PHYSICAL REVIEW C **92**, 015805 (2015)

First application of the Trojan horse method with a radioactive ion beam: Study of the ^{18}F(p,α)^{15}O reaction at astrophysical energies

S. Cherubini,[1,2,*] M. Gulino,[1,3] C. Spitaleri,[1,2] G. G. Rapisarda,[1,2] M. La Cognata,[1] L. Lamia,[2] R. G. Pizzone,[1] S. Romano,[1,2] S. Kubono,[4,5] H. Yamaguchi,[5] S. Hayakawa,[1,5] Y. Wakabayashi,[5] N. Iwasa,[6] S. Kato,[7] T. Komatsubara,[8] T. Teranishi,[9] A. Coc,[10] N. de Séréville,[11] F. Hammache,[11] G. Kiss,[12] S. Bishop,[4,13] and D. N. Binh[5,14]

[1] *INFN-LNS, Catania, Italy*
[2] *Dipartimento di Fisica ed Astronomia, Università di Catania, Catania, Italy*
[3] *Università di Enna KORE, Enna, Italy*
[4] *Riken, Wako, Saitama, Japan*
[5] *Center for Nuclear Study, The University of Tokyo, Japan*
[6] *Department of Physics, Tohoku University, Sendai, Japan*
[7] *Department of Physics, Yamagata University, Yamagata, Japan*
[8] *Rare Isotope Science Project, Institute for Basic Science, Yuseong-daero, Yuseong-gu, Daejeon 305-811, Korea*
[9] *Department of Physics, Kyushu University, Fukuoka, Japan*
[10] *Centre de Spectrométrie Nucléaire et de Spectrométrie de Masse, IN2P3, F-91405 Orsay, France*
[11] *Institut de Physique Nucléaire, IN2P3, F-91405 Orsay, France*
[12] *Institute for Nuclear Research (MTA-ATOMKI), Debrecen, Hungary*
[13] *TUM, Garching, Germany*
[14] *30 MeV Cyclotron Center, Tran Hung Dao Hospital, Hoan Kiem District, Hanoi, Vietnam*

(Received 23 June 2014; revised manuscript received 1 June 2015; published 21 July 2015)

Measurement of nuclear cross sections at astrophysical energies involving unstable species is one of the most challenging tasks in experimental nuclear physics. The use of indirect methods is often unavoidable in this scenario. In this paper the Trojan horse method is applied for the first time to a radioactive ion beam-induced reaction studying the ^{18}F(p,α)^{15}O process at low energies relevant to astrophysics via the three-body reaction ^{2}H(^{18}F,α^{15}O)n. The knowledge of the ^{18}F(p,α)^{15}O reaction rate is crucial to understand the nova explosion phenomena. 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 literature are not satisfactory and new investigations of the ^{18}F(p,α)^{15}O reaction cross section will be useful. In the present work the spin-parity assignments of relevant levels have been discussed and the astrophysical S factor has been extracted considering also interference effects.

DOI: 10.1103/PhysRevC.92.015805 PACS number(s): 26.50.+x, 25.70.Hi, 29.38.−c

I. INTRODUCTION

In many astrophysical scenarios radioactive nuclei are fundamental in two aspects: directly because of their role in the nucleosynthesis path and indirectly as information carriers that allow to develop and check astrophysical models. Unfortunately, the difficulties typical of measurements of nuclear reaction cross sections at astrophysical energies greatly increase when using radioactive ion beams (RIBs). This is mainly due to the available intensities of these beams, at least three orders of magnitude lower than the stable ones. In this framework, the development and the use of reliable indirect methods to measure these cross sections becomes even more important than in the case of experiment with stable beams.

The Trojan horse method (THM) has been widely developed and exploited over the past two decades to study bare nuclear cross sections at very low energy and it is now routinely used to study reactions between charged particles even at zero energy. A detailed description of the method can be found elsewhere [1–12] and goes beyond the scope of this paper: a review of the method can be found in Ref. [13]. Here we present a pioneering work where the THM has been applied for the first time to a reaction induced by a RIB, namely the ^{18}F(p,α)^{15}O process at nova energies.

The γ-ray emission following the nova explosion is dominated by the 511 keV energy line, coming from the annihilation of positrons produced by the decay of radioactive nuclei. Among them, ^{18}F is especially important because of its expected abundance in the nova environment and because of its lifetime, that matches well with the timescale for the nova ejecta to become transparent to γ-ray emission. In order for γ-ray astronomy to be helpful in understanding the nova explosion phenomena, it is then crucial to know the rate of the nuclear reactions producing and destroying ^{18}F. Indeed, at relevant temperatures ($T_9 \approx 0.2$–0.4), which correspond to Gamow windows energies in the center-of-mass of $E_{\mathrm{c.m.}} \approx 100$–$400$ keV, the ^{18}F(p,α)^{15}O reaction is expected to dominate over the ^{18}F(p,γ) by roughly a factor of 1000 and it is the uncertainty in this reaction rate that gives the main nuclear contribution to the overall uncertainty in the final abundance of ^{18}F [14,15]. In the energy range of interest the cross section of this reaction is dominated by the contribution from states in the ^{19}Ne compound nucleus around

---

[*] cherubini@lns.infn.it

the $^{18}\mathrm{F} + p$ threshold. Especially important is the knowledge of the partial widths and spin-parity of these resonance states, in order to verify possible interference effects affecting the rate. However, in spite of many and long-lasting attempts to infer information on the $^{18}\mathrm{F}(p,\alpha)^{15}\mathrm{O}$ reaction by both direct and indirect measurements (see, e.g., Refs. [16–32]), the situation is still not satisfactory.

II. THM AND EXPERIMENTAL SETUP

In order to get new complementary information on this process, the $^{18}\mathrm{F}(p,\alpha)^{15}\mathrm{O}$ reaction has been studied in inverse kinematics by applying the THM to the three body reaction $^{2}\mathrm{H}(^{18}\mathrm{F},\alpha^{15}\mathrm{O})n$. If one succeeds in selecting the phase-space region where this reaction proceeds through a quasifree reaction mechanism, then its cross section can be factorized [1–12]. The THM half off energy shell (HOES) bare nucleus cross section of the $^{18}\mathrm{F}(p,\alpha)^{15}\mathrm{O}$ reaction can hence be easily deduced even at very low energies overcoming the suppression effects coming from Coulombian and/or centrifugal barriers penetrability factors and the uncertainties due to the poor knowledge of spectroscopic information. The fundamental step in applying this method is the selection of the events that proceed through quasifree reaction mechanism among those coming from all other possible mechanisms. To this aim, two out of the three reaction products must be detected with typical energy and angular resolution of 1% and $0.1^\circ-0.2^\circ$ respectively. In particular, some reconstructed kinematical variables (such as relative energies of the outgoing particles) are especially sensitive to the angular resolution of the experimental setup. Given the characteristics of the radioactive beam used in the present experiment and to achieve the angular resolution required by the THM, the experimental setup [11] was designed so that it was possible to track the beam particles event by event and to detect ejectiles going in a large solid angle. The beam tracking system, based on a pair of parallel plate avalanche counters (PPACs), allowed for an angular resolution of 0.14°. The two ejectiles were detected by using two planes of position sensitive detectors covering the angular ranges $2^\circ-11^\circ$ and $11^\circ-31^\circ$ with respect to the geometrical center of the target. In particular a pair of double-sided multistrip silicon detectors (DSSSD), was used to detect the heaviest ejecta. The lighter ones were detected by using the silicon array for Trojan horse modular system (ASTRHO) of INFN Laboratori Nazionali del Sud equipped with eight bidimensional position-sensitive detectors (BPSD, 45×45 mm^2,500 μm thick, spatial resolution 1 mm) similar to those described in Refs. [33,34]. For each detector the x and y position and the energy of the impinging particles were recorded together with the time of flight. A standard energy calibration procedure was used for all detectors while the x-y position coordinates given by the BPSD were calibrated by placing grids in front of them. The emission angles of the ejectile tracks with respect to the measured beam track were reconstructed with an overall angular resolution of 0.2°.

The $^{18}\mathrm{F}$ beam was produced via the $^{18}\mathrm{O}(p,n)^{18}\mathrm{F}$ reaction using the CNS Radioactive Ion Beam (CRIB) separator of the Center for Nuclear Study (CNS) of the University of Tokyo, installed at RIKEN accelerator facility in Wako, Japan [35,36]. The characteristics of the $^{18}\mathrm{F}$ beam during the experiment were the following: beam energy peaked at 47.9 MeV (FWHM 1.9 MeV), maximum beam intensity of 2×10^6 pps and purity better than 98%. The intensity was higher than 5×10^5 pps throughout the measurement. The secondary target was made of a thin (typically 150 μg/cm^2) CD$_2$ foil. The chosen beam energy fulfills the prescriptions for the validity of the impulse approximation [37]: (i) the wavelength associated to the entry channel is smaller than the nuclear radius of deuteron ($\lambda = 1.54$ fm), in order to maximize the probability that quasifree reaction mechanism occurs; (ii) the incident center-of-mass energy (4.82 MeV) is higher than the binding energy of deuteron.

The used setup assures that the coincidence efficiency is independent from the excitation energy. A detailed Monte Carlo simulation was performed for the used geometry and kinematics assuming that the $\alpha+^{15}\mathrm{O}$ breakup is isotropic in the center-of-mass system. The actual beam energy profile, the reconstructed beam tracks distribution and the measured beam position on the target were used in the simulation. The result of the simulation was used to calibrate the solid angle coverage of the detectors. In order to select events coming from the reaction of interest, several cuts were applied on the data set. In particular it was requested that only one of BPSD and one strip of one DSSSDs fired with multiplicity equal to 1 on each detector and that the time of flight of the two particles was within the correlation time window. The events coming from reactions of $^{18}\mathrm{F}$ on carbon were easily removed thanks to the difference 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 particles versus that of other pairs (e.g., $E_{\alpha\text{-}^{15}\mathrm{O}}$ vs $E_{\alpha\text{-}n}$), it was possible to separate the phase-space region spanned by the events coming from the $^{2}\mathrm{H}(^{18}\mathrm{F},\alpha^{15}\mathrm{O})n$ reaction that partially overlaps with those coming from other possible reactions on deuterium, namely $^{2}\mathrm{H}(^{18}\mathrm{F},\alpha^{15}\mathrm{N})p$, $^{2}\mathrm{H}(^{18}\mathrm{F},p\,^{18}\mathrm{O})p$, and $^{2}\mathrm{H}(^{18}\mathrm{F},p\,^{18}\mathrm{F})n$. Figure 1 shows the Q-value spectrum that was obtained by applying this event selection procedure (solid histogram) overlaid to the total Q-value spectrum (dashed histogram). The line shown in this figure is a Gaussian fit with $\mu = 0.668$ MeV, to be compared with the theoretical Q value of 0.658 MeV, and $\sigma = 0.322$ MeV, in agreement with the overall experimental resolution. The good agreement between the experimental and the theoretical value gives confidence in the correct identification of the events coming from the reaction of interest.

III. DATA ANALYSIS

In order to apply the THM, it is essential to select the events coming from the quasifree reaction mechanism in the $^{2}\mathrm{H}(^{18}\mathrm{F},\alpha^{15}\mathrm{O})n$ reaction among other reaction mechanisms. The strongest evidence of the predominance of the quasifree mechanism is given by the shape of the momentum distribution for the $p-n$ intercluster motion in deuteron [8]. Data are shown in Fig. 2 by black dots. The solid line in Fig. 2 represents the Hulthén function in momentum space with standard parameter values [38]. The fair agreement between

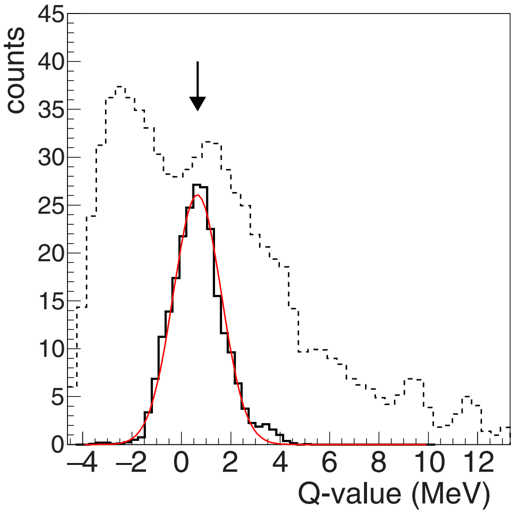

FIG. 1. (Color online) Q-value spectra. The Q-value spectrum for the ^{2}H(^{18}F,α^{15}O)n reaction (black solid histogram) is overlaid to the total Q-value spectrum (dashed line). The arrow represents the theoretical Q value (0.658 MeV) for the reaction at hand. The red line is a Gaussian fit with $\mu = 0.668$ MeV and $\sigma = 0.322$ MeV, in agreement with the expected theoretical value and the experimental resolution.

the data and theoretical curve gives confidence in the selection of events coming from the quasifree reaction channel and allows us to use a plane wave impulse approximation in the data analysis [38]. Indeed, it is well known that distortion effects influence the behavior of the momentum distribution at higher values of momentum. Consequently, the rest of the analysis was done choosing the events having a spectator momentum lower than 60 MeV/c. Assuming that the events selected according to the previous procedure come from the quasifree contribution to the reaction yield, the THM HOES bare nucleus cross section of the ^{18}F(p,α)^{15}O process can be deduced dividing the yield of the ^{2}H(^{18}F,α^{15}O)n reaction by a kinematical factor and the momentum distribution of p and n inside the deuteron [1–13]. The THM HOES bare nucleus cross section, $\sigma^{N}_{\mathrm{HOES}}$, for the ^{18}F($p$,$\alpha$)^{15}O reaction, unaffected by suppression effects due to Coulomb and centrifugal [12] barriers, measured by THM down to zero (and even negative) $p + ^{18}$F relative energy, is shown in Fig. 3. The obtained spectrum was fitted using a least-squares fit of multiple Gaussian. The σ of the Gaussians was fixed to 53 keV based on the energy resolution calculated for the present experiment. The excitation energies coming from the fit together with the error on the peak position are listed in Table I. The systematic error on the peak position due to assumed width of the Gaussians in the fit has been estimated to be 10 keV. For comparison energies and J^{π} coming from Refs. [31,32,39,40] are also reported in Table I.

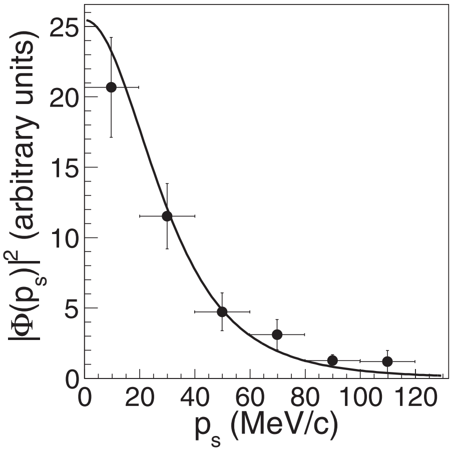

FIG. 2. Momentum distribution for the p-n intercluster motion in deuteron. The solid line is the Hulthén function in momentum space.

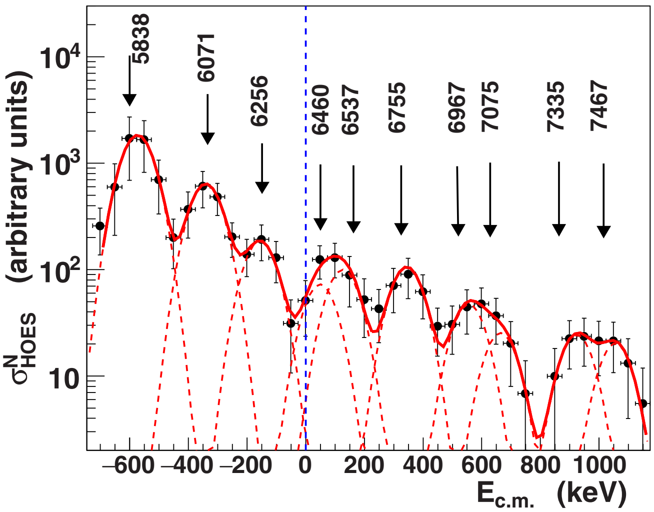

FIG. 3. (Color online) The nuclear cross section spectrum in function of the $p - ^{18}$F cm energy for the events that pass the conditions described in the text. The blue vertical line shows the position of the threshold for the ^{18}F + p reaction ($E_{\mathrm{th}} = 6.41$ MeV). The red dashed lines represent the Gaussians used for fitting the data as explained in the text. The red solid line is the total fit. The numbers above the arrows represents the peak positions in ^{19}Ne excitation energy obtained from the fitting procedure.

Further analysis has been done by considering only the energy region of interest for astrophysical purposes, i.e., the observed excited states at energies 6255, 6460, 6537, 6755, 6968, and 7075 keV.

Though the cross section of the ^{18}F(p,α)^{15}O reaction was indirectly measured by THM in the center-of-mass angular range $70^{\circ} < \theta_{cm} < 120^{\circ}$, the statistics of the present data do not allow us to extract the angular distributions of the populated resonances and hence a self-assignment of the J^{π} values is not possible in this case. However, as the THM data are not affected by suppression effects coming from the Coulomb and centrifugal barrier [12,13], the population of the excited states in the compound nucleus is linked to the J^{π} of the levels [41]. Hence, for each populated ^{19}Ne excited state observed in the present experiment, a certain J^{π} value has been assumed by comparison with those available in the literature, as discussed below, and it is reported in parentheses in Table I. Using these assumptions, data from each resonance have been integrated over the full angular range by means the

TABLE I. Summary of the ^{19}Ne resonance parameters in the energy range explored by the experiment compared to results from other works. The energies of Ref. [39] reported in parenthesis have been not measured. Energies from Ref. [31] as well as those from the present paper have a systematic error of 10 keV.

$E_{\text{c.m.}}$ (keV) (present work)	E (keV) (present work)	C. D. Nesaraja *et al.* [39]	D. R. Tilley *et al.* [40]	A. S. Adekola *et al.* [31]	A. M. Laird *et al.* [32]
-574 ± 17	5837		5832 ± 9		
			$6013\pm 7\ (3/2,1/2)^-$		$6014 \pm 2(3/2^-)$
-341 ± 16	6070				$6072 \pm 2(3/2^+,5/2^-)$
				6089 ± 2	
			6092 ± 8		$6097 \pm 3(7/2,9/2)^+$
			6149 ± 20		$6132 \pm 3(3/2^+,5/2^-)$
-156 ± 18	6255				
			6288 ± 7	$6289 \pm 2(1/2^+,3/2^+)$	$6289 \pm 3(5/2,11/2)^-$
		$6419 \pm 6(3/2^+)$		$6419 \pm 6(3/2^-)$	$6416 \pm 3(3/2^-,5/2^+)$
		$(6422) \pm 30(11/2^+)$			
		$6437 \pm 9(1/2^-)$	6437 ± 9		$6440 \pm 3(11/2^+)$
		$6449 \pm 7(3/2^+)$			
49 ± 14	$6460(3/2^+,5/2^-)$				$6459 \pm 3(5/2^-)$
126 ± 15	$6537(7/2^+,9/2^+)$	$(6504) \pm 30(7/2^+)$ $(6542) \pm 30(9/2^+)$			
		$6698 \pm 6(5/2^+)$			6700 ± 3
344 ± 18	$6755(3/2^-)$	$6741 \pm 6(3/2^-)$	$6742 \pm 7\ (3/2,1/2^-)$	$6747 \pm 5(3/2^-)$	$6742 \pm 2(3/2^-)$
		$(6841) \pm 30(3/2^-)$			
		$6861 \pm 6(7/2^+)$	6861 ± 7		$6862 \pm 2(7/2^-)$
556 ± 19	$6968(5/2^+)$	$(6939) \pm 30\ (1/2^-)$ $(7054) \pm 30(5/2^+)$			
664 ± 10	$7075(3/2^+)$	$7075.7 \pm 1.6(3/2^+)$	7067 ± 9	$7089 \pm 5(3/2^+)$	
		⋮	⋮		
924 ± 11	7335		7326 ± 15		
1056 ± 13	7467	$7420 \pm 14(7/2^+)$ $7500 \pm 9(5/2^+)$	7531 ± 15	7431	

corresponding Legendre polynomial and multiplied for the corresponding penetrability factor of the centrifugal barrier. This procedure, reported in Refs. [1–13], allows us to get the OES cross section used to deduce the energy dependence of the astrophysical factor $S(E)$. As THM cannot provide for the absolute normalization of results, the obtained $S(E)$ spectrum was then normalized to the results of direct measurements on the well-known resonance at 7075 keV.

From the literature, the J^π values of the two resonances at energies 7075 keV and 6755 keV are well known to be $3/2^+$ and $3/2^-$, respectively, and these values have been assumed throughout the present analysis.

The resonance at $E = 6968$ keV has not been observed in previous measurements. Nonetheless, following Ref. [39], two nearby levels are predicted at 6939 keV ($J^\pi = 1/2^-$) and at 7054 keV ($J^\pi = 5/2^+$). The resonance at $E = 6968$ keV could then be associated with these predicted levels. In this case, fixing a value of $J^\pi = 1/2^-$ results in a cross-section value that is unlikely because it is larger than that of the resonance at $E = 7075$ keV. Moreover, the fact that the resonance at $E = 6968$ keV is not evident in direct measurements suggests instead a relatively high l assignment. So $J^\pi = 5/2^+$ ($l = 2$) has been assumed for this level in the present work for the calculation of the astrophysical S factor, though we cannot exclude higher assignments of the value of l for this resonance.

Likewise, the ^{19}Ne state at $E = 6537$ keV has not been observed in previous measurements and it has been associated in this analysis with the calculated levels at 6504 keV ($J^\pi = 7/2^+$) or 6542 keV ($J^\pi = 9/2^+$) both with $l = 2$ [39]. Both values of the resonance parameters result in a strong suppression of the cross section due to the centrifugal barrier penetrability and hence do not influence the final value of the astrophysical S factor. Just for computational purposes the spin-parity assignment for this level was fixed to be $7/2^+$.

The situation regarding the lower-energy region is less clear. In the present experiment only a level at 6460 keV is observed. Above the proton threshold several resonances are foreseen by comparing ^{19}Ne to its mirror nucleus ^{19}F [39] and some of them have been observed [22,31,32]. In particular, a resonance

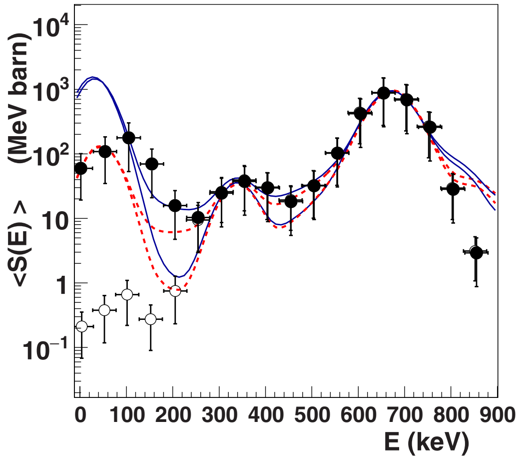

FIG. 4. (Color online) The ^{18}F(p,α)^{15}O astrophysical S factor from the present experiment. The full dots are THM experimental data with the assumption of $J^\pi = 3/2^+$ for the resonance at $E = 6460$ keV, the open ones correspond to the assumption of $J^\pi = 5/2^-$ (the difference from this last assumption to the other possible value $1/2^-$ and $3/2^-$ being negligible within the errors). The blue solid and red dashed lines shown in figure are calculations reported and discussed in Ref. [30] smeared to the present experimental resolution. Each pair represents the upper and lower limit for each calculation in Ref. [30].

at $E = 6459$ keV has been observed in Ref. [32] and it has been interpreted as part of a triplet of states with possible spins and parities ($3/2^-$ or $5/2^+$) at 6416 keV, ($11/2^+$) at 6440 keV, and ($5/2^-$) at 6459 keV. Calculations presented in Ref. [39] attribute to four states in the same energy region the spin-parity values of $1/2^-$ (6419 keV), $3/2^+$ (6422 keV and 6449 keV) and $11/2^+$ at the unobserved state at 6422 keV. Though only the level at 6449 keV and that at 6459 keV are within the fit error for the 6460 keV peak observed in the present work, calculations of the contribution to the total cross section due to this very level have been performed assuming all of the J^π values mentioned above. If the spin-parity value is fixed to be $11/2^+$ or $5/2^+$ this contribution is strongly suppressed by the centrifugal barrier penetrability factor and hence these J^π assignments are rejected. On the other hand, there is no reason to rule out the other values of J^π for this level, namely $1/2^-, 3/2^-, 5/2^-$, and $3/2^+$. Calculations showed that the differences on the contribution of the 6460 keV level to the astrophysical S factor for spin-parity assignment $1/2^-$, $3/2^-$, and $5/2^-$ are negligible within the errors. To conclude the discussion on the 6460 keV level, it is worth noting that possible interference effects in THM are not calculated but are already contained in the data [13,41]. So the other possible assignment $3/2^+$ to the 6460 keV level will automatically take into account interference effects, if any.

Finally, in the subthreshold region, the excited state observed here at $E = 6255$ keV was assigned a $J^\pi = 11/2^-$, as already proposed in Ref. [32]. This choice gives better agreement with existing data [30–32] though other J^π assignments cannot be ruled out on the basis of the present analysis.

In Fig. 4 the results obtained in this work for the astrophysical S factor are presented: assuming $J^\pi = 3/2^+$ for the 6460 keV state the result is reported as full dots while the $J^\pi = 5/2^-$ assumption for the same level gives the astrophysical S factor shown as open dots. Since levels in this region could not be resolved in the present experiment, the value of $S(E)$ obtained with the $3/2^+$ and $5/2^-$ assumptions represents, respectively, an upper and a lower limit for the astrophysical factor $S(E)$. In Fig. 4 the experimental points are also compared with the calculations for the astrophysical S factor presented in Figs. 3 and 4 of Ref. [30] smeared at the experimental resolution obtained in this work. In particular, the solid lines represent the upper and lower limits for an R-matrix calculation where the interference among the three states with $J^\pi = 3/2^+$ at energies 6419, 6449, and 7075 keV has been considered. The dashed lines represent the same limits for the case with interference between the two states at $E = 6449$ keV and $E = 7075$ keV only. In this latter calculation the authors of Ref. [30] attributed the value $J^\pi = 3/2^-$ to the $E = 6419$ keV state in ^{19}Ne. Data from the present experiment have been normalized to these calculations imposing that the integral of the resonance at 7075 keV is the same in direct and THM data.

In the energy region below 100 keV, depending on the J^π assignment chosen for the 6460 keV level, the present data either agree fairly well with the region given by the dashed lines in Fig. 4 ($J^\pi = 3/2^+$, full dots) or become much lower ($J^\pi = 5/2^-$, open dots) than any previous result. In both cases the data obtained in this work seems to exclude the existence of three interfering states having $J^\pi = 3/2^+$ represented by the solid lines Fig. 4.

IV. CONCLUSIONS

In conclusion, the THM was applied for the first time to study a reaction induced by a radioactive ion beam. Even with the use of indirect methods such as THM, the measurement of cross sections of interest for nuclear astrophysics remains one of the most difficult tasks in nuclear physics, because the low radioactive ion beam intensity adds on top of the low cross sections typical of astrophysical nuclear processes.

The THM data have been used to obtain the nuclear cross section for the ^{18}F(p,α)^{15}O reaction and, by comparison with pieces of information present in the literature, to infer information about the J^π of the ^{19}Ne nucleus excited states. From this it was possible to extract the astrophysical S factor for the ^{18}F(p,α)^{15}O process. In particular resonances in ^{19}Ne at energies 6255, 6460, 6537, 6755, 6968, and 7075 keV have been observed and studied, as they mostly influence the energy region of interest for the nova phenomena. A value of $J^\pi = 5/2^+$ has been assigned to the excited state at $E = 6968$ keV. For the $E = 6537$ keV both $J^\pi = 7/2^+$ or $9/2^+$ are compatible with the present data as this contribution to the astrophysical S factor is negligible. In the subthreshold region, the excited state at $E = 6255$ keV was assigned a $J^\pi = 11/2^-$, following Ref. [32].

Finally, in the near-threshold region, the data are consistent with a single resonance located at $E = 6460$ keV. Different spin assignments have been considered, namely $J^\pi = 3/2^+$ (Fig. 4, full dots) and $J^\pi = 1/2^-, 3/2^-$, or $5/2^-$ (Fig. 4, open dots). The comparison between the experimental data and the calculations of Ref. [30] seems to exclude the presence of two excited states near the proton threshold having $J^\pi = 3/2^+$, enforcing what was already reported in Refs. [31,32]. It is worth noting that, if the value $J^\pi = 3/2^+$ is assigned to the $E = 6460$ keV state, the effects coming from its interference with the $E = 7075$ keV state are implicitly present in the THM data. Therefore, once measured unambiguously, the J^π of this excited state, a straightforward indication of the value of the astrophysical S factor, including interference effects, in the energy region of interest for novae could immediately come from THM data.

ACKNOWLEDGMENTS

The authors are indebted to the AVF and CRIB technical staff for their invaluable contribution to the experiment and to the INFN-LNS workshop and electronics laboratory staff headed by B. Trovato and C. Calì, respectively. Also we thank C. Marchetta from the target laboratory at INFN-LNS. This work was supported in part by the Italian Ministry of University and Research under Grant No. RBFR082838 (FIRB2008). This work was partly supported by JSPS KAKENHI (Grants No. 21340053 and No. 25800125).

[1] C. Spitaleri, *Proceedings of the Fifth Hadronic Physics Winter Seminar, Folgaria, TN, Italy* (World Scientific, Singapore, 1990).

[2] S. Cherubini, V. N. Kondratyev, M. Lattuada, C. Spitaleri, D. Miljanic, M. Zadro, and G. Baur, Astrophys. J. **457**, 855 (1996).

[3] C. Spitaleri, L. Lamia, A. Tumino, R. G. Pizzone, S. Cherubini, A. Del Zoppo, P. Figuera, M. La Cognata, A. Musumarra, M. G. Pellegriti, A. Rinollo, C. Rolfs, S. Romano, and S. Tudisco, Phys. Rev. C **69**, 055806 (2004).

[4] G. Baur and S. Typel, Prog. Theor. Phys. Suppl. **154**, 333 (2004).

[5] A. M. Mukhamedzhanov, L. D. Blokhintsev, S. Brown, V. Burjan, S. Cherubini, V. Z. Goldberg, M. Gulino, B. F. Irgaziev, E. Johnson, K. Kemper, V. Kroha, M. La Cognata, L. Lamia, A. Momotyuk, R. G. Pizzone, B. Roeder, G. Rogachev, S. Romano, C. Spitaleri, R. E. Tribble, and A. Tumino, Nucl. Phys. A **787**, 321c (2007).

[6] A. Tumino, C. Spitaleri, A. M. Mukhamedzhanov, G. G. Rapisarda, S. Cherubini, V. Crucillà, Z. Elekes, Z. Fulop, M. Gulino, G. Gyurky, G. Kiss, M. La Cognata, L. Lamia, F. Mudo, R. G. Pizzone, S. Romano, M. L. Sergi, and E. Somorjai, Phys. Rev. Lett. **98**, 252502 (2007).

[7] A. Tumino, C. Spitaleri, A. M. Mukhamedzhanov, G. G. Rapisarda, L. Campajola, S. Cherubini, V. Crucillà, Z. Elekes, Z. Fulop, L. Gialanella, M. Gulino, G. Gyurky, G. Kiss, M. La Cognata, L. Lamia, A. Ordine, R. G. Pizzone, S. Romano, M. L. Sergi, and E. Somorjai, Phys. Rev. C **78**, 064001 (2008).

[8] M. Gulino, C. Spitaleri, S. Cherubini, V. Crucillà, M. La Cognata, L. Lamia, R. G. Pizzone, S. Romano, M. L. Sergi, A. Tumino, Chengbo Li, Z. Elekes, E. Somorjai, V. Burjan, V. Kroha, and A. M. Mukhamedzhanov, J. Phys. G: Nucl. Part. Phys. **37**, 125105 (2010).

[9] M. La Cognata, A. M. Mukhamedzhanov, C. Spitaleri, I. Indelicato, M. Aliotta, V. Burjan, S. Cherubini, A. Coc, M. Gulino, Z. Hons, G. G. Kiss, V. Kroha, L. Lamia, J. Mrazek, S. Palmerini, S. Piskor, R. G. Pizzone, S. M. R. Puglia, G. G. Rapisarda, S. Romano, M. L. Sergi, and A. Tumino, Astrophys. J. **739**, L54 (2011).

[10] L. Lamia, C. Spitaleri, V. Burjan, N. Carlin, S. Cherubini, V. Crucillà, M. G. Munhoz, M. G. Del Santo, M. Gulino, Z. Hons, G. G. Kiss, V. Kroha, S. Kubono, M. La Cognata, Chengbo Li, J. Mrazek, A. M. Mukhamedzhanov, R. G. Pizzone, S. M. R. Puglia, Q. Wen, G. G. Rapisarda, C. Rolfs, S. Romano, M. L. Sergi, E. Somorjai, F. A. Souza, A. S. de Toledo, G. Tabacaru, A. Tumino, Y. Wakabayashi, H. Yamaguchi, and S. H. Zhou, J. Phys. G: Nucl. Part. Phys. **39**, 015106 (2012).

[11] M. Gulino, S. Cherubini, G. G. Rapisarda, S. Kubono, L. Lamia, M. La Cognata, H. Yamaguchi, S. Hayakawa, Y. Wakabayashi, N. Iwasa, S. Kato, T. Komatsubara, T. Teranishi, A. Coc, N. De Sereville, F. Hammache, and C. Spitaleri, J. Phys.: Conf. Ser. **420**, 012149 (2013).

[12] M. Gulino, C. Spitaleri, X. D. Tang, G. L. Guardo, L. Lamia, S. Cherubini, B. Bucher, V. Burjan, M. Couder, P. Davies, R. deBoer, X. Fang, V. Z. Goldberg, Z. Hons, V. Kroha, L. Lamm, M. La Cognata, Chengbo Li, C. Ma, J. Mrazek, A. M. Mukhamedzhanov, M. Notani, S. O'Brien, R. G. Pizzone, G. G. Rapisarda, D. Roberson, M. L. Sergi, W. Tan, I. J. Thompson, and M. Wiescher, Phys. Rev. C **87**, 012801 (2013).

[13] R. E. Tribble, C. A. Bertulani, M. La Cognata, A. M. Mukhamedzhanov and C. Spitaleri, Rep. Prog. Phys. **77**, 106901 (2014).

[14] A. Coc, M. Hernanz, J. Jose, and J. P. Thibaud, Astron. Astrophys. **357**, 561 (2000), and references therein.

[15] R. Diehl, Rep. Prog. Phys. **76**, 026301 (2013).

[16] M. Wiescher and K. U. Kettner, Astrophys. J. **263**, 891 (1982).

[17] K. E. Rehm, M. Paul, A. D. Roberts, D. J. Blumenthal, J. Gehring, D. Henderson, C. L. Jiang, J. Nickles, J. Nolen, R. C. Pardo, J. P. Schiffer, and R. E. Segel, Phys. Rev. C **52**, R460(R) (1995).

[18] R. Coszach, M. Cogneau, C. R. Bain, F. Binon, T. Davinson, P. Decrock, T. Delbar, M. Gaelens, W. Galster, J. Goerres, J. S. Graulich, R. Irvine, D. Labar, P. Leleux, M. Loiselet, C. Michotte, R. Neal, G. Ryckewaert, A. C. Shotter, J. Vanhorenbeeck, J. Vervier, M. Wiescher, and P. Woods, Phys. Lett. B **353**, 184 (1995).

[19] K. E. Rehm, M. Paul, A. D. Roberts, C. L: Jiang, D. J. Blumenthal, S. M. Fischer, J. Gehring, D. Henderson, J. Nickles, J. Nolen, R. C. Pardo, J. P. Schiffer, and R. E. Segel, Phys. Rev. C **53**, 1950 (1996).

[20] K. E. Rehm, C. L. Jiang, M. Paul, D. J. Blumenthal, L. A. Daniel, C. N. Davids, P. Decrock, S. M. Fischer, D. Henderson, C. Lister, J. Nickles, J. Nolen, R. C. Pardo, J. P. Schiffer, D. Seweryniak, and R. E. Segel, Phys. Rev. C **55**, R566 (1997).

[21] J. S. Graulich, F. Binon, W. Bradfield-Smith, M. Cogneau, R. Coszach, T. Davinson, T. Delbar, M. Gaelens, W. Galster, J. Gorres, D. Labar, P. Leleux, M. Loiselet, J. McKenzie, R. Neal, G. Ryckewaert, A. C. Shotter, J. Vanhorenbeeck, J. Vervier, M. Wiescher, and P. Woods, Nucl. Phys. A **626**, 751 (1997).

[22] S. Utku, J. G. Ross, N. P. T. Bateman, D. W. Bardayan, A. A. Chen, J. Gorres, A. J. Howard, C. Iliadis, P. D. Parker, M. S.

Smith, R. B. Vogelaar, M. Wiescher, and K. Yildiz, Phys. Rev. C **57**, 2731 (1998); **58**, 1354 (1998).

[23] Y. M. Butt, J. W. Hammer, M. Jaeger, R. Kunz, A. Mayer, P. D. Parker, R. Schreiter, and G. Staudt, Phys. Rev. C **58**, R10 (1998).

[24] J. S. Graulich, S. Cherubini, R. Coszach, S. El Hajjami, W. Galster, P. Leleux, W. Bradfield-Smith, T. Davinson, A. Di Pietro, A. C. Shotter, J. Gorres, M. Wiescher, F. Binon, and J. Vanhorenbeeck, Phys. Rev. C **63**, 011302 (2000), and references therein.

[25] D. W. Bardayan, J. C. Blackmon, W. Bradfield-Smith, C. R. Brune, A. E. Champagne, T. Davinson, B. A. Johnson, R. L. Kozub, C. S. Lee, R. Lewis, P. D. Parker, A. C. Shotter, M. S. Smith, D. W. Visser, and P. J. Woods, Phys. Rev. C **63**, 065802 (2001).

[26] D. W. Bardayan, J. C. Batchelder, J. C. Blackmon, A. E. Champagne, T. Davinson, R. Fitzgerald, W. R. Hix, C. Iliadis, R. L. Kozub, Z. Ma, S. Parete-Koon, P. D. Parker, N. Shu, M. S. Smith, and P. J. Woods, Phys. Rev. Lett. **89**, 262501 (2002).

[27] N. de Séréville, A. Coc, C. Angulo, M. Assunção, D. Beaumel, B. Bouzid, S. Cherubini, M. Couder, P. Demaret, F. de Oliveira Santos, P. Figuera, S. Fortier, M. Gaelens, F. Hammache, J. Kiener, A. Lefebvre, D. Labar, P. Leleux, M. Loiselet, A. Ninane, S. Ouichaoui, G. Ryckewaert, N. Smirnova, V. Tatischeff, and J.-P. Thibaud, Phys. Rev. C **67**, 052801(R) (2003), references therein.

[28] R. L. Kozub, D. W. Bardayan, J. C. Batchelder, J. C. Blackmon, C. R. Brune, A. E. Champagne, J. A. Cizewski, T. Davinson, U. Greife, C. J. Gross, C. C. Jewett, R. J. Livesay, Z. Ma, B. H. Moazen, C. D. Nesaraja, L. Sahin, J. P. Scott, D. Shapira, M. S. Smith, J. S. Thomas, and P. J. Woods, Phys. Rev. C **71**, 032801(R) (2005).

[29] N. de Séréville, C. Angulo, A. Coc, N. L. Achouri, E. Casarejos, T. Davinson, P. Descouvemont, P. Figuera, S. Fox, F. Hammache, J. Kiener, A. M. Laird, A. Lefebvre-Schuhl, P. Leleux, P. Mumby-Croft, N. A. Orr, I. Stefan, K. Vaughan, and V. Tatischeff, Phys. Rev. C **79**, 015801 (2009).

[30] C. E. Beer, A. M. Laird, A. S. J. Murphy, M. A. Bentley, L. Buchman, B. Davids, T. Davinson, C. A. Diget, S. P. Fox, B. R. Fulton, U. Hager, D. Howell, L. Martin, C. Ruiz, G. Ruprecht, P. Salter, C. Vockenhuber, and P. Walden, Phys. Rev. C **83**, 042801 (2011).

[31] A. S. Adekola, D. W. Bardayan, J. C. Blackmon, C. R. Brune, K. Y. Chae, C. Domizioli, U. Greife, Z. Heinen, M. J. Hornish, K. L. Jones, R. L. Kozub, R. J. Livesay, Z. Ma, T. N. Massey, B. Moazen, C. D. Nesaraja, S. D. Pain, J. F. Shriner, Jr., N. D. Smith, M. S. Smith, J. S. Thomas, D. W. Visser, and A. V. Voinov, Phys. Rev. C **83**, 052801(R) (2011).

[32] A. M. Laird, A. Parikh, A. St. J. Murphy, K. Wimmer, A. A. Chen, C. M. Deibel, T. Faestermann, S. P. Fox, B. R. Fulton, R. Hertenberger, D. Irvine, J. Jose, R. Longland, D. J. Mountford, B. Sambrook, D. Seiler, and H. F. Wirth, Phys. Rev. Lett. **110**, 032502 (2013).

[33] T. Yanagimachi, T. Doke, N. Hasebe, T. Imai, T. Kashiwagi, J. Kikuchi, T. Kohno, W. P. Liu, K. Munakata, T. Motobayashi, H. Murakami, K. Nagata, A. Nakamoto, and H. Yamaguchi, Nucl. Instrum. Methods Phys. Res. Sec. A **275**, 307 (1989).

[34] K. Ieki, M. Ogiwara, Y. Ando, N. Iwasa, H. Murakami, and T. Motobayashi, Nucl. Instrum. Methods Phys. Res. Sec. A **297**, 312 (1990).

[35] Y. Yanagisawa, S. Kubono, T. Teranishi, K. Ue, S. Michimasa, M. Notani, J. J. He, Y. Ohshiro, S. Shimoura, S. Watanabe, N. Yamazaki, H. Iwasaki, S. Kato, T. Kishida, T. Morikawa, and Y. Mizoi, Nucl. Instrum. Methods Phys. Res. Sec. A **539**, 74 (2005).

[36] Y. Yamaguchi, Y. Wakabayashi, G. Amadio, S. Hayakawa, H. Fujikawa, S. Kubono, J. J. He, A. Kim, and D. N. Binh, Nucl. Instrum. Methods Phys. Res. Sec. A **589**, 150 (2008).

[37] G. F. Chew and G. C. Wick, Phys. Rev. **85**, 636 (1952).

[38] M. Zadro, D. Miljanic, C. Spitaleri, G. Calvi, M. Lattuada, and F. Riggi, Phys. Rev. C **40**, 181 (1989).

[39] C. D. Nesaraja, N. Shu, D. W. Bardayan, J. C. Blackmon, Y. S. Chen, R. L. Kozub, and M. S. Smith, Phys. Rev. C **75**, 055809 (2007).

[40] D. R. Tilley, H. R. Weller, C. M. Cheves, and R. M. Chasteler, Nucl. Phys. A **595**, 1 (1995).

[41] H. Fuchs *et al.*, Phys. Lett. B **37**, 285 (1971).