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Boulay, F., Bastin, B., De Oliveira Santos, F. et al. (30 more authors) (2018) Measurement of  $^{19}\text{Ne}$  spectroscopic properties via a new method of inelastic scattering to study novae. *Journal of Physics: Conference Series*. 012003. ISSN 1742-6596

<https://doi.org/10.1088/1742-6596/940/1/012003>

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To cite this article: F. Boulay *et al* 2018 *J. Phys.: Conf. Ser.* **940** 012003

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# Measurement of $^{19}\text{Ne}$ spectroscopic properties via a new method of inelastic scattering to study novae.

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## Abstract.

The accuracy of the predictions of the  $\gamma$  flux produced by a classical nova during the first hours after the outburst is limited by the uncertainties on several reaction rates, including the  $^{18}\text{F}(p,\alpha)^{15}\text{O}$  one. Better constraints on this reaction rate can be obtained by determining the spectroscopic properties of the compound nucleus  $^{19}\text{Ne}$ . This was achieved in a new inelastic scattering method using a  $^{19}\text{Ne}$  radioactive beam (produced by the GANIL-SPIRAL 1 facility) impinging onto a proton target. The experiment was performed at the VAMOS spectrometer. In this article the performances (excitation energy range covered and excitation energy resolution) and limitations of the new technique are discussed. Excitation energy resolution of  $\sigma=33$  keV and low background were obtained with this inverse kinematics method, which will allow extracting the spectroscopic properties of  $^{19}\text{Ne}$ .

## 1. Introduction

The classical description of a nova consists of an explosion that occurs in a binary system of stars. Typically, the outer layer of a main sequence star is accreted by gravitational attraction onto the surface of a companion white dwarf star (WD), where nuclear reactions are occurring. The surface temperature increases and can reach several hundreds of millions degrees depending on the mass and the type (either ONe or CO) of the WD. At these critical temperatures, the electronic degeneracy of the WD surface matter that prevents the expansion of the gas is lifted giving rise to the explosion and expulsion of matter into the interstellar medium.

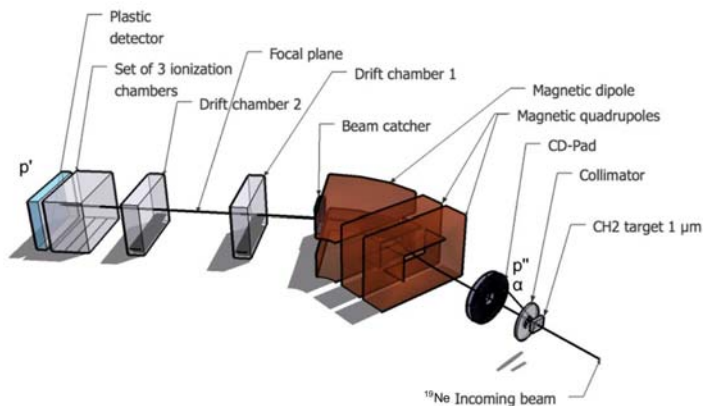
Some of the nuclei produced via proton capture reactions are radioactive. The detection of their characteristic  $\gamma$ -lines, by a satellite such as INTEGRAL, would allow to constrain the scenario of the explosion, with the proviso of knowing very well the reaction rates. According to models [1], the  $^{18}\text{F}$  nucleus 511 keV decay transition should dominate the low-energy  $\gamma$  spectrum ( $\leq 2$  MeV) during the first hours after the outburst.  $^{18}\text{F}$  has a reasonable half-life (110 min)



and is predicted to be sufficiently produced to be a good candidate for observation. To date, the evaluation of the  $^{18}\text{F}(p,\alpha)^{15}\text{O}$  reaction rate at the relevant astrophysics energy range, called Gamow window (GW) is mainly based on the spectroscopic properties of the compound nucleus  $^{19}\text{Ne}$  ( $^{18}\text{F}+p$ ). The lack of direct measurements within the GW is explained by the low beam intensities of  $^{18}\text{F}$  available at the current radioactive ions beam facilities and the low cross section. The existing uncertainties on the  $^{18}\text{F}(p,\alpha)^{15}\text{O}$  reaction rate covers several orders of magnitude at typical novae temperatures [2]. To better constrain this reaction rate, a new investigation of the  $^{19}\text{Ne}$  spectroscopic properties was performed at GANIL using a novel experimental setup.

## 2. Method and experimental setup

The inelastic scattering reaction  $^{19}\text{Ne}(p,p')^{19}\text{Ne}^*$  was used to populate the  $^{19}\text{Ne}$  states of interest, located around the proton threshold  $S_p=6.41$  MeV ( $S_\alpha=3.528$  MeV). The advantage of such a reaction mechanism is the statistical and non-selective feeding of all states. States that are not accessible via selective reactions like transfer reactions were indeed seen in this experiment. The kinematics of the protons  $p'$  allowed to reconstruct the excitation energy spectrum of  $^{19}\text{Ne}^*$  and to study the states of interest. These states, located in the GW region, can decay following three different channels. The  $\gamma$  decay channel has a very low probability. Thus no dedicated detector was used to measure them. The two main decay channels correspond to charged particle emissions ( $^{19}\text{Ne} \rightarrow ^{18}\text{F} + p''$  or  $^{19}\text{Ne} \rightarrow ^{15}\text{O} + \alpha$ ). The angular distribution of the emitted charged particles ( $\alpha$  or  $p''$ ) can be used to reconstruct the spin of the  $^{19}\text{Ne}$  states in a model independent way. The coincidence between the proton  $p'$  and the emitted particles can be used to extract the individual branching ratios.



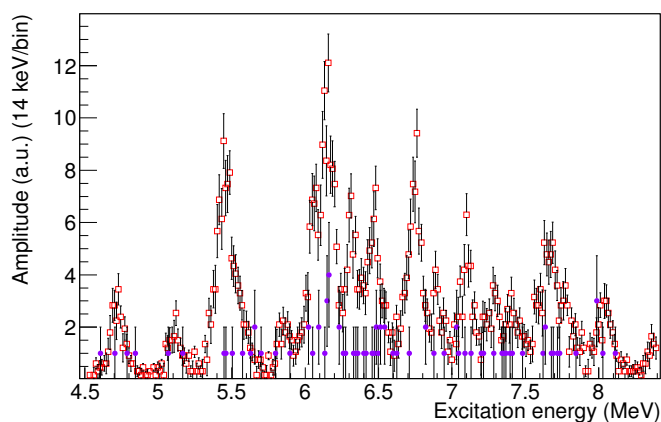
**Figure 1.** General layout of the experimental setup. The different detectors used in the experiment are indicated.

The  $^{19}\text{Ne}$  radioactive beam was produced at the GANIL-SPIRAL 1 facility. It was accelerated to 10 MeV/u by the CIME cyclotron and sent onto a  $1\ \mu\text{m}$  thin polyethylene target  $(\text{CH}_2)_n$ . The beam intensity was up to  $1 \times 10^8$  pps with a purity of 100 %. During the experiment, several beam cuts were applied in the accelerator section to improve as much as possible the beam position and its energy resolution. In those conditions the average incident  $^{19}\text{Ne}$  flux on target was of  $2 \times 10^7$  pps. In inverse kinematics, the proton  $p'$  has to be detected at zero degree to get the best energy resolution. The large acceptance VAMOS spectrometer [3] was used to reject the incident beam ions and to ensure the  $p'$  energy measurement of the protons with an energy resolution up to  $\frac{1}{500}$  (see Fig. 1). VAMOS was used for the first time to detect protons. The  $\alpha$  particles and protons  $p''$  were identified and characterized with a silicon  $\Delta E$ -E telescope called CD-PAD [4] located at 10 cm downstream the target.

### 3. Analysis and preliminary results

#### 3.1. Excitation energy

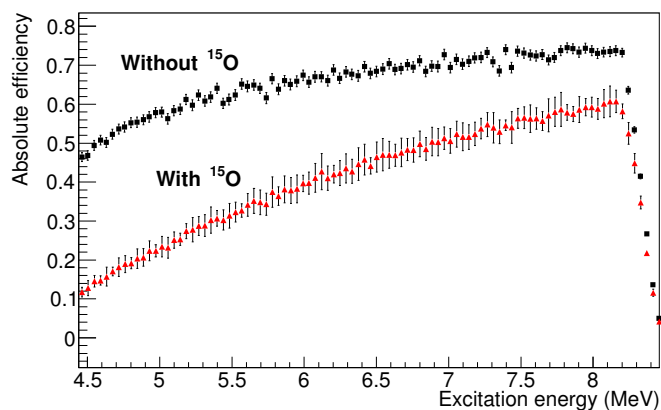
The large magnetic rigidity acceptance of VAMOS allowed measuring coincidences of  $p'$  scattered particles with  $\alpha$  and  $p''$  decay particles in a wide excitation energy range from 4.5 to 8.5 MeV (see Fig. 2) and from 7 to 8.5 MeV respectively. With this setup resolutions of 44 keV at 4.5 MeV to 33 keV at 8.1 MeV were achieved. The amplitude of the excitation energy spectrum was normalized to the beam time and corrected relative to the contribution of the carbon in the target. To perform this correction, measurements with a  $0.4 \mu\text{m}$  thick carbon target (during 15 % of the experiment) were realized (see Fig. 2) and pointed out a background level compatible with zero (observed counts in the spectrum are compatible with an hydrogen contamination usually present in thin carbon targets).



**Figure 2.** Excitation energy spectrum of  $^{19}\text{Ne}$  reconstructed by the VAMOS spectrometer with protons  $p'$  detected at  $0^\circ$  in coincidence with alpha particles recorded with the CD-PAD  $\Delta E$ -E telescope located behind the target (open squares). States are populated through the inelastic reaction mechanism  $^{19}\text{Ne}(p,p')^{19}\text{Ne}^*$ . In circles, the spectrum obtained when the  $(\text{CH}_2)_n$  target was substituted with a thin carbon target.

#### 3.2. Drawback of the method

A source of contamination was observed in the data, it is related to  $^{15}\text{O}$  and  $^{18}\text{F}$  coming from the decay of  $^{19}\text{Ne}^*$ . They are kinematically forward focused in the laboratory frame with a magnetic rigidity difference of about 20 % with respect to the dipole nominal value set for the experiment. The large acceptance of VAMOS allows thus a simultaneous detection of some of these particles with the proton  $p'$ . The heavy ions have a much higher energy deposit in the VAMOS drift chambers. Therefore, they produced saturation of the signals collected on the strips of the drift chambers leading to the destruction of the proton  $p'$  signal of interest.



**Figure 3.** Absolute efficiency as a function of the excitation energy deduced from a simulation in the case the proton  $p'$  is detected by VAMOS in coincidence with decaying  $\alpha$  particles recorded in the CD-PAD (black curve). The curve in red illustrates the loss of statistics and efficiency due to the heavy ions saturation effect on the drift chamber. Both simulations error bars include the uncertainty on the angular momentum distributions.

In order to correct these losses induced by heavy ions, a simulation that includes the full kinematics, the geometry of the CD-PAD, the angular and the magnetic rigidity acceptances

of the VAMOS spectrometer was developed and used. Figure 3 shows the absolute detection efficiency simulated as a function of the excitation energy reconstructed via the p' scattered particles measured in VAMOS in coincidence with an  $\alpha$  decay particle detected in the CD-PAD. Same work has been completed in the case of coincidences of p' with p'' decay particles.

### 3.3. Benchmarking of the new technique

Table 1 provides a comparison between the properties (excitation energy, proton to alpha width ratio, total width) extracted in this experiment and the ones from the literature [5] for the well known  $\frac{3}{2}^+$  state located at  $E_x=7.074$  MeV. There is a good agreement between these values. The uncertainties in excitation energy given in the literature are better than ours as determined from a compilation of several experiments. Our resolution is however the best achieved up to now for this type of experiment in inverse kinematics. The current limitation in energy resolution is mainly due to the target thickness. The resolution for the partial widths is degraded in this experiment because of the efficiency correction that has to be applied due to the heavy ions contamination. The spin of this state has not been assigned yet because additional corrections has to be applied (a precise knowledge of the beam position is needed for instance).

Properties	This experiment	Literature [5]
Excitation energy	7.076(3) MeV	7.074(2) MeV
$\Gamma_{tot}$	35(4) keV	39(2) keV
$\frac{\Gamma_p}{\Gamma_\alpha}$	0.64(5)	0.638(5)

**Table 1.** Summary of the 7.074 MeV state properties measured in this experiment and from the literature [5].

## 4. Conclusions

Thanks to the performances of the VAMOS spectrometer, we realized a new spectroscopic study of  $^{19}\text{Ne}$  with a high energy resolution ( $\sigma = 44$  to  $33$  keV) for an inverse kinematics measurement. The heavy ions coming from the decay of  $^{19}\text{Ne}^*$ ,  $^{15}\text{O}$  and  $^{18}\text{F}$ , induced statistics losses. A correction function was defined through a simulation of this experiment and applied to the data. It allowed us to extract relevant spectroscopic properties such as the total width, as well as the proton and the  $\alpha$  partial widths ratio. A comparison of the results obtained from this work for the well-known state at 7.074 MeV with the values given in the literature has been made and pointed out the power and accuracy of our method. New spectroscopic properties will be extracted for all the states located around the GW. For future experiments, a thin layer of aluminium could be used after the VAMOS dipole in order to stop the heavy ions. Its thickness should not impact too much the protons energy and angular resolution.

### 4.1. Acknowledgements

This work has been supported by the European Community FP7 - Capacities - Integrated Infrastructure Initiative - contract ENSAR n° 262010. This work was also supported by the France-Romanian IN2P3-IFIN-HH collaboration n° 03-33, by the France-Czech LEA NuAG collaboration and the NAVI collaboration. The authors would also like to thank the technical teams of GANIL for their strong implications in this experiment.

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