The Treiman-Yang Criterion: validating the Trojan Horse Method by experimentally probing the reaction mechanism

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Abstract. Proper selection of the quasi-free (QF) break-up channel in a three-body reaction is a key aspect for the applicability of the Trojan Horse Method (THM). The Treiman-Yang (TY) Criterion is a model-independent experimental test for the dominance of the QF mechanism, and hence constitutes one of the strongest validity tests of the THM. An experiment was performed at LNS to apply the test to the $\mathrm{d}(^{10}\mathrm{B},{}^{7}\mathrm{Be}\ \alpha)\mathrm{n}$ reaction. Here, the criterion is described and some preliminary data from the experiment are shown.

1 Introduction

The quasi-free break-up mechanism, depicted in figure 1a for the $\mathrm{d} + {}^{10}\mathrm{B} \rightarrow {}^{7}\mathrm{Be} + \alpha + \mathrm{n}$ reaction, can be described as the virtual interaction (here $\mathrm{p} + {}^{10}\mathrm{B} \rightarrow {}^{7}\mathrm{Be} + \alpha$) of the incident particle (here ${}^{10}\mathrm{B}$) with only a cluster (here p) of the other reactant, named 'participant', emitted in a virtual decay (here $\mathrm{d} \rightarrow \mathrm{p} + \mathrm{n}$), while the other cluster remains undisturbed. Under suitable conditions, for instance if the participant is non-relativistic (small momentum transfer) and has spin $1/2$ (see [1] for a more detailed discussion), the spin-averaged square-modulus amplitude $\overline{|M|^2}$ for the QF channel can be factorized into the amplitudes for the two virtual processes and the propagator.

The Trojan Horse Method (see [2] for a review and [3] for a THM measurement of the $\mathrm{p} + {}^{10}\mathrm{B} \rightarrow {}^{7}\mathrm{Be} + \alpha$ via the $\mathrm{d}({}^{10}\mathrm{B},{}^{7}\mathrm{Be}\,\alpha)\mathrm{n})$ is an indirect technique for measuring cross sections of astrophysically relevant two-body reactions, by selecting the QF channel of an appropriate three-body reaction. In THM measurements, the most typical competitor to the QF is the sequential decay

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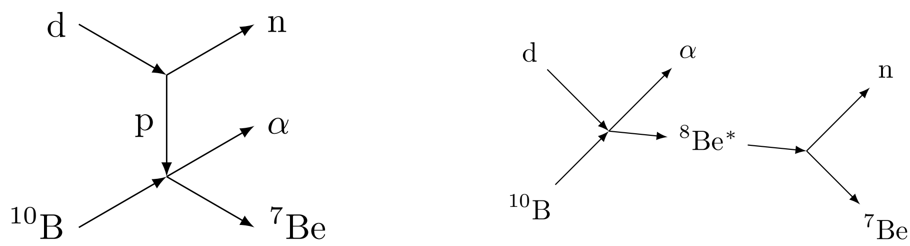

(a) Quasi-Free Breakup. (b) Sequential Decay.

Figure 1. Two of the infinitely many diagrams that could contribute to the $\mathrm{d} + {}^{10}\mathrm{B} \to {}^{7}\mathrm{Be} + \alpha + \mathrm{n}$.

(figure 1b), but in principle many other mechanisms can contribute to the reaction amplitude. It is thus pivotal to correctly select the kinematical locus where the QF channel dominates: several validity tests are usually employed in the THM analysis (see [2, 3]), but none of them is sufficient to completely ensure the dominance of the QF mechanism.

2 The Treiman-Yang Criterion

The Treiman-Yang Criterion was first proposed for high energy particle interactions [4] (where the QF was initially observed), then extended to non-relativistic nuclear reactions [1]. It is a very strong, model-independent experimental test for the preponderance of the quasi-free break-up mechanism.

In general, the spin-averaged amplitude for a three-body reaction depends on 5 kinematical variables. It is useful to choose them among the Mandelstam variables $s_{12} = |\mathbb{P}_1+\mathbb{P}_2|^2$ and $t_{12} = |\mathbb{P}_1-\mathbb{P}_2|^2$, where $\mathbb{P}_i$ is the four-momentum of particle i, or their non-relativistic analogues (defined in [1]): a convenient set for the $\mathrm{d} + {}^{10}\mathrm{B} \to {}^{7}\mathrm{Be} + \alpha + \mathrm{n}$ reaction is $s_{\mathrm{d\,B}}, t_{\mathrm{d\,n}}, t_{\mathrm{B}\,\alpha}, s_{\mathrm{n\,Be}}, s_{\alpha\,\mathrm{Be}}$. The amplitude of any specific channel will depend on a subset of these variables.

It can be shown [1] that, if the amplitude $\overline{|M|^2}$ of the QF channel of a reaction is factorizable (as in section 1), then it will be a function of $t_{\mathrm{d\,n}}, s_{\alpha\,\mathrm{Be}}, t_{\mathrm{B}\,\alpha}$ only. One can then experimentally check that $\overline{|M|^2}$ doesn't vary with $s_{\mathrm{d\,B}}$ and $s_{\mathrm{n\,Be}}$, to rule out any mechanism whose amplitude depends on them.

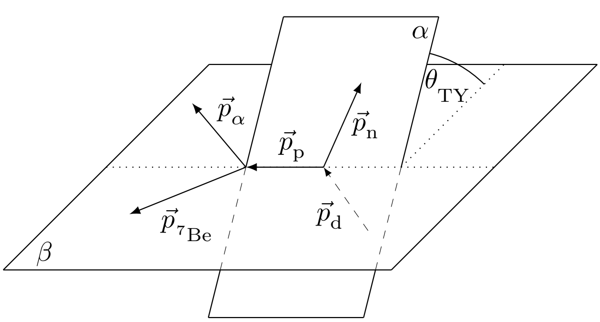

Figure 2. Representation (introduced by [5]) of the particles' momenta before and after the reaction $\mathrm{d} + {}^{10}\mathrm{B} \to \alpha + {}^{7}\mathrm{Be} + \mathrm{n}$ in the ${}^{10}\mathrm{B}$ rest frame, given that it proceeds through QF breakup. θ_{TY} is the angle between the $(\vec{p}_{\mathrm{d}}, \vec{p}_{\mathrm{n}})$ plane (α) and the $(\vec{p}_{\alpha}, \vec{p}_{\mathrm{Be}})$ plane (β).

It is readily seen that, regardless of the reaction mechanism, $t_{\mathrm{d\,n}}, s_{\alpha\,\mathrm{Be}}, t_{\mathrm{B}\,\alpha}$ and $s_{\mathrm{d\,B}}$ are all constant under a "Treiman-Yang rotation", defined in the $\vec{p}_{\mathrm{B}} = 0$ frame as the rotation of $\vec{p}_{\alpha}$ and $\vec{p}_{\mathrm{Be}}$ around $\vec{p}_{\alpha} + \vec{p}_{\mathrm{Be}}$. Thus, if the reaction proceeds through QF breakup and factorization is possible, $\overline{|M|^2}$ must be constant under TY rotations. The particles' momenta then follow the scheme in figure 2: in the

^{10}B rest frame, $\vec{p}_{\mathrm{p}}$ equals $\vec{p}_\alpha + \vec{p}_{\mathrm{Be}}$ and it's the intersection between the planes $(\vec{p}_d, \vec{p}_n)$ and $(\vec{p}_\alpha, \vec{p}_{\mathrm{Be}})$, so the TY rotation corresponds to rotating the two planes by an angle θ_{TY}.

A kinematical region of a reaction is therefore said to pass the TY Criterion when $\overline{|M|^2}$ doesn't depend on θ_{TY}. Although not a sufficient condition, this test is a strong signature for QF dominance.

3 The Experiment

Previous experimental attempts to apply the Treiman-Yang Criterion for reactions at low beam energies date back to 1980 [5]. In June 2016, a dedicated experiment was carried out at Laboratori Nazionali del Sud in Catania in order to verify the Criterion for the $\mathrm{d}(^{10}\mathrm{B}, {}^{7}\mathrm{Be}\,\alpha)\mathrm{n}$. The measurement took place in Camera2000, with a 27.5 MeV ^{10}B beam coming from the Tandem Accelerator and impinging on a 142 µg/cm^2 thick CD_2 target. Figure 3 shows a scheme of the setup.

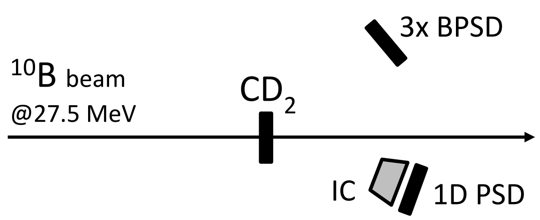

Figure 3. Schematic view of the experimental setup.

As is clearly seen in figure 2, in order to explore different θ_{TY} it's necessary to measure some reaction products out of the horizontal plane: a vertical stack of three Bidimensional Position Sensitive Detectors (BPSD) was therefore employed to detect the α particles. Beryllium ions were instead detected on-plane and identified by a ΔE-E telescope (see figure 4) made with an Ionization Chamber (IC) filled with isobutane gas placed in front of a one-dimensional Position Sensitive Detector (PSD).

The analysis of the data acquired in the experiment is still in progress. The detectors have been calibrated, and good energy and position resolution has been obtained for both the PSD and BPSD: for illustration, in figure 5 it is seen that the reference holes in the calibration grid of a BPSD are reproduced quite well. The results obtained from the partial and preliminary analysis make us confident that the experimental run was technically successful.

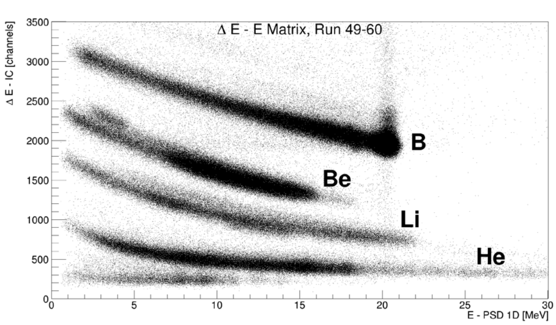

Figure 4. Typical ΔE-E spectrum from the IC-PSD telescope.

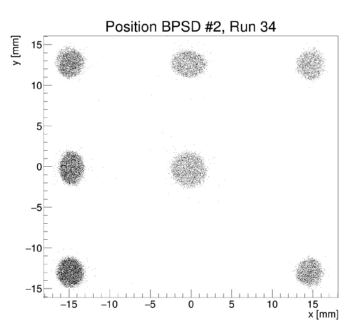

Figure 5. Measured position of particles that hit a BPSD preceded by a grid.

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