EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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

Investigating the key *rp* process reaction ^{61}Ga(p,γ)^{62}Ge reaction via ^{61}Zn(d,p)^{62}Zn transfer

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Abstract: We propose to study the ^{61}Zn(d,p)^{62}Zn reaction in inverse kinematics for the first time, using the ISOL Solenoidal Spectrometer currently being installed at ISOLDE. This measurement represents the mirror analog of the astrophysically important ^{61}Ga(p,γ)^{62}Ge process (a reaction that cannot be presently studied with conventional means) and will allow for the first ever constraints to be placed on the stellar reaction rate. In particular, the energies and spectroscopic factors obtained for excited states in ^{62}Zn will be used to determine the resonant properties of proton-unbound levels in the nucleus ^{62}Ge, which are expected to dominate the ^{61}Ga(p,γ)^{62}Ge reaction in X-ray bursts. This study is very timely as the ^{61}Ga(p,γ)^{62}Ge reaction directly affects astronomical observables that are currently being obtained by the latest generation of space-based telescopes with unprecedented precision.

Requested shifts: 7 days (14 shifts)
Installation: ISOL Solenoidal Spectrometer

1 Physics Case

Type-I X-ray bursts are interpreted as thermonuclear explosions in the atmospheres of accreting neutron stars in close binary systems [1]. These astronomical scenarios exhibit brief recurrent bursts of intense X-ray emission and represent some of the most frequent and violent stellar events to occur in our Galaxy. Recently, space-borne satellites such as the Rossi X-ray Timing Explorer (RXTE) and Chandra X-ray telescope have produced a wealth of observational data on Type-I X-ray bursts, marking a new era in X-ray astronomy [2]. However, despite the vast quantities of observational data now available, many key questions about the exact nature of X-ray bursts remain, particularly with regards to the shape and structure of the observed light curves [3]. Consequently, in order to fully exploit the remarkable achievements of X-ray astronomy, similar advances in our understanding of the underlying nuclear physics processes governing nucleosynthesis and energy generation are required. Moreover, as neutron stars represent some of the most extreme states of nuclear matter, a complete understanding of Type-I X-ray bursts is likely to have significant implications beyond the field of nuclear astrophysics.

In between bursts, energy is generated at a constant rate by the β-limited hot CNO cycles. However, during the burst, sufficiently high temperatures are achieved ($T_{\text{peak}} \sim 0.8 - 1.5$ GK) such that it is possible to "breakout" from the hot CNO cycles into a whole new set of thermonuclear reactions, known as the *rp*-process [4]. This process involves a series of rapid proton captures resulting in the synthesis of very proton-rich nuclei up to the Sn – Te mass region and could be a candidate for the production of the astrophysically important *p*-nuclei such as ^{92}Mo and ^{96}Ru, although the exact escape mechanism is not clear. Recently, significant increases in computing power have allowed for detailed theoretical models of X-ray burst nucleosynthesis to be used to estimate the impact of individual reaction rate uncertainties on both final isotopic yields and overall energy output [5,6]. In particular, a number of key waiting points have been identified along the *rp* process path [e.g. ^{56}Ni and ^{60}Zn], shown in Fig. 1, that dramatically affect the energy generation in X-ray bursts, as well as the products of nucleosynthesis.

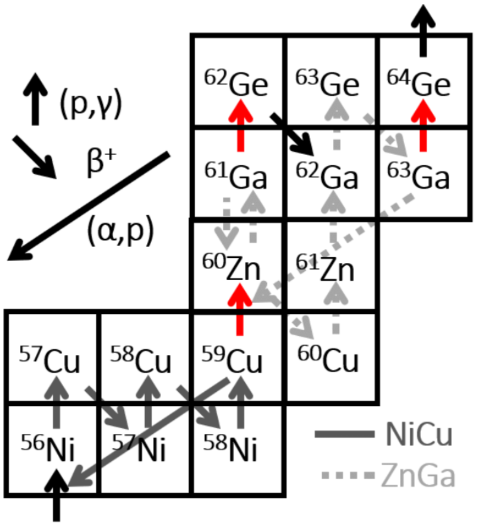

Figure 1 - Nuclear reaction network around ^{60}Zn in astrophysical X-ray bursts.

A study by Cyburt *et al.* [6] investigated the dependence of X-ray bursts on uncertainties in (p,γ), (α,γ), and (α,p) nuclear reaction rates using fully self-consistent models that account for feedbacks between changes in nuclear energy generation and changes in astrophysical conditions. Rather surprisingly, despite varying 1931 different nuclear processes through their associated uncertainties, only a handful of reactions were found to have a significant affect on both the burst light curve and final isotopic compositions [6]. Of these, the ^{61}Ga(p,γ)^{62}Ge reaction, which bypasses the ^{60}Zn waiting, was highlighted as being particularly significant (Figs. 2 and 3) and at present, its rate over the temperature range of X-ray bursts is effectively unknown.

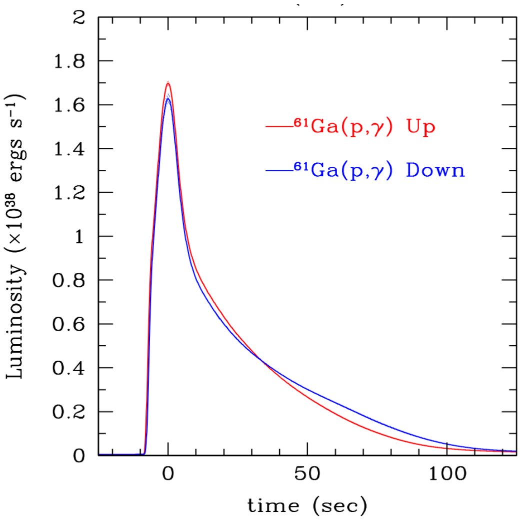

Figure 2 - Effect of varying the ^{61}Ga(p,γ) reaction rate on the observed light curve [6].

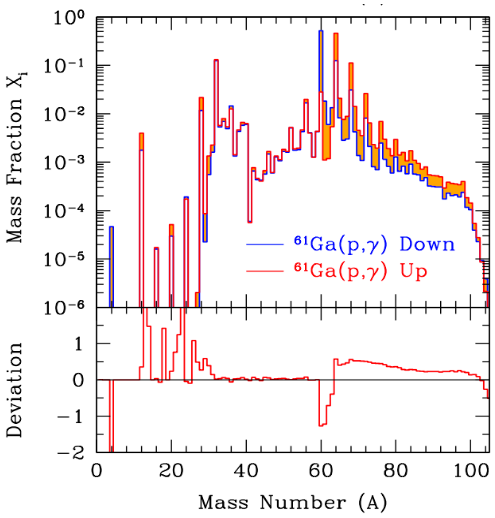

Figure 3 - Effect of varying the ^{61}Ga(p,γ) reaction rate on final isotopic abundances [6].

Most recently, Meisel *et al.* [7] used the MESA simulation code to investigate the impact of nuclear reaction rate uncertainties, previously identified as influential [6], and compared these model parameters to astronomical observations of a textbook X-ray burst source, **GS 1826-24** [8]. In that study [7], the ^{61}Ga(p,γ) reaction was again highlighted as having a considerable effect on X-ray bursts light curve. However, more intriguingly, it was noted that the influence of the astrophysical ^{61}Ga(p,γ) reaction on the distance-redshift determination also significantly hinders the possibility of extracting the neutron star mass-radius ratio by matching the modelled and observed light curves of X-ray bursts (see Fig. 4). Furthermore, the ^{61}Ga(p,γ) reaction may enhance Urca cooling processes in X-ray bursts and the positive identification of these would provide unique evidence of nuclear reactions in the crust of neutron stars.

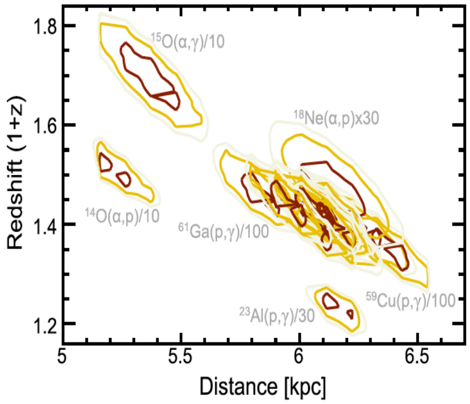

Figure 4 - The 68% (red lines), 95% (yellow lines), and 99% (grey lines) confidence intervals for the distance-redshift determination performed comparing light curves to the GS 1826-24 2007 bursting epoch.

The astrophysical ^{61}Ga(p,γ)^{62}Ge reaction, like many reactions that occur in the explosive astrophysical environments, is expected to be dominated by the contribution of resonant capture to excited states in ^{62}Ge, located above the proton-emission threshold. However, studying such systems, that lie far from stability, is extremely challenging and, in fact, in many cases is not presently possible. This is particularly relevant for the case of the astrophysical ^{61}Ga(p,γ) reaction, as almost no experimental information exists for excited states in ^{62}Ge.

Recently, it has been shown that investigations of mirror nuclei offer a unique solution to this issue [9-11]. The properties of excited states in pairs of mirror nuclei are almost identical and, therefore, by obtaining spectroscopic information for key analog states in the neutron-rich system, it is possible to accurately determine the rates of astrophysical processes, involving proton-rich nuclei that cannot be accessed experimentally [9-11]. Specifically, the location of resonant states may be ascertained from theoretical calculations of mirror energy differences, while extracted neutron spectroscopic factors can be used to estimate proton partial widths, Γ_p, of unbound states, thereby constraining the associated resonance strengths. Consequently, we propose to utilise the intense radioactive beams of ^{61}Zn available at CERN, as well as the newly installed ISOL Solenoid Spectrometer (ISS), to study excited states in the astrophysically important mirror nucleus ^{62}Zn, via ^{61}Zn(d,p) transfer. This information will then be used to place the first ever constraints on the astrophysical ^{61}Ga(p,γ)^{62}Ge reaction rate in X-ray burster environments, thereby allowing a detailed comparison between the latest theoretical models and astronomical observations.

2 Experimental details

We propose to measure the ^{61}Zn(d,p) reaction in inverse kinematics using a radioactive beam of ^{61}Zn at 7.5 MeV/u to bombard a ~100 μg/cm^2 thick CD$_2$ target, in order to probe excited states in the nucleus ^{62}Zn. At these energies, the angular distributions for transfer to final states of differing l are more pronounced and forward peaked, compared to lower energy measurements, such that assignments of the transferred angular momentum are more distinct. In particular, we aim to measure the neutron spectroscopic factors of low-l transfer levels in the excitation energy region of 2 – 3.5 MeV. Such states, for which the cross section peaks at forward centre-of-mass angles, represent analogs of resonances in the ^{61}Ga(p,γ)^{62}Ge reaction and as such, by determining their properties, it is possible to evaluate the stellar reaction rate.

The resulting protons following ^{61}Zn(d,p) transfer will be detected with the ISS Spectrometer, which has already been successfully employed to measure the ^{206}Hg(d,p) reaction [12]. However, in contrast to Ref. [12], we intend to utilise the newly developed Liverpool Silicon array that allows for greater angular coverage of light reaction products [13], together with the state-of-the-art, Manchester fast-counting ionization chamber for heavy ion recoils [14]. The extracted cross sections and angular distributions will be compared to calculations using the ADWA code TWOFNR [15], to obtain information on the spectroscopic factors of final states. The spin-parity assignments of states in ^{62}Zn are already well established and it is known to have a relatively low level-density in the excitation energy region of relevance for the astrophysical ^{61}Ga(p,γ) reaction (E_x = 2 – 3.5 MeV) [16]. As such, we expect that our predicted energy resolution of <100 keV will be more than sufficient to easily separate the most astrophysically significant, strong spectroscopic factor states.

The experimental configuration for the ^{61}Zn(d,p) measurement is shown in Fig. 5. The silicon array will be positioned −28 cm from the target as measured to the nearest detector edge, covering a range in z from the target of −28 to −78 cm. The solenoid field will be set at 2.5 T. With these settings, protons emitted at $5° < \theta_{cm} < 40°$ will be incident on the array for all states up to 3.5 MeV. This range of angles covers the maxima for astrophysically important low-l transfers. Elastically scattered deuterons will be detected in an annular silicon detector positioned at z = +17 cm. The proposed measurement does not necessarily require recoil detection, in analogy with Tang *et al.* [12]. However, in this case, we intend to use a fast-counting ionization chamber at the focal plane to the ISS. This will allow us to obtain an excitation energy spectrum of ^{62}Zn that is free from background from fusion-evaporation protons and α particles. Furthermore, a timing reference from the ionisation chamber will help to remove any unwanted multiple proton orbits, that may return to the array far from the target position.

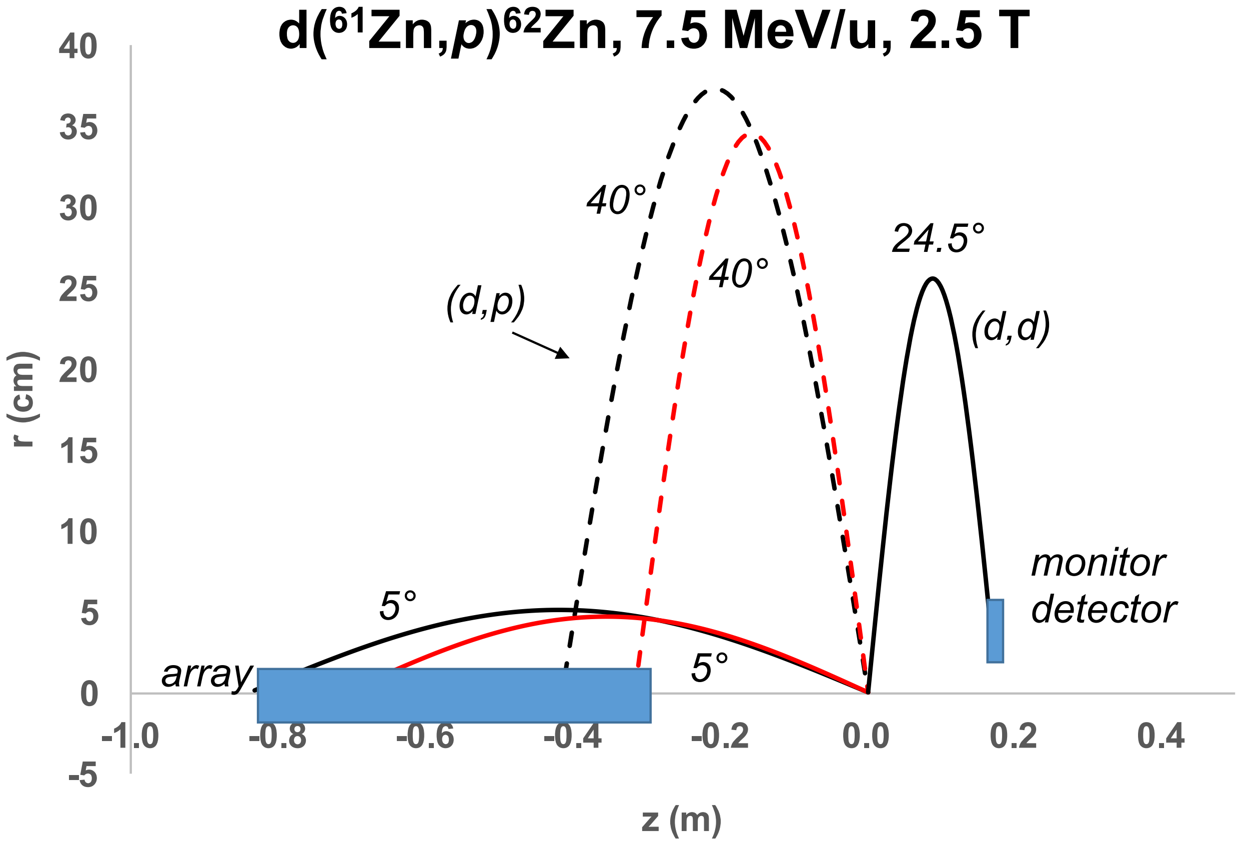

Figure 5 - Proposed experimental setup within the solenoidal spectrometer. Distances are relative to the target position. For the (d,p) reaction, the black lines represent population of the ground state, while the red lines indicate population of an excited state at 3.5 MeV.

3 Beam time request

Beam intensities of up to 4 x 10^6 pps have been reported for ^{61}Zn on the ISOLDE yield database. Consequently, we assume that a beam intensity of ~2 x 10^5 pps of ^{61}Zn should be reasonably achievable at HIE-ISOLDE. From discussions with beam experts at CERN, it is expected that RILIS ionized neutron-deficient Zn beams will be largely free from contamination. In particular, Ga (which has previously been observed as a contaminant in running neutron-rich Zn beams at CERN) is expected to be produced with rates 7 orders of magnitude lower than Zn for the proposed study. That being said, we would still intend to run with and without RILIS to establish any potential background contamination peaks.

The array has an efficiency of 70% in the azimuthal angle and 95% in the theta angle. Protons in the angular range $5° < \theta_{cm} < 40°$ will be incident on the array. Using cross sections estimated using the ADWA code TWOFNR, a CD_2 target ~100 μg/cm^2 thick and assuming a spectroscopic factor of ~0.1 for excited states in the energy region 2 – 3.5 MeV, we estimate that ~70 counts per day will be observed in the whole array for the states of interest. The array will be divided into 10 angular bins and, as such, in order to obtain a spectroscopic factor at the level 0.1 to a precision of ~20%, we would require 15 shifts of beam on target (corresponding to ~350 counts across the entire array for each state). For a measurement of the background, we intend to run without RILIS for 2 shifts.

The present proposal offers an exceptional opportunity to extend the science scope of the ISS to measurements of astrophysical importance. Moreover, by constraining uncertainties in the ^{61}Ga(p,γ)^{62}Ge reaction, it will not only provide invaluable information for state-of-the-art models of X-ray burster scenarios but will also allow for direct comparisons to be made with the latest set of astronomical data, making it extremely timely.

Summary of requested shifts:

18 shifts of protons are requested for this measurement. This will be split in three, with 15 shifts running with RILIS, 2 shifts running without RILIS and 1 shift for beam optimisation.

References:

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Appendix

DESCRIPTION OF THE PROPOSED EXPERIMENT

The experimental setup comprises: *(name the fixed-ISOLDE installations, as well as flexible elements of the experiment)*

Part of the Choose an item.	Availability	Design and manufacturing
[if relevant, name fixed ISOLDE installation: MINIBALL + only CD, MINIBALL + T-REX]	☐ Existing	☐ To be used without any modification
ISOL Solenoidal Spectrometer	☒ 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

HAZARDS GENERATED BY THE EXPERIMENT

(if using fixed installation) Hazards named in the document relevant for the fixed [MINIBALL + only CD, MINIBALL + T-REX] installation.

Additional hazards:

Hazards			
Thermodynamic and fluidic			
Pressure			
Vacuum			
Temperature	4 K		
Heat transfer			
Thermal properties of materials			
Cryogenic fluid	LHe, ~1650 l, LN_2, ~200 l, 1.0 Bar		
Electrical and electromagnetic			
Electricity	O V, 300 A		
Static electricity			
Magnetic field	2.5 T		
Batteries	☐		
Capacitors	☐		
Ionizing radiation			
Target material	Deuterated Polyethylene [CD_2]		
Beam particle type (e, p, ions, etc)	^{61}Zn		
Beam intensity	4 x 10^5 pps		
Beam energy	7.5 MeV/u		
Cooling liquids			
Gases			
Calibration sources:	☒		
• Open source	☒ (alpha calibrations source 4236RP)		
• Sealed source	☐ [ISO standard]		
• Isotope	148Gd, 239Pu, 241Am, 244Cm		
• Activity	1 kBq, 1 kBq, 1 kBq, 1 kBq		

Use of activated material:			
• Description	☐		
• Dose rate on contact and in 10 cm distance	[dose][mSV]		
• Isotope			
• Activity			
Non-ionizing radiation			
Laser			
UV light			
Microwaves (300MHz-30 GHz)			
Radiofrequency (1-300MHz)			
Chemical			
Toxic			
Harmful			
CMR (carcinogens, mutagens and substances toxic to reproduction)			
Corrosive			
Irritant			
Flammable			
Oxidizing			
Explosiveness			
Asphyxiant	Helium		
Dangerous for the environment			
Mechanical			
Physical impact or mechanical energy (moving parts)			
Mechanical properties (Sharp, rough, slippery)			
Vibration			
Vehicles and Means of Transport			
Noise			
Frequency			
Intensity			
Physical			
Confined spaces			
High workplaces			
Access to high workplaces			
Obstructions in passageways			
Manual handling			
Poor ergonomics			

0.1 Hazard identification

Average electrical power requirements (excluding fixed ISOLDE-installation mentioned above): N/A.