EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Proposal to the ISOLDE and Neutron Time-of-Flight Committee

Resonant proton scattering of ^{22}Mg and ^{21}Na

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Abstract

In our letter-of-intent, INTC-I-051, we discussed the physics case for scattering and transfer reactions involving light nuclei in the break-out region of the rp-process. The committee found the physics case compelling and supported the letter-of-intent under the premise that beams of proper quality were developed and that an adequate detector set-up was presented. As these two requirements have been met recently we now propose to study resonant proton scattering of ^{22}Mg to identify the states at 1.733 MeV and 2.575 MeV in ^{23}Al that have been reported from the ^{24}Mg(^{7}Li,^{8}He)^{23}Al reaction but that remained unobserved in the only resonant proton scattering experiment performed with ^{22}Mg sofar. In particular we should be able to investigate the character of the proton emission of the 2.575 MeV state which may also have a significant inelastic branch. We also propose to perform resonant proton scattering on ^{21}Na above α particle threshold with ^{18}Ne to study states in ^{22}Mg. States above α threshold are generally of interest for the ^{18}Ne(α,p)^{21}Na reaction. The experiment aims to study the decay of the states at 8.31 MeV, 8.18 MeV and potentially also of the 8.51 MeV state.

Requested shifts: 35 shifts, split into 2 runs over 2 years

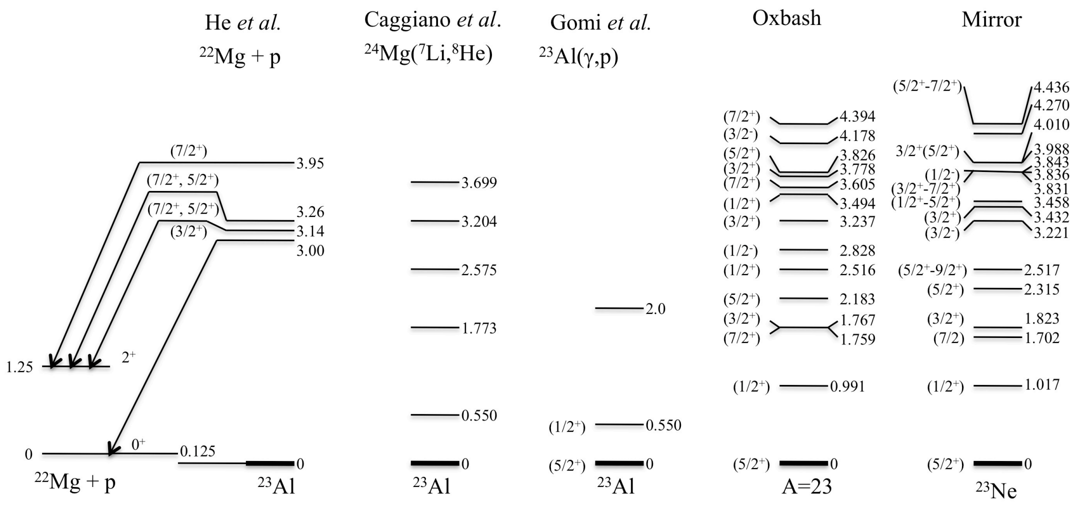

Figure. 1 The level structure of ^{23}Al from proton scattering, ^{24}Mg(^{7}Li,^{8}He) and Coulomb dissociation. A theoretical A=23 scheme together with the level scheme of the mirror nucleus ^{23}Ne are given to the right [12].

Introduction

The thermonuclear runaway of the rp-process that is thought to drive novae and X-ray bursters has been discussed in several reviews [1,2,3] after this process was first introduced by Wallace and Woosley [4]. In brief, mass flow onto the surface of a white dwarf or neutron star with remnant seed nuclei should be able to create the conditions needed for an explosive scenario. Typical temperatures and densities for this to occur have been suggested to be in the range; T~ 0.1- 1 GK and $\rho \sim 10^2 - 10^6$ g/cm^3 where the higher values are reached for mass transfer to a neutron star and are believed to trigger X-ray bursts. Calculations indicate that the full process may proceed as far as to mass A~100 [5]. A major question for the rp-process is which reaction path it will follow to avoid stagnation in mini-networks in the region of the light Ne and Na isotopes. Here, one aim has been to predict the amount of monoenergetic γ-rays that can be emitted by proton rich material after freeze out. If such γ-rays are produced they could potentially be used as a signature of proton rich nucleosynthesis in certain astrophysical objects. The idea is similar to the observation of localized monoenergetic γ-rays observed in Cas A and GRO J0852-4642 [6]. In the rp-process case it has been suggested to use the 1.275 MeV line in ^{22}Ne for this purpose. A similar topic is also the mapping of the galactic distribution of ^{26}Al [7]. Yet another motivation for nuclear reaction studies in the break-out region is to understand the power generation well enough to be able to reproduce the explosive process in full. Here connections can be made with observed light curves [8] which is one aim of X-ray burst simulations [9]. In the lighter mass region significant effort has been put into determining the rates of the ^{17}F(p,γ)^{18}Ne [10] and ^{21}Na(p,γ) [11] reactions by direct measurement. However, the picture is still far from clear and many other reaction rates are

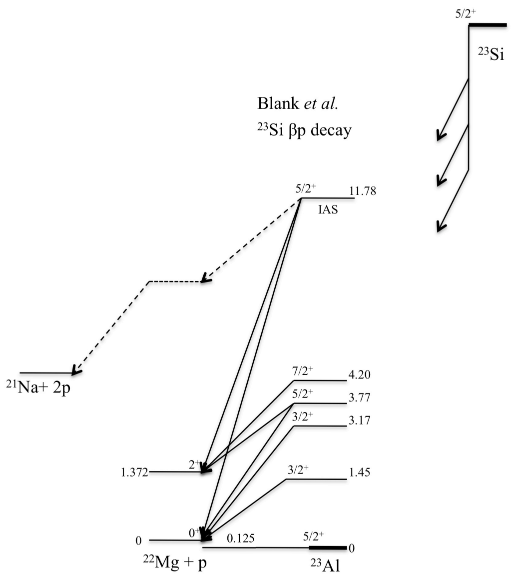

Figure 2. Decay pattern following β-emission of ^{23}Si.

still missing in order to have network calculations based on experimentally deduced quantities.

The experiment proposed here focusses on determining the structure close to proton and α-particle threshold for the two isotopes ^{23}Al and ^{22}Mg. The ^{22}Mg(p,γ) ^{23}Al reaction has not been measured directly yet and it is therefore of interest use other methods to establish a full picture of its level structure. Although the proton separation energy is low (~125 keV) proton capture on this isotope provides a way to bypass the β-decay to ^{22}Ne mentioned above. As of yet only one attempt has been made to populate proton resonances in ^{23}Al but unfortunately only states above ~3 MeV was seen in that study [12]. Thus, with the current experiment we propose to populate states below this energy. Here one can note that βp and βpp decay studies involving ^{23}Si have also been carried out [13]. For ^{22}Mg the level structure has been studied extensively [14] close to and below proton threshold in connection to the ^{21}Na(p,γ) ^{22}Mg reaction. However, it has been concluded that another reaction involving ^{21}Na, i.e. ^{18}Ne(α,p)^{21}Na, can be directly involved in the break-out into the full rp-process [15]. As the cross section for α capture is small this reaction is still studied indirectly at the relevant energies. The contribution of the proposed experiment is to investigate proton resonances close to the α-particle threshold up to ~8.5 MeV. Other interesting α capture reactions include the often mentioned ^{14}O(α,p)^{17}F reaction which has the role of reprocessing material between cycles before break-out. Typical minimum temperatures for break-out via the ^{18}Ne(α,p)^{21}Na reaction is estimated to T >0.5 GK and depends on density.

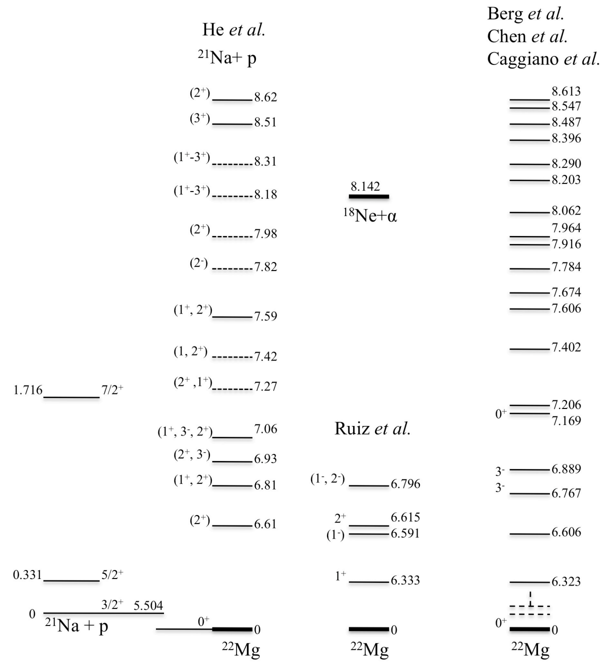

Figure. 3 The level structure of ^{22}Mg from proton scattering and reactions [25].

The structure of ^{23}Al

The ground state

The ground state spin and parity has been determined using β-NMR to $5/2^+$ [16].

The 550 keV state

At least three attempts have been made to populate the first excited state in ^{23}Al using the ^{24}Mg(^{7}Li,^{8}He) reaction. Wiescher et al. published the first evidence for an excited state in ^{23}Al using this reaction at 191 MeV at NSCL [17]. The state remained unresolved from the ground state and the energy was given as 470 ± 40 keV (proton threshold 125 keV). This value was an averaged value including a reanalysis of an experiment by Benenson *et al.* [18]. A follow-up experiment was carried out by Caggiano *et al.* [19] in 2001 using a ^{7} Li beam at 50.1 MeV/u and a resolved peak at 550 keV was observed (see Fig. 1). The corresponding state in the mirror ^{23}Ne is at ~1 MeV. The lower energy for the state in ^{23}Al is attributed to a Thomas-Ehrman shift supposedly due to pronounced single particle structure. Caggiano *et al.* calculated the proton width to be 74.0 eV. This width differed by a factor of 2 from the one previously published by Wiescher *et al.* In 2005 Gomi *et al.* [20] did Coulomb dissociation of ^{23}Al at 50 MeV/u and published a value of $\Gamma_\gamma = 7.2 \cdot 10^{-7}$ eV. This value was well in line with the value predicted by Caggiano *et al.*, $\Gamma_\gamma = 5.5 \cdot 10^{-7}$ eV. The assumption is that the state has spin and parity $1/2^+$. The capture is predicted to proceed via this state and directly to the ground state with about the same rate for T = 0.4-0.8 GK. According to current knowledge the direct capture dominates below and above this temperature.

Figure. 4 Left panel: The new scattering chamber during testing. Right panel: The detecors during mounting.

Higher lying states from $^{24}Mg(^{7}Li,^{8}He)$

Caggiano *et al.* also observed a state at 1.773 MeV while this state was not observed by Gomi *et al.* The width of the state has been estimated to ~ 1 keV and could be within reach for resonant scattering depending on intensity. The state at 2.575 MeV is speculated to correspond to the first $5/2^+$ predicted by theory. The width of this state for decay to the ground state in ^{22}Mg has been calculated to be ~ 3 keV while the decay to the the first excited state at 1.25 MeV may be 20 keV [12]. According to theory there are thus only two states below this energy that could fit the 1.773 MeV state. These have spin and parity $7/2^+$ and $3/2^+$, respectively. One can note that the level at 2.0 MeV for the study of Gomi *et al.* given ref. [12] is not discussed in ref. [20]. The levels at 3.204 MeV and 3.699 MeV will be above the energy reachable with REX-ISOLDE.

States observed in proton scattering

An interesting result of the first resonant scattering experiment described in ref. [12] is that no states were observed below 3.0 MeV. The experiment was carried out at CNS at RIKEN using the ^{3}He(^{22}Ne,^{22}Mg)n reaction producing a 4.38 MeV/u beam of $4.4 \cdot 10^4$ pps with a purity of 3% and an energy spread of 0.18 MeV/u. The beam spot was 15 × 11 mm. The flight path between target and detector system was ~25 cm. These factors may have influenced the possibility to observe weaker resonances. Contrary to expectation the states that were observed were all between 3.0 MeV and 3.95 MeV. The state at 3.0 MeV is identified as the theoretical second $3/2^+$ state (see Fig. 1). The predicted width of the state is 44 keV, close to the observed 32± 5 keV. The structure of the state is believed to be a $d_{3/2}$ proton coupled to the ^{22}Mg 0^+ ground state. The two states at 3.14 and 3.26 are similarly believed to be based om the ^{22}Mg 2^+ state coupled to protons in the $d_{3/2}$ and $s_{1/2}$ orbits including mixing. A potential corroboration of this assumption is that the proton decay is dominantly to the 2^+ state in ^{22}Mg.

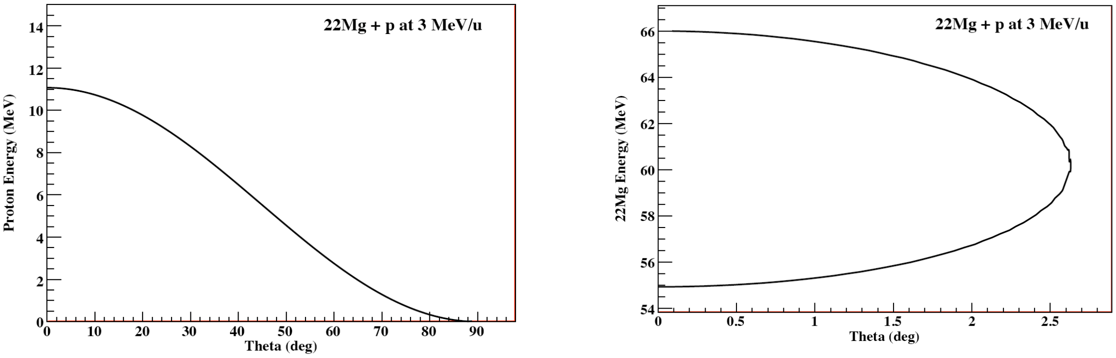

Figure. 5 Left panel: Proton energies and scattering angles at 3 MeV/u. Right panel: Same as to the right for an incoming ^{22}Mg beam.

States observed in βp

Blank *et al.* [13] have performed proton spectroscopy following β –decay of ^{23}Si. In short, decay from the IAS to the ground state and the 2+ state in ^{22}Mg was observed. Proton lines corresponding to the assumed decay of excited states in ^{22}Mg with spins $3/2^+$ - $7/2^+$ were assigned but the assignment was not firm.

The structure of ^{22}Mg near ^{18}Ne + α threshold

Direct measurement of the ^{18}Ne(α,p)^{21}Na reaction has sofar only been done above ~1.5 GK [21] i.e. significantly above the threshold energy at 8.14 MeV. Ruiz *et al.* [22] observed states up to 6.796 MeV using resonant proton scattering i.e. below the α threshold. Chen *et al.* [23] used the ^{12}C(^{16}O,^{6}He)^{22}Mg reaction to identify several states close to α threshold (see Fig. 3). However, although several reactions have been used to populate potential states of interest very little has been known concerning the spins and parities of the relevant states. In a recent study by Chae *et al.* [24] it was attempted to use the ^{24}Mg(p,t)^{22}Mg reaction to determine spin and parities via angular distributions but those results differ when compared to the recent proton scattering experiment of ref. [25]. Consequently, there is a need for new experiments to determine spins and parities of the states close to α threshold. Of particular interest for an experiment at REX-ISOLDE is to scan the energy region between 8.5 MeV and 8.14 MeV but it would also be possible to investigate the states at 7.98 MeV and 7.82 MeV and further below the threshold.

The experimental set up.

A new scattering chamber has been constructed and was delivered to ISOLDE in 2010. The diameter is ~1 m and the layout allows for flight paths close to this length. Several ports exists for target manipulation ((CH_2)n targets for proton scattering) and cable feed throughs etc. The long flight path is an important feature since a well defined scattering angle is vital in order to maintain good energy resolution due to the finite beam spot size when the beam is brought to a stop in the target. The chamber has been tested before delivery and is ready for use (see Fig. 4).

The detector system consists of six Double Sided Si Strip detectors (DSSSDs) that can be mounted at different distances and angles from the target. Four of the detectors are circular and two are square DSSSDs. They are transmission mounted and can be used in telescope configurations for particle identification. The circular detectors are 300 and 500 μm thick and have 64 sectors and 32 rings for position determination. The dead layer is 0.5 μm and 1.5 μm on the front and back side, respectively. The circular detectors have outer radii of 85 mm. Two have an inner radius of 32 mm and two an inner radius of 15 mm. The square detectors with sides of 7 cm have 32 strips in the horizontal and vertical directions. A thick backing detector of 1 mm of the square type exisits in addition to 300 μm and 500 μm detectors (see Fig 4).

Beams of mass A~20 that scatter on protons go into a forward cone of a few degrees if they escape the target while the scattered protons cover angles up to 90 degrees (see Fig. 5). The target thicknesses for the different cases have been calculated with SRIM but may vary depending on the region of resonances as discussed above.

Targetry

Sufficient yields of ^{22}Mg and ^{21}Na have been produced using SiC targets at ISOLDE already at the SC. The yield book states a ^{22}Mg yield of 8.8E5 p/μC. The main issue for the Mg beam has been the purity (the lifetime is 3.9 s). The development of the beam has been on the priority list of the upgrade group. Recent tests have concluded that a full stripping of ^{22}Mg should be possible using a thin carbon foil with an efficiency of 10%. The contaminating Na isobar is then separated from the beam in the analyzing magnet before the target station. With a post acceleration efficiency, without stripping, of ~10% the yield will be ~1E4 p/μC after stripping which is sufficient for a scattering experiment. The yield of ^{21}Na has also been measured from a SiC target at the SC to be 7.6E7. In both cases hot plasma sources were used. The ^{21}Na yield is consequently sufficient for a scattering experiment.

Summary

We propose to perform resonant proton scattering using beams of ^{22}Mg and ^{21}Na to study resonant states in ^{23}Al and ^{22}Mg. In particular we want investigate the character of the proton emission of the 1.733 and 2.575 MeV states in ^{23}Al and scan for possibly unobserved states. We also propose to perform proton scattering on ^{21}Na to study states in ^{22}Mg above α threshold. The experiment aims to study the decay of the states at 8.31 MeV, 8.18 MeV and 7.98 MeV and potentially also of the 8.51 MeV state with particular emphasis on spin and parity assignments.

Summary of requested shifts:

We request 20 shifts for the ^{22}Mg beam including 3 shifts for beam set up. For the ^{21}Na case we ask for 15 shifts including 1 shift for beam set up.

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Appendix

DESCRIPTION OF THE PROPOSED EXPERIMENT

The experimental setup comprises:

Part of the Choose an item.	Availability	Design and manufacturing
Scattering chamber. In place since 2010.	☒ Existing	☒ To be used without any modification
		A vacuum chamber and a set of silicon strip detectors. Pumps for vacuum. Electronics for data acquistion. Voltage supplies for detectors. All standard equipment.
[Part 1 of experiment/ equipment]	☐ Existing	☐ To be used without any modification ☐ To be modified
	☐ New	☐ Standard equipment supplied by a manufacturer ☐ CERN/collaboration responsible for the design and/or manufacturing
[Part 2 experiment/ equipment]	☐ Existing	☐ To be used without any modification ☐ To be modified
	☐ New	☐ Standard equipment supplied by a manufacturer ☐ CERN/collaboration responsible for the design and/or manufacturing
[insert lines if needed]		

HAZARDS GENERATED BY THE EXPERIMENT

(if using fixed installation) Hazards named in the document relevant for the fixed [COLLAPS, CRIS, ISOLTRAP, MINIBALL + only CD, MINIBALL + T-REX, NICOLE, SSP-GLM chamber, SSP-GHM chamber, or WITCH] installation.

Additional hazards:

Hazards			
	[Part 1 of the experiment/equipment]	*[Part 2 of the experiment/equipment]*	*[Part 3 of the experiment/equipment]*
Thermodynamic and fluidic			
Pressure	No		
Vacuum	1E-6 mbar		
Temperature	No (room temperature)		
Heat transfer	No		
Thermal properties of materials	No		
Cryogenic fluid	None		
Electrical and electromagnetic			
Electricity	[50] [V], [1E-6][A]*6		
Static electricity			
Magnetic field	none [T]		
Batteries	☐		
Capacitors	☐		
Ionizing radiation			
Target material	(CH2)n (Polyethylene plastic)		
Beam particle type (e, p, ions, etc)	22Mg and 21Na		

Beam intensity	~10E4 pps		
Beam energy	3 MeV/u		
Cooling liquids	No		
Gases	No		
Calibration sources:	☐		
• Open source	☐		
• Sealed source	☐ [ISO standard]		
• Isotope			
• Activity			
Use of activated material:	No		
• Description	☐		
• Dose rate on contact and in 10 cm distance	[dose][mSV]		
• Isotope			
• Activity			
Non-ionizing radiation			
Laser	No		
UV light	No		
Microwaves (300MHz-30 GHz)	No		
Radiofrequency (1-300MHz)	No		
Chemical			
Toxic			
Harmful			
CMR (carcinogens, mutagens and substances toxic to reproduction)			
Corrosive			
Irritant			
Flammable			
Oxidizing			
Explosiveness			
Asphyxiant			
Dangerous for the environment			
Mechanical			
Physical impact or mechanical energy (moving parts)	No		
Mechanical properties (Sharp, rough, slippery)	No		
Vibration	No		
Vehicles and Means of Transport	No		
Noise			
Frequency	No		
Intensity	No		
Physical			
Confined spaces	No		
High workplaces	No		
Access to high workplaces	No		
Obstructions in passageways	No		
Manual handling	No		
Poor ergonomics	No		

0.1 Hazard identification

3.2 Average electrical power requirements (excluding fixed ISOLDE-installation mentioned above): *(make a rough estimate of the total power consumption of the additional equipment used in the experiment)*

4 crates with 500 W power supplies