IL NUOVO CIMENTO **39 C** (2016) 368
DOI 10.1393/ncc/i2016-16368-8

Colloquia: SEA2016

Direct nuclear reaction experiments for stellar nucleosynthesis

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received 28 November 2016

Summary. — During the last two decades indirect methods where proposed and used in many experiments in order to measure nuclear cross sections between charged particles at stellar energies. These are among the lowest to be measured in nuclear physics. One of these methods, the Trojan Horse method, is based on the Quasi-Free reaction mechanism and has proved to be particularly flexible and reliable. It allowed for the measurement of the cross sections of various reactions of astrophysical interest using stable beams. The use and reliability of indirect methods become even more important when reactions induced by Radioactive Ion Beams are considered, given the much lower intensity generally available for these beams. The first Trojan Horse measurement of a process involving the use of a Radioactive Ion Beam dealt with the ^{18}F(p,α)^{15}O process in Nova conditions. To obtain pieces of information on this process, in particular about its cross section at Nova energies, the Trojan Horse method was applied to the ^{18}F(d,α ^{15}O)n three body reaction. In order to establish the reliability of the Trojan Horse method approach, the Treiman-Yang criterion is an important test and it will be addressed briefly in this paper.

1. – Introduction

Nuclear cross sections between charged particles at stellar energies are among the most difficult to be measured in nuclear physics because their cross sections can easily drop down to the micro- nano- end even picobarn region. It is well known that this behavior is the outcome of the low probability of tunneling through the Coulomb barrier between the interacting nuclei when their relative energy is much lower than the barrier itself [1].

In order to overcome the experimental problems connected to these measurements, new experimental techniques as well as indirect methods where proposed and used in many experiments over the last decades. In particular, the Trojan Horse method (THM) [2-14], not discussed here, has proved to be particularly flexible and reliable and it was applied to the measurement of the cross sections of various reactions of astrophysical interest.

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Nonetheless, when reactions induced by Radioactive Ion Beams (RIBs) are considered, the yield of the processes at hand is in general so low that even using indirect methods the total detection efficiency becomes an issue. Detection systems with high efficiency and high resolution are hence needed, such as the system called ASTRHO that has been developed and used by the Catania nuclear astrophysics group [15]. Indeed, the first measurement of ^{18}F(p,α)^{15}O process in Nova conditions by applying the Trojan Horse method to the ^{18}F(d,α ^{15}O)n reaction was performed using this system.

Though the usual THM analysis has been applied to reactions induced by RIBs, checks of the quasi-free reaction mechanism, that is the key element of the method, in this case are even more important than in experiments involving stable beams. One of the most significant hints for the presence of a quasi-free mechanism in a nuclear reaction is the Treiman-Yang (TY) criterion [16]. This criterion has already been exploited in order to establish the quasi-free nature of a reaction mechanism by the Catania group in the past [17].

In this paper the results obtained for the study of the ^{18}F(p,α)^{15}O reaction, performed using the CRIB apparatus of the Center for Nuclear Study of the University of Tokyo located in the Wako RIKEN Campus, will be shortly reported as an example of the application of the THM to RIB-induced reactions. Also, an experiment recently performed at INFN-Laboratori Nazionali del Sud to apply the TY criterion to a nuclear reaction using a modern experimental setup will be briefly addressed.

2. – The ^{18}F(p, α)^{15}O reaction at Nova temperature

The knowledge of the ^{18}F(p,α)^{15}O reaction rate is crucial to understand the nova explosion phenomena [18]. The cross section of this reaction is characterized by the presence of several resonances in ^{19}Ne and possibly interference effects among them.

The results reported in the literature are not satisfactory and new investigations of the ^{18}F(p,α)^{15}O reaction cross section will be useful. In a recent work we applied the THM to study this reaction via the ^{18}F(d,α ^{15}O)n process with three body in the final state [19]. The spin-parity assignments of relevant levels have been discussed and the astrophysical S-factor has been extracted considering also interference effects. In our experiment we could not fix the resonance parameters using our data, so we evaluated the S-factor using those available in the literature, that sometimes are not univocally established. The results of this study are represented in fig. 1. Lines in fig. 1 are from calculations reported in [20] with resolution smeared to that of the experiment. It has to be noted that the low energy end of the spectrum dramatically depends upon the J^π assumption for the resonance at $E = 6460$ keV in ^{19}Ne.

In order to obtain the spin-parity parameters in an independent way and to be able to evaluate the S-factor from THM data, a new experiment was performed at CRIB. The analysis of this experiment is still ongoing.

3. – The Treiman-Yang criterion

The Treiman-Yang criterion is one of the most powerful experimental tests for verifying the pole approximation prediction when describing a quasi-free reaction mechanism. The application of the Quasi-Free (QF) break-up mechanisms in the past was mostly connected to an extensive study of nuclear structure [21-24]. Basically, these mechanisms are direct processes in which the interaction between an impinging nucleus and the target can cause the break-up of the target (TBU) or of the projectile (PBU). In

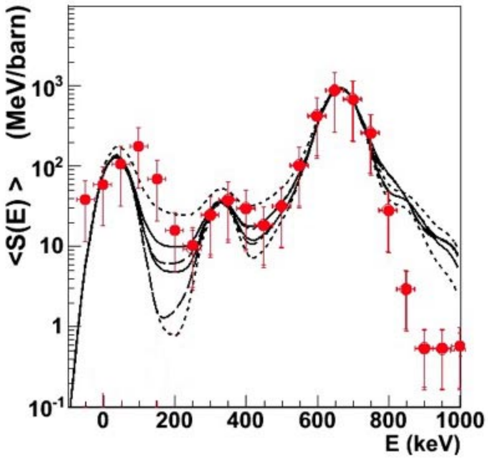

Fig. 1. – The ^{18}F(p, α)^{15}O astrophysical S-factor from the experiment reported here. The full dots are THM experimental data with the assumption of $J^{\pi} = 3/2^{+}$ for the resonance at $E = 6460$ keV in ^{19}Ne. Refer to [19] for details on data analysis. The lines are calculations from [20] smeared to the present experimental resolution.

particular, QF ones are processes having three particles in the exit channel one of which can be thought as "spectator". Sketching for simplicity a TBU process, the picture is that of an interaction between the impinging nucleus and part of the nucleons of the target (called "participant"), while the other counterpart (also coming from the target in this case) does not participate to the reaction. The two groups of nucleons are said to be clusters and the wave function of the whole nucleus has a strong probability for the two-cluster structure. The spectator in this picture will be then "free" from any effect due to the interaction between the incoming nucleus and the participants [25].

The analysis of the QF reactions is usually performed in the framework of the Impulse Approximation (IA) [26]. Assuming that the nucleus A has a cluster A = S+T configuration and impinges on the nucleus B, the A+B→c+d+S QF process can be described through the Feynman diagram shown in fig. 2, where only the first term of the Feynman series is retained. The right-side vertex refers to the A nucleus virtual decay into its constituents T and S, while the left-side vertex to the virtual two-body reaction B+T→c+d, leaving S as spectator.

Several attempts have been made for testing the pole-approximation of fig. 1 and to select the phase space region where QF is the dominant reaction mechanism intervening in the A+B→c+d+S three-body reaction. In particular, Shapiro *et al.* [27] demonstrated that the pole mechanism is the simplest reaction mechanism intervening in the A+B→c+d+S reaction.

The TY criterion [16, 27] establishes that the amplitude of the reaction with 3 bodies in the final state should be invariant under rotation of the plane defined by the momenta of particles c and d about the sum of these momenta, in a reference frame in which the projectile or the cluster nucleus T is at rest. The quantities s′,t′,t do not change if in the anti-laboratory system (that is the system for which the momentum of particle T is equal 0) the momenta of the particles c and d are rotated with respect their sum, this direction corresponding to the one of the intermediate T particle momentum. In these condition the differential cross section must remain constant under this rotation. This situation can be visualized as the rotation of the plane α with respect to the intersection

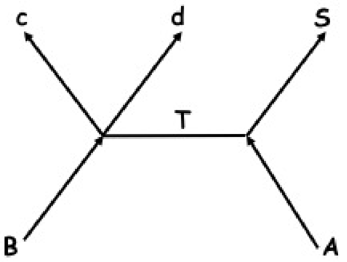

Fig. 2. – Feynman diagram for the quasi-free reaction A+B→c+d+S. A is a nucleus that has a strong clusterization into T+S. The cluster S remains a spectator in the reaction while T reacts with B. The right-side vertex refers to the A nucleus virtual decay, while the B+T→c+d process takes place at the left-hand one.

axis (defined by the transferred momentum vector) with plane β as shown in fig. 3. This Treiman-Yang criterion is a necessary condition for the pole mechanism of a reaction [27].

In the last 20 years, the THM was developed to study reactions of interest for nuclear astrophysics. As already mentioned, QF-reaction processes are at the base of this method. The application of the TY to a reaction in the THM regime would be another important evidence of the reliability of the method itself.

By referring to fig. 2, the matrix element of the reaction can be factorized into two parts corresponding to the two vertices of the graph. Factorization tests, such as the Treiman-Yang (TY) criterion can then be performed to verify the polar nature of the reaction. The TY test has been largely applied to (p, 2p) or (α,2α) quasi-free scattering processes in the past. Additionally, quasi-free reaction processes have been also investigated, giving an unambiguous signature of the pole-approximation validity in the case of the ^{9}Be(^{3}He,$\alpha\alpha$)^{4}He reaction studied at 2.8 MeV [17], in which the authors measured the triple-differential cross section for different experimental conditions and obtained data consistent with the isotropic distribution predicted in the case of a pole mechanisms.

In order to extend and check the pole approximation validity by means of the TY

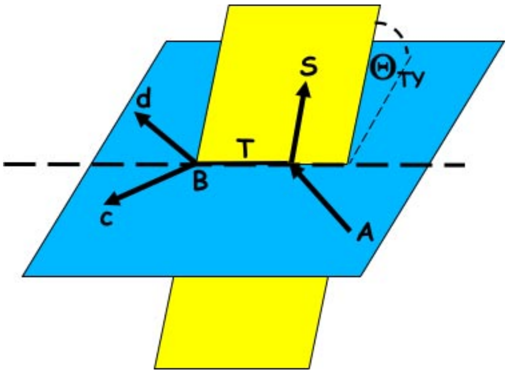

Fig. 3. – Pictorial description of the Treiman-Yang criterion. The criterion implies that, assuming the A+B→c+d+S can be described in terms of a QF mechanism described by the Feynman diagram of fig. 2, its cross section has to be invariant for rotation of the yellow α plane around the direction of the momentum of particle T. The angle between the α and blueish β plane is called Treiman-Yang angle Θ_{TY}.

criterion, we recently applied it to the ^{2}H(^{10}B,^{7}Be α)n reaction induced using a ^{10}B beam. The p+n cluster configuration was guaranteed by the use of a ^{2}H target nucleus and the emitted ^{7}Be and α particles in the binary virtual reaction H(^{10}B,^{7}Be)α were detected in coincidence. The experiment was be performed at INFN-LNS in June 2016. A ^{10}B beam with energy in the range 20–50 MeV was delivered by the LNS Tandem accelerator and was used to bombard a 100–150 μg/cm^2 thick CH_2 target, with an intensity of roughly 1 nA. The experimental setup allow to detect the emitted ^{7}Be and α particles in the three-body reaction by a set of mono- and bi-dimensional position-sensitive detectors. In particular, a telescope consisting of a Ionization Chamber (IC) and a mono-dimensional position-sensitive detector (PSD) with active area $50\,\mathrm{mm} \times 10\,\mathrm{mm}$ was used on one side of the beam axis to detect the ^{7} Be ions produced in the reaction. The distance from the target was 400 mm centered at 10 degrees. On the other side with respect to the beam axis, a system consisting of three bi-dimensional position-sensitive detectors (BPSD), with active area of $45\,\mathrm{mm} \times 45\,\mathrm{mm}$, mounted as a vertical array of 3 by 1 detectors, was placed at a distance of roughly 600 mm from the target and at an angle of 15 degrees with respect to the beam axis. This array of BPSD allow to detect α particles with an outgoing angle between roughly -0.5 to 20 degrees with respect to the plane defined by the beam axis and the IC-PSD telescope so to allow for the exploration of a large region in Θ_{TY}. Both PSD and BPSD have a position resolution better than 1 mm (in both directions in the case of BPSD). This allows to achieve the angular resolution (order of 0.1 degrees) required to reconstruct the kinematics of the reaction under study and to calculate delicate variables such as the spectator momentum and the Treiman-Yang angle for each event. The data acquired during the experiment are presently being analyzed.

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