \) order in chiral perturbation theory [33, 34, 35, 36, 37] and using these results a fit approaching the quality of modern phenomenological \( NN \) potentials was possible [38, 39].

Inelastic nucleon-nucleon reactions have attracted a lot of interest over the years in the context of studies of the strong interaction. In particular, proton-proton bremsstrahlung has been much studied both theoretically and experimentally following the proposal of Ashkin and Marshak [40] that this simple reaction could be used to discriminate among the various competing potentials, due to its sensitivity to their off-shell structure which could not be inferred from elastic scattering measurements. The agreement of early proton-proton bremsstrahlung (pp\( \gamma \)) models [41, 42, 43, 44] with the existing experimental data was rather good due to the relatively poor accuracy of the latter [45, 46, 47].

The advances in experimental techniques have made possible the relatively high precision experiment at TRIUMF [48] having as result a series of new theoretical investigations [49, 50, 51, 52]. The TRIUMF experimental data have been normalized by a factor 2/3 in order to facilitate comparison with theory [48] leading to controversies [53] and making impossible a definitive comparison of the various existing models for pp\( \gamma \) with experiment. Even so, a systematic disagreement between theory and experiment has been observed for certain asymmetric proton angles. It was hoped that new experiments [54, 55, 56, 57] would improve the situation, but the release of the very high accuracy data of the KVI pp\( \gamma \) experiment [57, 58] has revealed a sizable discrepancy between theory and experiment. This is in spite of the developments on the experimental side and of the continuous increase in sophistication of the theoretical models developed for the description of the this reaction. The observed discrepancies are a characteristic of microscopical models for bremsstrahlung, while soft-photon theorem based models [59, 60] allow for a good description of the available data. At the same time, in the recent years, studies with contradictory results [61, 62] about the sensitivity of bremsstrahlung observables to off-shell effects have been performed. Most of the microscopic models developed in the last decade include contributions of meson-exchange currents and of the \( \Delta \) isobar [63, 64]. Proton-proton bremsstrahlung offers a unique testing ground for these rela-
tively little studied contributions. A good knowledge of the meson-exchange currents is required for an accurate description of neutron-proton bremsstrahlung, where they are extremely important. For this to be possible the mentioned discrepancy between theory and experiment has to be cured.

In the above historical presentation we have limited ourselves to two reactions currently employed in the study of the strong interaction. The list is of course much longer, but it is only these two that have been covered during the research presented in this thesis. The order of discussion in the chapters to come is reversed and follows the order in which these two topics have been investigated.

The first three chapters are dedicated to the study of proton-proton bremsstrahlung. The starting point of the present investigation of $pp\gamma$ has been the already mentioned fact that at the time of the release of the high-accuracy KVI experimental data a large discrepancy with the theoretical predicted values for the differential cross section had been observed for an important fraction of the kinematical cases covered by this experiment. Chapter 2 outlines the status $pp\gamma$ calculations as of 1999. The ingredients of the relativistic covariant model for bremsstrahlung of Martinus et al. [52, 63, 65, 66] are presented together with a brief description of the model developed by Nakayama and coworkers [67, 49, 64, 68]. The latter serves as a support for the later conclusion that all microscopic calculations produce similar results. We have already mentioned that soft-photon models for bremsstrahlung allow for a reasonable reproduction of the $pp\gamma$ differential cross-sections. As an example we present results of the model of Korchin and Scholten [60, 69].

The $pp\gamma$ model of Martinus et al. does not take into consideration corrections of the Coulomb interaction. Within a relativistic covariant model, formulated in momentum space, this would be a difficult task. We argue that Coulomb corrections to $pp\gamma$ could be important under special circumstances even at 190 MeV, the energy of the KVI bremsstrahlung experiment. We have constructed a non-relativistic toy model for proton-proton bremsstrahlung which fully accounts for these effect in the $^1S_0$ partial wave, whose ingredients are presented in Chapter 3. Two versions of this toy model are presented: the first incorporates a separable approximation of the nucleon-nucleon interaction, while for the second a modified version of the effective field theory model of strong interaction in presence of the Coulomb interaction due to Kong and Ravndal [70] is used. Calculations are performed in a mixed representation. To conclude the chapter a comparison with results of $pp\gamma$ model of Heller and Rich [71] is presented, which serves also as a check for our calculation.

In Chapter 4 two possible sources for the observed discrepancy between theory and KVI experimental data are discussed: Coulomb effects and sensitivity of the bremsstrahlung cross section to the on-shell $NN$ interaction. To study the former the toy model developed in Chapter 2 is used, while for the latter a detailed study of the contributions of individual $NN$ partial waves is performed. It is shown that for the problematic KVI kinematics $pp\gamma$ cross section is highly sensitive to the details of the low energy $NN$ interaction. It is discussed how, by carefully considering the details of the low energy $NN$ interaction, the discrepancy can be reduced, though not completely.

In the second part of the thesis, represented by Chapters 5 and 6, the elastic scattering of two nucleons is studied. One of the ingredients of the Martinus model is the quasipoten-
tial OBE developed by Hummel and Tjon [72, 73, 74] in the context of the study electron-deuteron scattering, with origins in the OBE model of Fleischer and Tjon [10, 75, 76]. As in any OBE model the medium-range central attraction is described by the introduction of the fictitious $\sigma$ meson. It has long been known that the dominant part of these contributions are due to correlated two-pion exchanges (TPE). With the advent of effective field theories it has become possible to classify the two-pion exchange contributions according to their importance in a specified energy region. It has thus become practical to extend OBE exchange models such that their kernels include two-pion exchange contributions in a systematic way. Such an approach is possible only for non-relativistic models, since the effective theory for the two-nucleon system is an expansion in terms of the three-momentum of the participating nucleons. In the case of a relativistic model terms at a certain order in the effective expansion combine with terms of higher order to make up relativistic covariant amplitudes. Therefore, even though such an approach is not manifestly systematic, it bears similar features to an effective expansion when carefully treated. In Chapter 5 the extension of the OBE model of Fleischer and Tjon along these lines is presented. We start by a review of the original model and then present some basic facts about chiral symmetry and its implications for the $NN$ interaction. All possible interaction terms with at most two derivatives, allowed by chiral symmetry, are constructed and only those terms that according to Weinberg's chiral power counting contribute up to fourth order in the chiral expansion are kept (first order is the one pion exchange and there are no contributions at second order). Besides the traditional pseudovector pion-nucleon coupling, $\pi\pi NN$ terms are now present in the interaction Lagrangian: the Weinberg-Tomozawa term and two-pion interactions corresponding to the low-energy coupling constants (LECs) $c_1, c_3$ and $c_4$, present in chiral perturbation theory [77]. The heavy-meson interactions are kept. In the remaining part of the chapter the explicit expressions of the TPE contributions is presented together with the algorithm used for their numerical evaluation.

Chapter 6 is entirely dedicated to the presentation of the results of the modified OBE model. We start with the phenomenological interpretations of the LECs [78] followed by a comparison of the coordinate space TPE and OBE potentials. For the former the coordinate space expressions derived by Kaiser [33, 35, 36, 37] up to $N^3LO$ in chiral perturbation theory have been used. They are thought to provide a good approximation to the full relativistic result. The main sections of this chapter are represented by the results for the peripheral partial waves for elastic $NN$ scattering followed by results for lower partial waves. For the description of the former OPE and TPE contributions are sufficient. For the latter the full model is used (heavy mesons+OPE +TPE). A few preliminary fits of the full model to the elastic $np$ scattering data, obtained by a readjustment of the heavy-meson coupling constants and cut-off parameters, are presented.