Theoretical understanding of pion production in nucleon-nucleon collisions - a status report

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A status report is given for the current theoretical understanding of pion production close to threshold. In the first part of the talk predictions of a meson exchange model are compared to recent polarized data for the reactions $pp \rightarrow pp\pi^0$ as well as $pp \rightarrow pn\pi^+$ revealing, that the former reaction is badly described whereas the predictions for the latter turn out to be consistent with the data. Recent progress in the application of chiral perturbation theory allows to understand this difference.

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The highly accurate data for pion production in nucleon–nucleon collisions close to the production threshold are a challenge for theoreticians. When the first close to threshold data for the total cross section of the reaction $pp \rightarrow pp\pi^0$ appeared in 1990, existing models fell short by a factor of 5–10 [1, 2]. Many different mechanisms were proposed to cure this discrepancy: heavy meson exchanges [3], (off-shell) pion rescattering [4, 5], excitations of baryon resonances [6], and pion emission from exchanged mesons [7]. The total cross sections for the reactions $pp \rightarrow pn\pi^+$ and $pp \rightarrow d\pi^+$ on the other hand could always be described within a factor of 2 — the amplitude is dominated by the (on–shell) rescattering contribution [1].

Recently the database on pion production was vastly enhanced due to a large program at IUCF to measure double polarized observables for the pion production reactions [8, 9, 10]. Unfortunately, until now there is only one model published whose results can be compared to those highly accurate data [11]. This model includes the direct or one body terms, pion rescattering, where the interaction of the virtual pion with the second nucleon is taken from a microscopic model, and an additional diagram that was introduced as an effective parameterization for the missing short range mechanisms. The strength parameter of the latter is the only free parameter.
of the model. It was adjusted to the total cross section of $pp \rightarrow pp\pi^0$ close to the threshold. After the publication of the data it turned out, that the model predictions are very successful for the production channels involving charged pions whereas it badly fails for the differential observables for the $\pi^0$ production (c.f. Fig. 1). Thus, also here we find a striking difference between the production of charged and neutral pions.

How can we understand this? A natural tool to use is that of effective field theory, since the dynamics of the pions as pseudo Goldstone bosons is largely controlled by chiral symmetry. In the literature there is a vast number of publications studying the $s$–wave of the $pp \rightarrow pp\pi^0$ channel [12, 13]. However, most of them employ the original Weinberg counting scheme and thus ignore the large momentum scale inherent to meson production reactions. The only work so far where this insight was applied rigorously is Ref. [14]. Here it was found that the chiral expansion converges for pion $p$–waves and only tree level diagrams enter up to $N^2LO$. In the case of
s–waves, however, within this counting loops enter at $NLO$. At leading order there is already a remarkable difference between the production of $\pi^0$ and $\pi^+$: the leading order rescattering vanishes in the former case whereas it is sizable in the latter, driven by the so called Weinberg–Tomazawa term. For the leading loop contributions we observe a similar pattern: the loops add up to zero for the $pp \rightarrow pp\pi^0$ channel whereas there is a remainder for the charged pions (note: at this order loops that contain a Delta isobar add up to zero in both channels) [15]. At $N^2LO$ the number of loop diagrams is quite large and a couple of low energy constants enter, that might be estimated from resonance saturation.

Thus we may conclude at this stage, that the reactions $pp \rightarrow pn\pi^+$ as well as $pp \rightarrow d\pi^+$ are well under control theoretically. This is not true for the reaction $pp \rightarrow pp\pi^0$. However, effective field theory arguments can be used to understand this finding.

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