

Application of Trojan Horse Method to radioactive ion beams induced reactions

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Abstract. In the last decades, many indirect methods have been developed to measure the cross section of nuclear reactions at the low energies interesting in many astrophysical scenarios. The Trojan Horse Method uses a three body reaction, involving by a strong clusterized nucleus, to infer information about a two body reaction of interest, selecting the events that proceed through the quasi-free reaction mechanism. To reconstruct the reaction kinematic and to identify the useful reaction mechanism, the energy and angle of at least two of the three outgoing particles must be carefully measured. Moreover, enough statistics is required, as the quasi-free events usually represent just a small fraction of the acquired statistic.

These requirements hardly match with the typical characteristics of radioactive ion beams: low intensity, large divergence and possible presence of contaminants. For this reason, only recently the Trojan Horse Method has been applied to study reactions induced by radioactive beams. This application gives also the opportunity to measure cross section of neutron induced reactions on radioactive isotopes, even if they have a short lifetime.

In the following some results obtained in the study of the reactions $^{18}\text{F}(p,\alpha)^{15}\text{O}$ and $^{18}\text{F}(n,\alpha)^{15}\text{N}$ will be presented.



1. Introduction

The Trojan Horse Method (THM) is an indirect method largely exploited to get information about the cross section of nuclear reactions interesting for nuclear astrophysics [1, 2]. At the low energies involved in many astrophysical scenarios, the cross section drops down exponentially due to the presence of the Coulomb barrier. To overcome this problem, the THM uses an appropriate reaction having three body in the final state, namely $A + a \rightarrow B + C + s$, to measure the cross section of the reaction $A + x \rightarrow B + C$. The nucleus a , called Trojan Horse nucleus, must have a strong cluster structure $x-s$. In the events proceeding through the quasi-free reaction mechanism (QF), a breaks-up inside the nuclear field of the A nucleus: the x cluster takes part to the nuclear reaction, while the s cluster acts as a spectator. For this process, the cross section of the $A + a \rightarrow B + C + s$ reaction can be simply factorized, and that one of the $A + x \rightarrow B + C$ reaction can be easily deduced [1, 2].

The most used Trojan Horse nucleus is the deuteron d , whose cluster structure $p-n$ allows to study the cross section of reactions induced by protons. Recently, the deuteron has been successfully used to study neutron induced reactions [3, 4, 5].

To perform a THM experiment, the energies and angles of at least two out of the three ejectiles in the $A + a \rightarrow B + C + s$ reaction must be detected. So, making an hypothesis about the nature of the undetected particle, it is possible to reconstruct the whole kinematics and to select the reaction channel of interest [6]. The kinematic strongly depends on the angles of the outgoing particles. For this reason, it is important to measure with good accuracy the position of the ejectiles. Consequently, in the usual THM experiments, the beam spot diameter is reduced to 1 or 2 mm, the thickness of the target is kept as thin as possible, and position sensitive detectors are used in the experimental set-up to detect both energy and position of the ejectiles. Moreover, to apply the factorization of the cross section of the three body reaction, so inferring information about the reaction of interest, only the events proceeding through a QF reaction mechanism must be selected, among different reaction mechanisms that can populate the same final state. As the QF events are a small fraction of the whole statistics (generally of the order of 10%, depending strongly on the reaction), it is mandatory to collect enough events to obtain reasonable statistical errors.

Because of these experimental requirements, only recently the method has been applied to study reactions induced by radioactive ion beams (RIB). To overcome the experimental difficulties due to the typical low intensity, presence of contaminants and large divergence of RIBs, a more efficient experimental set-up has been designed and used. In particular, to increase the statistic, an experimental set-up covering a larger solid angle has been used. Moreover, the reconstruction of the angles of ejectiles has been improved measuring the beam direction, to allow for a better identification the events of interest.

The first reaction studied by the THM using RIB was the $^{18}\text{F}(p,\alpha)^{15}\text{O}$. This reaction is important to understand the γ -ray data coming from novae explosion. Indeed, the γ -ray emission is dominated by the 511 keV energy line, coming from the electron-positrons annihilation. Positrons mostly come from the β -decay of radioactive nuclei, and among them the ^{18}F has lifetime that well match the timescale for the novae ejects to become transparent to γ -ray emission. To estimate the abundance of ^{18}F , it is important to know the cross sections of the reactions that produce and destroy ^{18}F , as the $^{18}\text{F}(p,\alpha)^{15}\text{O}$. Two experiments were performed using similar experimental set-up in two different laboratories: RIKEN-JP and TAMU-USA. The differences between the two experiments and the results obtained are discussed in the following sections. Finally, an interesting indication of the possibility to measure the $^{18}\text{F}(n,\alpha)^{15}\text{N}$ reaction by using the THM is presented in the last section.

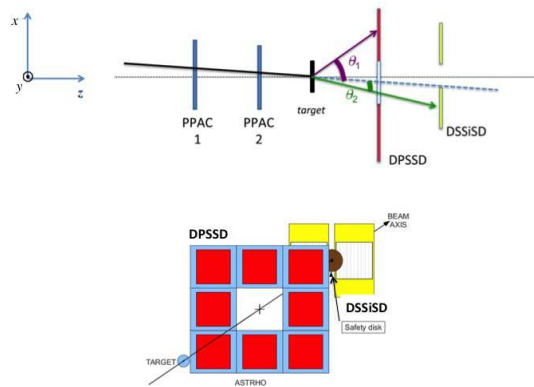


Figure 1. Schema of the experimental set-up used in the study of the $^{18}\text{F}+d$ reaction at CRIB-RIKEN. As an example a beam track and the tracks of two reaction products are represented.

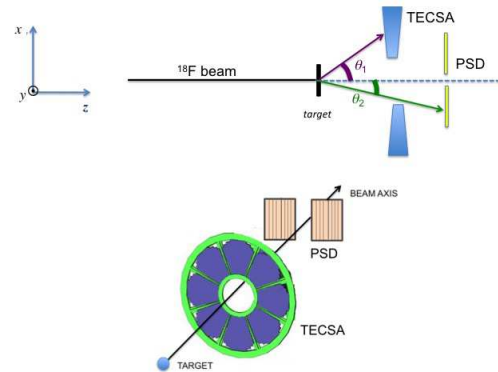


Figure 2. Schema of the experimental set-up used in the study of the $^{18}\text{F}+d$ reaction at MARS-TAMU. As an example a beam track and the tracks of two reaction products are represented.

2. First study with RIBs: the $^{18}\text{F}(p,\alpha)^{15}\text{O}$ reaction

The $^{18}\text{F}(p,\alpha)^{15}\text{O}$ reaction was studied by using the three body reaction $d(^{18}\text{F},\alpha)^{15}\text{O}n$. The ^{18}F beam was delivered onto a CD_2 solid target, and the charged reaction products were detected using two arrays of position sensitive detectors. The beam energy and the detectors set-up were optimized to explore the energy range of the $^{18}\text{F}(p,\alpha)^{15}\text{O}$ reaction of interest for astrophysics and to cover the phase space region where the QF reaction mechanism is present.

Two different experiments were performed [7, 8]. The first one was carried-out at the CRIB facility in RIKEN, Japan, using a beam of energy 47.9 ± 1.9 MeV and average intensity 5×10^5 pps [7]. The experiment was then repeated using a different experimental set-up at the MARS spectrometer installed at TAMU, USA, using a beam of energy 52.0 ± 2.6 MeV and average intensity of 3.5×10^5 pps [8]. In both experiments the beam purity was good, 98% at CRIB and 94% at MARS, and only a small percentage of ^{16}O and ^{12}C was present. The thickness of the used targets was $150\text{-}200 \mu\text{g}/\text{cm}^2$ for the CRIB experiment and $400\text{-}800 \mu\text{g}/\text{cm}^2$ for the TAMU experiment. A schematic view of the experimental set-up used for the two experiment is shown in fig. 1 and 2. In the figures, a beam track and the tracks of two detected ejectiles are sketched.

The experimental set-up used in the CRIB experiment consists in two parts: before the CD_2 target the beam direction was tracked event by event using a couple of PPAC detectors; after the target two planes of position sensitive silicon detectors were used to detect the reaction products.

In the experiment performed at TAMU the beam direction was defined by a set of mechanical collimators. The reaction products were detected by using arrays of silicon strip detectors.

2.1. The beam tracking system

To perform a beam track reconstruction event by event two Parallel Plate Avalanche Counters (PPAC) detectors placed at 510 mm and 107 mm before the target position and having a spatial resolution of 1 mm were used in the CRIB experiment. These detectors allow to reconstruct the beam track direction and its impinging position onto the target. The beam track is defined with a geometrical angular resolution of 0.14° . The emission angles of the detected ejectiles were

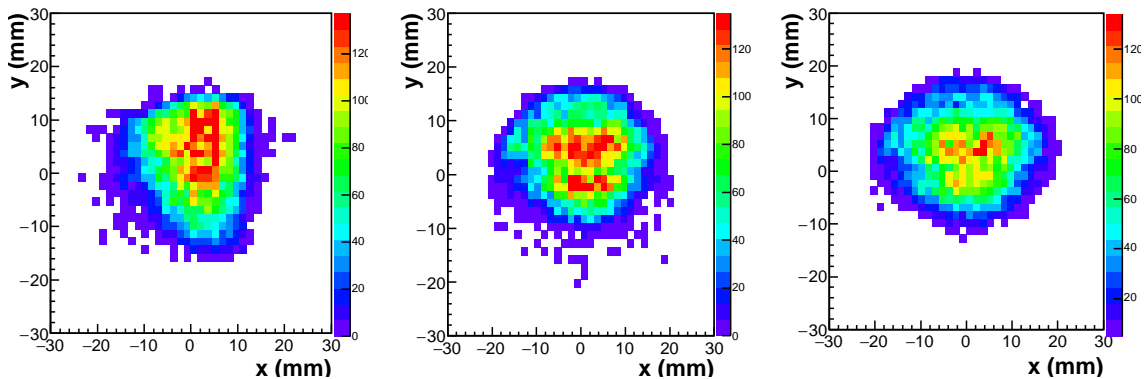


Figure 3. x - y position of the beam measured on PPAC 1 and PPAC 2 and beam spot reconstructed on the target position (from left to right respectively).

reconstructed with respect to the measured beam track, so improving the reconstruction of the kinematics.

In fig. 3 the beam position on the two PPAC detectors and the reconstructed beam spot in the target position are reported. It can be noted that, even if the beam spot into the target is small, the beam divergence is not negligible.

In the TAMU experiment, the beam spot into the target was defined by mechanical collimators. Its dimensions were $3 \times 5 \text{ mm}^2$. The angles of ejectiles were reconstructed by assuming a straight on beam direction.

2.2. The charged particle detectors

In a typical THM experiment, energies and angles of the reaction products are detected by using the coincidence of 2 one-dimensional position sensitive silicon detectors. Typically, two position sensitive detectors ($10 \times 50 \text{ mm}^2$, resistive backing layer) are placed at the opposite side with respect to the beam direction, using an in-plane configuration. To overcome the experimental difficulties coming from the use of RIB, in the study of the $^{18}\text{F}(p,\alpha)^{15}\text{O}$ reaction the use of a larger solid angle set-up was necessary to increase the global detection efficiency. In particular, two arrays of position sensitive detectors were used in coincidence: an array placed at forward angles is used for the ^{15}O , and the second array was devoted to α particles detection.

In the CRIB experiment, the ^{15}O was detected by using a pair of segmented Si detectors (DSSiSD see fig. 1). The two double sided silicon strip detectors manufactured by Micron Semiconductor ($50 \times 50 \text{ mm}^2$, 16 strips per side, width 3 mm) were placed symmetrically with respect to the beam axis at 287 mm from the target to cover the geometrical angular range 2° - 11° . The α particle was detected by using the ASTRHO (A Silicon Array for TRojan HORse) modular system of INFN, Laboratori Nazionali del Sud, equipped with 8 bidimensional position sensitive detectors manufactured by Hamamatsu Photonics (DPSSD see fig. 1). These detectors ($45 \times 45 \text{ mm}^2$) use a resistive layer to measure the position, allowing to keep low the numbers of signals. The position of the impinging particle is reconstructed with a spatial resolution of 1 mm in both x and y directions, The detectors were placed on a plane orthogonal to the beam axis, at a distance of 150 mm from the target, in a square configuration (3×3) around the beam axis (see fig. 1). The set-up covered the angular range 11° - 31° . For each detector, position and energy of particles were recorded together with the time of flight.

As the beam direction and its impinging position on the target were measured event by event, the emission angles of the reaction ejectiles were reconstructed starting from the real beam track

and reaction point. The solid angle covered by the detector arrays was estimated by performing a careful simulation of the detectors geometry, that takes into account the measured beam characteristics.

In the experiment performed at TAMU, two silicon position sensitive detectors (PSDs, type X1,16 strips each) placed symmetrically at distance of 340 mm from target were used to detect the ^{15}O in the angular range 3° - 12° . To detect the α particles, the TECSA array[9], made up of 8 YY1-300 Micron detectors (each one with 16 arch strips) was placed at 190 mm from target, covering the angular range 15° - 40° (see fig. 2). As the beam is supposed to go straight-on the geometrical angular position of the detectors was attributed to the detected particle.

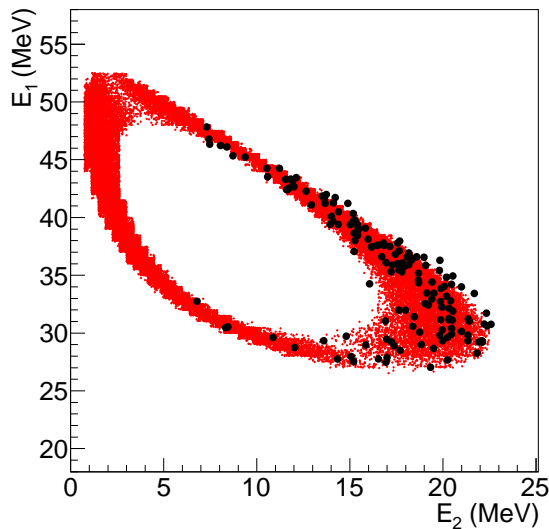


Figure 4. Correlation between the energies of the detected ejectiles. The black dots are experimental data having $\theta_1 = 6.5^\circ \pm 1.5^\circ$ and $\theta_2 = 29^\circ \pm 1.5^\circ$. The red dots represent the kinematic calculated for the reaction $d(^{18}\text{F}, \alpha ^{15}\text{O})n$ in the same angular interval.

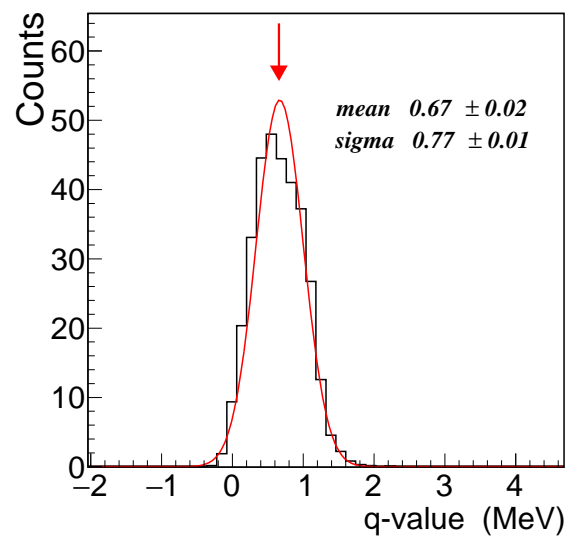


Figure 5. Reconstructed q-value for the $^{18}\text{F}(p, \alpha)^{15}\text{O}$ reaction. The arrow indicates the theoretical q-value. The solid line represents a gaussian fit of the data.

3. Results

The data analysis of a THM experiment mainly proceeds through the following steps: (a) identification of the process of interest, (b) selection of the events corresponding to the QF reaction channel, (c) extraction of the two body cross section of astrophysical interest.

In order to select events coming from the reaction of interest, several cuts were applied on the data. In the CRIB experiment, some cuts were imposed on the beam impinging positions into the two PPAC detector. Moreover it was requested that the time of flight of the two detectors was within the correlation time window. In both the experiments, it was requested that each of the two arrays of detectors was fired with multiplicity equal to 1. A constraint on the time of flight of the two particles was imposed. Moreover, it was required that the azimuthal angle between the two detected particles was about 180° , in order to select only in-plane events. The events coming from reactions of ^{18}F on carbon were easily removed thanks to the differences in phase space distribution of these events with respect to those induced on deuterium. Moreover, studying the bidimensional spectra of the relative energy of one pair out of three outgoing

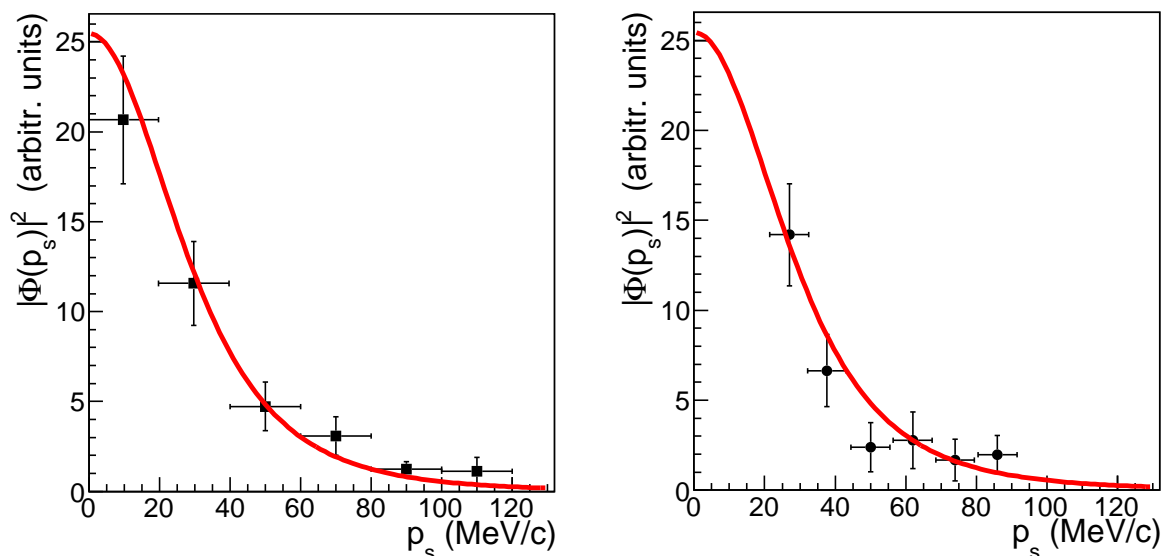


Figure 6. Momentum distribution of spectator inside the TH nucleus measured in the CRIB-JP experiment (left) and in the TAMU-USA experiment (right). The solid line represents the Hulthén function as foreseen for deuteron inter-cluster momentum distribution.

particles versus that of other pairs, it was possible to separate the phase space region spanned by the events coming from the $^{18}\text{F}+d \rightarrow ^{15}\text{O}+\alpha+n$ reaction that partially overlaps with those coming from other possible reactions on deuterium, namely $^{18}\text{F}+d \rightarrow ^{15}\text{N}+\alpha+p$, $^{18}\text{F}+d \rightarrow ^{18}\text{O}+p+p$ and $^{18}\text{F}+d \rightarrow ^{18}\text{F}+p+n$.

By using these conditions, it is possible to identify the events coming from the desired reaction. A typical correlation between the energies measured in the two detector arrays is reported in fig. 4. The experimental data (black dots) are compared with a kinematic calculation (red dots) for angles of the outgoing particles $\theta_1 = 6.5^\circ \pm 1.5^\circ$ and $\theta_2 = 29^\circ \pm 1.5^\circ$. The q-value reconstructed from the selected data is shown in fig. 5. The arrow position corresponds to the theoretical value. The solid line represents a gaussian fit, and the fit parameters are reported in the figure. A good agreement is evident both in fig. 4 and fig. 5, making us confident of the correct identification of the events coming from the reaction of interest.

The second step in a THM analysis is the selection of events that come from the QF channel in the $d(^{18}\text{F}, \alpha ^{15}\text{O})n$ reaction. The strongest evidence of the predominance of the QF mechanism is given by the shape of the momentum distribution for the p - n intercluster motion in deuteron. This is shown in fig. 6 for the CRIB and TAMU experiment (left and right panel respectively). The solid line in fig. 9 represents the Hulthén function in momentum space with the standard parameters values, as predicted if the plane-wave impulse approximation is used to describe the reaction mechanism. The rest of the analysis was done by imposing a cut on the momentum of the spectator particle. Namely, only events having the spectator momentum lower than 50 MeV/c were accepted.

Finally, the cross section of the $^{18}\text{F}(p,\alpha)^{15}\text{O}$ reaction is extracted by using the standard THM formalism [1, 2]. The cross section measured in the two experiments performed at CRIB-JP and at TAMU-USA is reported in fig. 7 as a function of the energy of the centre of mass of the ^{18}F - p system. The cross section is a *bare* nuclear cross section as it is free of Coulomb suppression effects. In the figure the arrows show the ^{19}N populated resonances. The energies of the excited

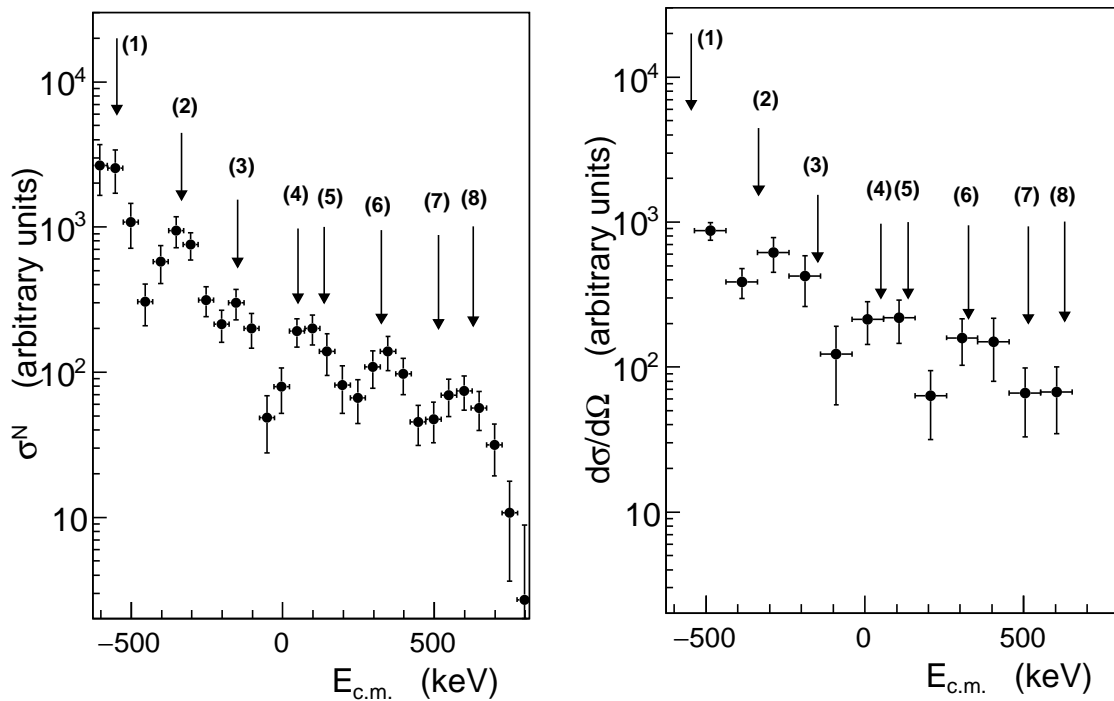


Figure 7. Bare nuclear cross section for the $^{18}\text{F}(p,\alpha)^{15}\text{O}$ reaction as a function of the centre of mass energy for the ^{18}F -p system measured in the CRIB-JP experiment (left) and in the TAMU-USA experiment (right). The arrows indicate the ^{19}N populated resonances.

states are reported in table 1. The different energy resolution achieved in the two experiments can be observed in the figure. As the used beam energy and the angular range coverage of the two experiments are similar, this difference can be attributed to the different resolution of the set-up used in the two experiments. Indeed, in the experiment performed at CRIB-JP an overall angular resolution of 0.3° for the outgoing particles direction was obtained. In the experiment performed at TAMU-USA the achieved angular resolution was of 0.7° for ^{15}O and of 1.1° for α particles.

The comparison of the results obtained in the two experiments stresses once more the importance of having a good angular resolution when the THM is applied. It becomes still more important when a RIB is used, as the background is generally more important.

The measured cross sections were used to calculate the reaction rate for the $^{18}\text{F}(p,\alpha)^{15}\text{O}$ reaction. In the energy region of interest for Novae it was estimated to be a factor 2 higher than the one previous used in the astrophysical models. The content of ^{18}F in Novae results consequently reduced by the same factor [10].

4. Study of neutron induced reaction by using RIB: the $^{18}\text{F}(n,\alpha)^{15}\text{N}$ reaction

An interesting application of the THM is the study of neutron induced reactions [3, 4, 5]. Indeed, even if the neutron induced reactions are not suppressed by Coulomb effects, their study presents many experimental difficulties. The use of deuteron as Trojan Horse nucleus allows us to study not only proton induced reactions, by selecting the three body reaction in which the neutron

Table 1. Energies of the populated ^{19}N resonances (see fig. 7)

Resonance	Energy (keV)
(1)	5837
(2)	6070
(3)	6255
(4)	6460
(5)	6537
(6)	6755
(7)	6967
(8)	7075

acts as a spectator, but also neutron induced reactions, if the three body reaction having the proton acting as spectator is considered. Namely, in the interaction between a nucleus A and a deuteron d , both the reactions $A + d \rightarrow B + C + n$ and the $A + d \rightarrow D + E + p$ occur. In the first case after the deuteron break-up the proton interacts with the A nucleus, while n is the spectator to the reaction $A + p \rightarrow B + C$. In the second case the neutron got a nuclear reaction with A , while the proton acts like a spectator to the reaction $A + n \rightarrow D + E$.

In the experiments presented here, the selection of events coming from the reaction $d(^{18}\text{F}, \alpha^{15}\text{N})p$ can allow to infer information about the two body reaction $^{18}\text{F}(n, \alpha)^{15}\text{N}$ by using the THM formalism, if the three body reaction proceeds through the QF reaction mechanism.

A preliminary study performed on the CRIB experimental data has shown the possibility to measure the neutron induced reaction, even if the experiment was not optimized for this goal. By using kinematic variables, it was possible to identify the three body reaction of interest as demonstrated by the well reconstruction of the q-value (see fig. 8). In the fig. 8, the arrow position corresponds to the theoretical q-value, and the solid line is a gaussian fit performed on the data. The fit parameters are reported in the figure. An indicator for the presence of the QF mechanism is given by the momentum distribution of the spectator for the selected events. This is shown in fig. 9. The data well reproduce the theoretical Hultèn function, as it is foreseen if deuteron is used as Trojan Horse nucleus.

Unfortunately the statistic of the experiment was not enough to get final results. A new experiment was than performed optimizing the set-up for the indirect study of the neutron induced reaction. The new experiment was performed at CRIB and the experimental set-up was improved, adding ΔE detectors to discriminate the mass of the heavier ejectile. The data analysis of this experiment is still in progress.

5. Conclusions

The THM has been successfully extended to study reaction induced by RIB. Because of the characteristics of RIB, improvements in the experimental set-up have been performed. Moreover a more difficult data analysis was necessary to discriminate the events useful for the application of the THM, so inferring information about the reaction of interest. A careful simulation of the experimental set-up was mandatory to correct data for the solid angle covered by the experimental apparatus.

A very interesting application of the method consists in the measure of neutron induced reaction by using RIB. A preliminary analysis has shown the potentiality of the method and further studies and investigations are in progress.

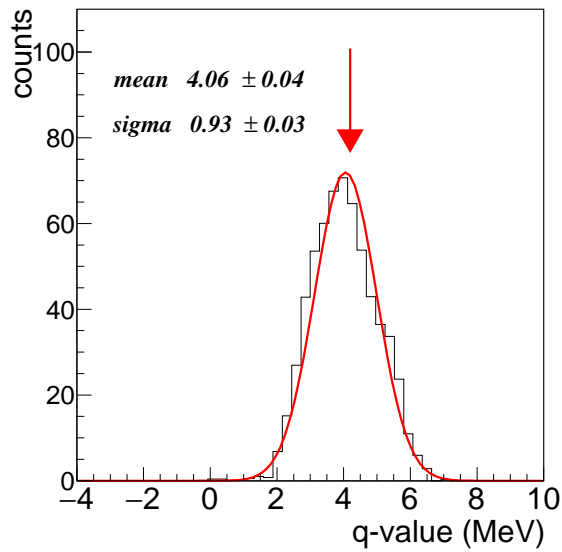


Figure 8. Reconstructed q -value for the $^{18}\text{F}(n,\alpha)^{15}\text{N}$. The arrow indicates the theoretical q -value. The solid line represents a gaussian fit of the data.

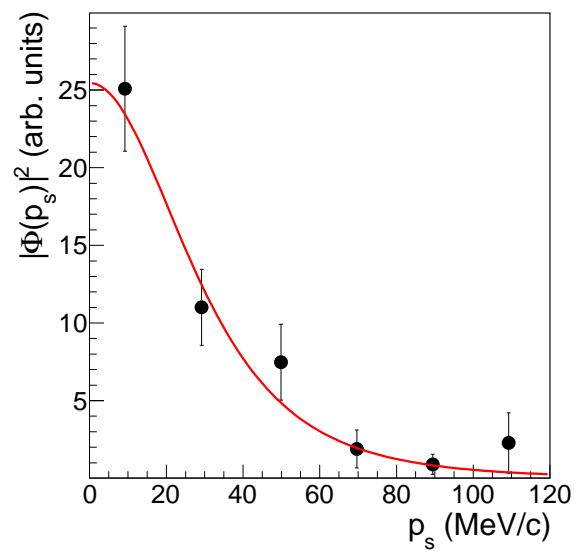


Figure 9. Distribution of the momentum of the spectator. The solid line represents the Hulthen function as predicted by the theory for deuteron.

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