# Current understanding of the reaction mechanism in two-nucleon transfer reactions

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**Abstract.** The current understanding of the reaction mechanism of proton-induced two-nucleon transfer reactions is reviewed. The ideal is to employ a theoretical formulation which accurately reflects the important physics, but which is nevertheless still fairly simple. The influence of sequential transfer of the two nucleons involved in a pickup reaction is the most obvious complication that has to be considered. This is discussed in detail.

## 1. Introduction

Two-nucleon transfer reactions offer a powerful method to study pairing correlations in atomic nuclei. In principle reactions such as $(p,^3\text{He})$ and $(p,t)$ should proceed in a very simple way, but there may be many complications. One issue which is especially contentious, is to what extent a sequential process competes with a direct, simultaneous two-nucleon reaction. In the former process, applicable to for example a $(p,t)$ reaction, the reaction is envisaged as a single-nucleon $(p,d)$ reaction as a first step, followed next by a $(d,t)$ reaction. Of course, this sequential mechanism can involve a number of intermediate states all ending in the same final state. Whereas some authors simply ignore the possibility of sequential transfer (See for example Ref. [1]), others (See for example Ref. [2]) believe that it is crucial to include it properly. Yet a third group (See for example Ref. [3]) readily admits the controversy, and then exploits the situation to justify their implementation of a simplistic theoretical analysis.

In this paper I review the historical development of our understanding of the two-nucleon pickup reaction. In addition, I will try to reconcile results of different studies which appear to be of a conflicting nature. Clearly a comprehensive review is not possible in a short contribution such as this, but I will attempt to include most of the salient insights which have contributed to our knowledge of the topic over the years.

## 2. Insight into proton-induced two-nucleon pickup

As would be expected, first attempts to interpret two-nucleon transfer made use of the same techniques previously employed successfully to analyze single-nucleon transfer, namely plane-wave Born approximation (PWBA), later distorted-wave Born approximation (DWBA). The nucleons in the target were consequently described as a single particle (di-nucleon) system bound to the core of the target system with quantum numbers based on conservation of oscillator

quanta. However, from the start it was already clear that structure amplitudes [4] which may be extracted from wave functions generated in a microscopic model, need to be employed for a realistic assessment of results from two-nucleon pickup. In spite of various  refinements to the theory, such as for example inclusion of finite range effects, it soon became clear that the theoretical analyses appear to underpredict absolute cross sections to a disconcerting extent. At roughly the same time as this was identified as a problem, the reaction $^{208}$Pb$(p,t)^{206}$Pb to the first $3^+$ state, which has unnatural parity and is thus forbidden in zero-range approximation (although not in finite range) was studied. The theoretical implications of sequential transfer was fully investigated and found to resolve the cross section problem [5]. A dissenting opinion emerged from the work of Nagarajan *et al.* [6].

Pinkston and Satchler summarize the issues that need to be addressed correctly in two-nucleon transfer as follows [7] :

- Exact treatment of finite range of interaction (not zero range)
- Include simultaneous plus sequential transfer
- Account for a non-orthogonality correction (which tends to cancel the one-step contribution)
- Allow intermediate system to be in a continuum state (breakup effect)
- Use correct potentials to generate distorted waves
- Use correct nuclear wave functions to construct two-nucleon overlaps

They point out that unless all these ingredients are treated correctly, results from such studies should be viewed with some caution. However, many recent papers (See for example Refs. [1, 3, 8]) very successfully analyze two-nucleon pickup in terms of a simplistic, single-step semi-microscopic cluster DWBA formulation. An example is shown in Fig. 1. It needs to be understood whether such a treatment is adequate, and if so, what its range of validity is in terms of target mass and incident energy.

As was mentioned before, the possible influence of a sequential transfer reaction mechanism is of profound importance. In order to investigate the relationship between cross section angular distributions which either include or exclude the sequential component, it is useful to consider the theoretical expressions. For this purpose we reproduce a brief summary of the theory, based on the formulation of Charlton [9] who writes the two-nucleon transfer $T$-matrix element, in a notation appropriate for a $(p,t)$ reaction, as

$$T_{tp} = \langle \chi_t^{(-)} \left| \widehat{V}_t + \widehat{V}_t G^{(+)} \widehat{V}_p \right| \chi_p^{(+)} \rangle, \tag{1}$$

where the wave functions $\chi$, potentials $\widehat{V}$, and Green's function have the meaning as described in Ref. [9] . This expression is then shown to be approximately equal to the sum of two terms:

$$T_{tp} \approx T_{tp}^{sim} + T_{tp}^{seq}, \tag{2}$$

where the simultaneous part is given by

$$T_{tp}^{sim} = \langle \chi_t^{(-)} \left| \widehat{V}_t \right| \chi_p^{(+)} \rangle, \tag{3}$$

and the sequential component by

$$T_{tp}^{seq} = \langle \chi_t^{(-)} \left| \widehat{V}_t G_d^{(+)} \widehat{V}_p \right| \chi_p^{(+)} \rangle. \tag{4}$$

The Green's function $G_d^{(+)}$ is related to $G^{(+)}$ in a simple way, as defined by Charlton [9].

As Satchler cautions [10], splitting the simultaneous and sequential parts of the mechanism in this way, is somewhat misleading. Nevertheless the expressions give some insight into the relationship between the simultaneous and sequential mechanisms involved in the reaction. Of

course, Eq. 3 is the normal DWBA expression for simultaneous transfer. Also, keep in mind that Eq. 4 applies to each intermediate state $\phi_i$ participating in the sequential process. The full contribution for all intermediate states can therefore be written as

$$T_{tp}^{seq} = \sum_i \langle \chi_t^{(-)} | \widehat{V}_t | \phi_i \rangle G_d^{(+)i} \langle \phi_i | \widehat{V}_p | \chi_p^{(+)} \rangle. \tag{5}$$

As Satchler points out [10], these participating states are normally expected to be close in excitation energy, so that $G_d^{(+)i}$ in Eq. 5 can be replaced by an average Green's function $\overline{G}^{(+)}$ applicable to all states, and together with the closure condition

$$\sum_i | \phi_i \rangle \langle \phi_i | = 1, \tag{6}$$

it means that there is a very simple relationship between the simultaneous and sequential expressions, namely that

$$T_{tp}^{seq} \propto \overline{G}^{(+)} T_{tp}^{sim}. \tag{7}$$

Eq. 7 implies that both mechanisms in which a two-nucleon transfer reaction may proceed have the same form. Consequently their cross section angular distributions are sensitive to pair interactions in exactly the same way. The main manifestation of the importance of a sequential transfer mechanism should be reflected in the magnitude of the observed absolute cross section. However, Charlton [9] finds no convincing difference between calculations which include or exclude sequential transfer in the $^{208}$Pb$(p,t)^{206}$Pb reaction for the natural parity transition to the $0^+$ ground state. In fact, comparing two different sets of optical potentials used to generate distorted waves, he concludes that inclusion of a sequential transfer mechanism serves only as a parameterization to improve agreement between experimental data and calculation, and that good agreement can be obtained anyway by means of a careful selection of the optical potentials. On the other hand, Igarashi *et al.* [5] find that although sequential transfer is not as dominant in the case of the natural parity as in the unnatural parity case, it is still substantial. The energy-dependant ratios of two-step to one-step processes are shown in Fig. 2 for both unnatural and natural parity transitions. As was pointed out earlier, this way of presenting the relative importance of the two different mechanisms, based on a splitting of the mechanisms instead of a proper coherent addition, may not be reliable. Nevertheless, it still suggests a strong incident energy dependence, the effect of which has to be taken into account when estimating the importance of sequential pickup.

Analyzing power is an observable which is predicted to be very sensitive to the reaction mechanism of two-nucleon transfer [5], and it does indeed display a sign difference for the unnatural parity transition in $^{208}$Pb$(p,t)^{206}$Pb depending on whether two-step pickup is taken into account or not. Furthermore, the progression of the analyzing power with incident energy is correctly reproduced [5]. On the other hand, the analyzing power angular distribution difference is not as clear for the natural parity transition.

## 3. Summary and conclusion

The extent to which the reaction mechanism for proton-induced two-particle transfer is understood was reviewed. Clearly important issues still need to be investigated, especially the importance of sequential transfer of the nucleon pair. This may have an important consequence for future applications of two-nucleon transfer reactions to reveal properties of nuclei far from stability.
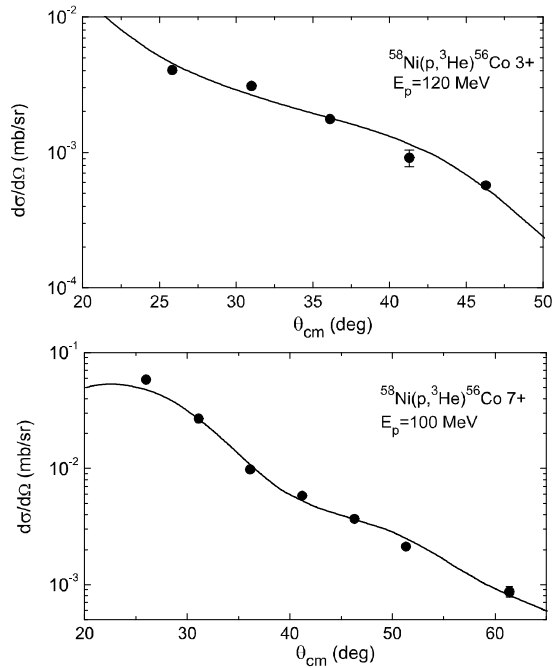
**Figure 1.** Two examples from Ref. [8] of cross section angular distribution for the reaction $^{58}$Ni$(p,^{3}$He$)^{57}$Co at incident energies as indicated for excitations to a $3^{+}$ (top panel) and a $7^{+}$ state (bottom panel). The curves are zero-range semi-microscopic di-nucleon cluster DWBA calculations as described by van Zyl [8].
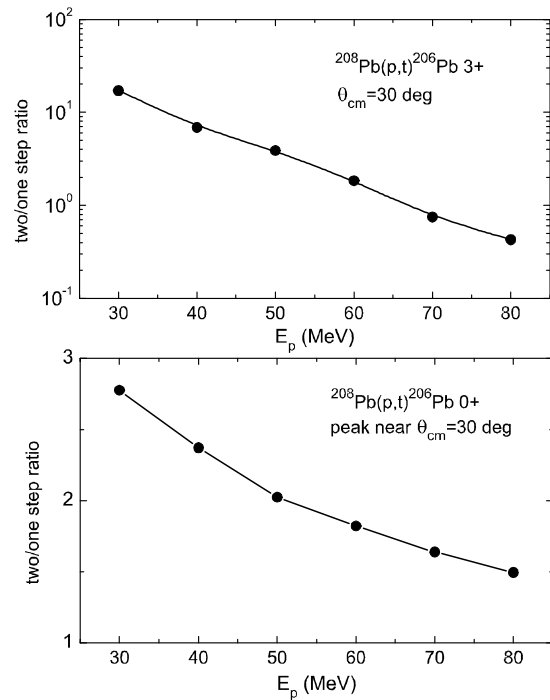
**Figure 2.** Ratio of two-step to one-step cross sections extracted from the work of Igarashi *et al.* [5] as a function of incident energy for the unnatural parity excitation (top panel) and natural parity excitation (bottom panel) for the reaction $^{208}$Pb$(p,t)^{206}$Pb. Note the logarithmic Y-axis scale of the top panel.

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