Spectroscopic study of ^{58}Zn for nucleosynthesis in type I X-ray bursts

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Abstract

This proposal aims at the precise measurement of the level structure of ^{58}Zn below and above the proton threshold. Excited states in ^{58}Zn will be populated after one-neutron knockout reactions on a secondary ^{59}Zn beam impinging onto a Beryllium target. Nothing is presently known about the excited levels in ^{58}Zn. Such experimental information is required for realistic estimates of the important ^{57}Cu(p,γ)^{58}Zn rate in type I X-ray bursts, which in turn, would increase the accuracy of simulations of these astrophysical phenomena. In addition to the primary astrophysical motivation for this experiment, we will also make, for the first time, a detailed isospin symmetry examination of the T = 1 A = 58 triplet through the measurement of the lifetime of the first 2^+ level in ^{58}Zn. This proposal will take full advantage of the large efficiency of the AGATA array since the population of the desired ^{58}Zn states occurs with rather low cross-section. As well, the fine angular resolution of AGATA will be invaluable for the lifetime measurement.

1 Motivation and introduction

1.1 Stellar nucleosynthesis in Type I X-ray bursts

Type I X-ray bursts are cataclysmic stellar events in which the nucleosynthesis and energy production occur through explosive burning of hydrogen and helium. Driven by thermonuclear runaways in the H/He-rich envelopes of accreting neutron stars in binary star systems, these phenomena are the most frequent thermonuclear stellar explosions in the Galaxy. Most of the proton-capture rates on neutron deficient nuclei are still highly uncertain and in most cases based only on theoretical estimates or statistical model calculations [1, 2, 3]. Indeed, at present only a very few direct (p,γ) measurements exist [4, 5, 6]. Because of the difficulty inherent in direct measurements, alternative approaches are necessary to reduce uncertainties in the stellar rates used in X-ray burst simulations, in many cases by orders of magnitude [2, 7, 8].

For proton-rich nuclei near the drip line, in many cases the reaction rate over X-ray burst temperatures is dominated by single resonances. The precise knowledge of the resonance energy E_r is particularly important, as it enters exponentially in the resonant component of the stellar reaction rate [9],

$$N_A < \sigma v >_{(p,\gamma)} = \frac{1.54 \times 10^{11}}{(\mu T_9)^{3/2}} \, \omega\gamma \, \sum_i exp\left(-\frac{\mathbf{E_{r,i}}}{kT}\right) \quad (cm^3 \, s^{-1} \, mole^{-1}) \tag{1}$$

where μ is the reduced mass of the system, T_9 is the temperature in 10^9 K, $\omega\gamma$ the resonance strength in MeV and kT the thermal energy.

Shell model calculations usually predict level energies with an uncertainty of $\geq$100 keV (see below), leading to several orders of magnitude uncertainty in the final reaction rate. Due to the exponential dependence of the reaction rate on the level energy, by reducing this uncertainty from 100 keV down to $\sim$5-10 keV, the accuracy in the determination of the reaction rates can be improved by about 2 to 3 orders of magnitude [8]. The required resolution of few keV is experimentally accessible via in-flight γ-ray spectroscopy experiments using highly-segmented germanium detectors. This has been experimentally demonstrated in several experiments at MSU [8, 10], which using this technique were able to reduce remarkably the uncertainties of the stellar rates of e.g. ^{32}Cl$(p,\gamma)^{33}$Ar [8] and ^{29}P$(p,\gamma)^{30}$S [10]. Recently a number of key reaction-rates whose uncertainties affect predictions of nucleosynthesis in type I X-ray bursts were identified, including the rate of the ^{57}Cu$(p,\gamma)^{58}$Zn reaction [11]. At present, nothing whatsoever is known about the level structure of ^{58}Zn, let alone the level structure above the ^{57}Cu+p threshold (S_p = 2280 keV). Shell model calculations for ^{58}Zn [12, 13] deviate by about 200 keV in the prediction of excited states in this nucleus. This results in variations up to a factor of 10 at X-ray burst characteristic temperatures of 1 GK. The situation is shown in Figure 1. Indeed, it was by a factor of 10 that this rate was varied within the sensitivity study of [11], resulting in the identification of this rate uncertainty as important for *rp*-process nucleosynthesis.

We aim to experimentally determine energies of relevant excited states in ^{58}Zn using a similar approach to the one described in Ref. [8]. This seems possible now thanks to the high primary (secondary) beam intensities available at GSI-FRS, and to the one-order of magnitude enhancement in γ-ray detection sensitivity provided by the AGATA tracking array, when compared to the previous RISING setup. In order to achieve such goal, it is foreseen to produce a secondary RIB of ^{59}Zn and induce neutron knockout reactions on a beryllium target. In order to evaluate the feasibility of the proposed experiment, theoretical spectroscopic

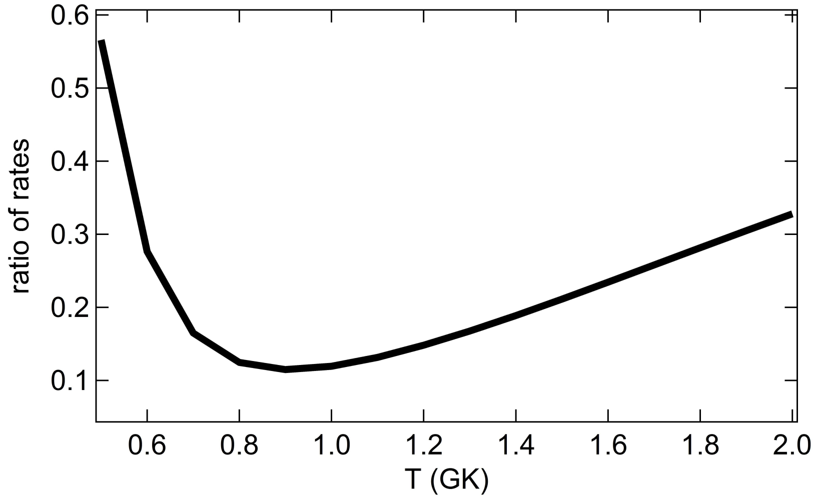

Figure 1: Ratio of ^{57}Cu(p, γ) rates calculated using two different shell model treatments [12, 13] over the temperature range relevant for X-ray bursts. Deviations up to a factor of 10 are observed.

factors [13] have been combined with calculated single-particle cross sections [14]. This yields the one-neutron removal cross-sections which are listed in the last column of Table 1. The first 2^+ and the 4^+ levels, with predicted cross sections of 3 and 0.5 mb respectively, seem to be easily accessible. Most of the remaining levels, especially those above the proton threshold $S_p = 2.28$ MeV which are of particular relevance for the rp-process, can be also measured over about 8 days of beam time (see last section for more details). This is demonstrated in Fig. 2, where these theoretical cross sections were fed into a Monte Carlo simulation in order to predict the response of the AGATA detector. The high efficiency of AGATA will become of pivotal relevance for the successful identification of the states with low cross sections at excitation energies above 2 MeV. An advantageous aspect is the fact that at such high gamma-ray energies the background level is relatively low. Furthermore, the knockout-mechanism chosen in this experiment allows one to gate on the outgoing ^{58}Zn fragments (see Section 2), which substantially improves the peak-to-total ratio in the γ-ray spectrum. The rather large yield expected for the first 2^+ level will also be used to determine its halflife, an aspect which is of relevenace for isospin symmetry studies (see below Section 1.2). Figure 1 shows the impact in the stellar reaction rate of the reaction ^{57}Cu$(p, \gamma)^{58}$Zn due to the present uncertainties in the level scheme of ^{58}Zn, which at present is purely based on Shell Model calculations. From the astrophysics point of view, improving the level scheme of this particular nucleus will be fundamental for reducing the current large uncertainty on the stellar reaction rate of the ^{57}Cu$(p, \gamma)^{58}$Zn reaction. The latter has been identified by the comprehensive sensitivity study of Ref. [11] as one of the key nuclear reactions whose uncertainty affects most the present X-ray burst studies.

Table 1: Spectroscopic factors, single-particle cross sections and total cross section (last column) for the one-neutron removal channel on ^{59}Zn. The states which are expected to contribute most to the stellar rate are highlighted in bold.

		$f_{7/2}$		$f_{5/2}$		$p_{3/2}$		$p_{1/2}$		σ_{th}
J$^\pi$	E$_x$ (keV)	C^2S	σ_{sp}	C^2S	σ_{sp}	C^2S	σ_{sp}	C^2S	σ_{sp}	(mb)
0^+	0					0.537	10.64			5.72
	2895					0.013	9.06			0.12
1^+	3026			0.0054	6.87	0.00021	9.00	0.0002	9.47	0.04
	3549			0.0002	6.75	0.0006	8.77	0.0031	9.24	0.04
2^+	1642	0.04	8.64	0.01	7.23	0.16	9.68	0.11	10.17	3.11
	2790	0.02	8.25	0	6.93	0	9.11	0	9.59	0.23
	3290	0.02	8.1	0	6.81	0	8.88	0	9.35	0.25
	3855	0.01	7.93	0	6.68	0	8.64	0	9.11	0.06
3^+	3533	0.01	8.02	0	6.75	0	8.78			0.12
4^+	2821	0.04	8.24	0.03	6.92					0.53

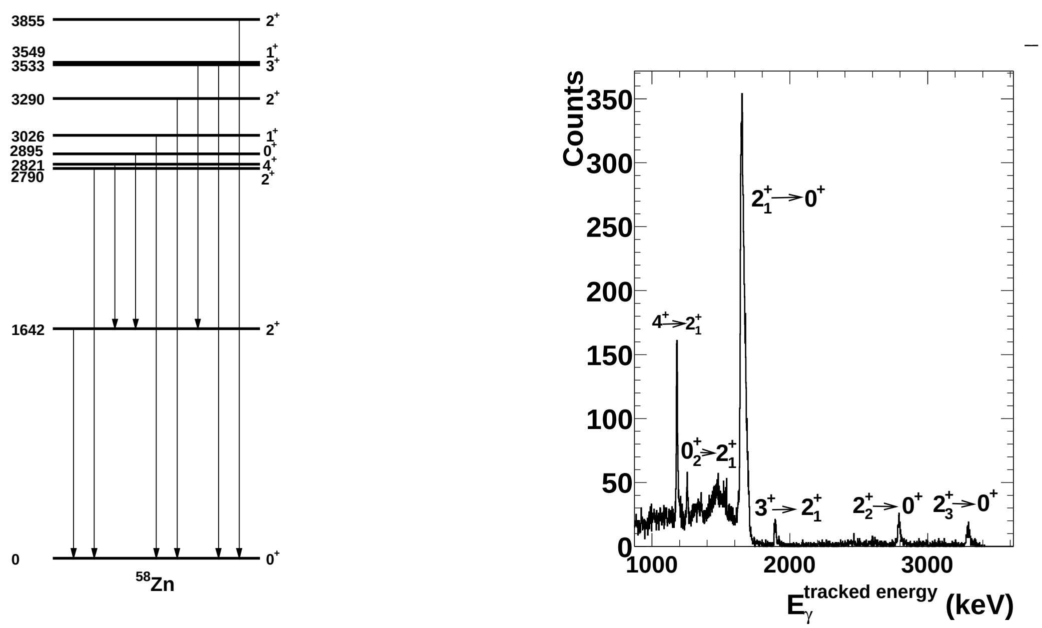

Figure 2: (Left) Level scheme for ^{58}Zn as predicted from SM calculations [13]. (Right) MC simulation of the AGATA response. Only transitions from states with a cross section above 0.1 mb have been included in the simulation.

1.2 Isospin symmetry

Since more than 30 years, isospin symmetry has been studied by observing the displacement energies of the isobaric ground states, as well as by studying the energy differences between excited states of mirror nuclei or T=1 triplets. The construction of large efficiency γ-ray arrays allowed for this kind of studies up to the 1 $f_{7/2}$ shell and high spin states. The energy differences among levels in the $f_{7/2}$ shell are relatively small, of the order of tens of keV, and assuming charge symmetry, it should in principle be explained entirely in terms of Coulomb effects. Only very recently, when data for $T = 1$ bands in the $N = Z$ odd-odd nuclei and in the more exotic $T_Z = -1$ members of the multiplets became available, it was clear that the Coulomb effects were not enough to describe the magnitude of the isospin symmetry breaking. The role of isospin non conserving nuclear forces seems to be at least as important as that of the Coulomb field in the observed Mirror Energy Difference (MED) between mirror nuclei (which are of pure isovector origin) and among the members of the triplets (TED) [16].

The main difficulty hindering the better understanding of the effects of Charge Symmetry Breaking (CSB) and Charge Independence Breaking (CIB) in the nuclear spectra, is the model description of the nuclear wave function. With the advent of Large Scale Shell Model (LSSM) codes, the calculated description for many *fp*-shell nuclei, has reached a rather high accuracy. The experimental MED for various couples of mirror nuclei of the $f_{7/2}$ shell have been well reproduced by LSSM calculations only with the inclusion of a "nuclear" isospin non-conserving term, with the form of a quadrupole pairing for the isovector MED and a conventional $J = 0$ pairing for the isotensor ones [16]. The measurement of excited states in the exotic nucleus ^{54}Ni, allowed recently for the study of the heaviest $T = 1$ isospin triplet in the $f_{7/2}$ shell [17].

In this proposal we expect to go one step further, and measure both the energy and the lifetime of the first excited state in ^{58}Zn, as well as the energy of the 4^+ level. The $A = 58$ triplet ^{58}Zn/^{58}Cu/^{58}Ni (as the A=54) corresponds to a two-valence particle (hole) triplet on top of the ^{56}Ni doubly magic nucleus. These triplets are especially well suited for descriptions based on shell model calculations. The knowledge of the $T_z = 1$ ^{58}Ni nucleus is excellent and the $T = 1$ $0^+, 2^+$ and 4^+ levels are also known in the odd-odd ^{58}Cu. Thus, the identification of the 2^+ and 4^+ excited states in ^{58}Zn will allow the determination of the isovector MED and the isotensor TED. The CSB term of the effective interaction is expected to contain on one side the real CSB contribution to the interaction, and on the other side possible corrections for nuclear correlation that have not been taken into account in the model calculation. The nuclear model contribution depends strongly on the nucleus and on the model space where the calculations are performed. In the framework of this proposal, it will become possible to check experimentally the persistency of the quadrupole pairing behaviour of the CSB term in the MED above the $f_{7/2}$ shell, as well as testing the need for a charge breaking $J = 0$ pairing term in the interaction to fit the experimental TED.

In addition, provided that isospin is a good quantum number, in this $A = 58$ triplet with $T = 1$ the reduced $E2$ matrix elements should have a linear dependence upon T_z, which follows from general arguments based on isospin symmetry [18]. Thus, the reduced transition probability $B(E2; 2^+ \rightarrow 0^+)$ provides an stringent test to this theoretical relation, which is given by

$$< J, T, T_z \parallel \mathbf{T}(E2) \parallel J-2, T, T_z >= S(J) + T_z\, V(J). \quad (2)$$

The coefficients $S(J)$ and $V(J)$ depend on the isoscalar and isovector components of the Hamiltonian, respectively. In the isospin triplet, for the most symmetric lowest $T = 1$ states (2^+_1, 4^+_1, ...) the ratio $V(J)/S(J)$ is positive. Therefore, it follows that

$$B(E2; 2^+ \rightarrow 0^+)(^{58}Zn) < B(E2; 2^+ \rightarrow 0^+)(^{58}Cu) < B(E2; 2^+ \rightarrow 0^+)(^{58}Ni). \quad (3)$$

In the proposed experiment, we intend to test experimentally the validity of the latter theoretical relationship for this $T = 1$ triplet. At present, the highly accurate value for the reduced transition probability in ^{58}Ni, $B(E2; 2^+ \rightarrow 0^+) = 10.0(4)$ W.u. [19], is in contrast with the poorly known value for ^{58}Cu, $B(E2; 2^+ \rightarrow 0^+) = 9.1(35)$ W.u. [20], and the absence of any experimental information on the excited states of ^{58}Zn. By measuring the lifetime of the first 2^+ state in ^{58}Zn, we will be able to prove the validity of the above theoretical relationship, and to assess the degree of validity of isospin as a good quantum number. Further, in the same experiment we will be able to measure, simultaneously, the ^{59}Zn proton-knockout channel, which will provide a further measurement of the lifetime value for the $2^+ \rightarrow 0^+$ transition in ^{58}Cu. Such measurement, will help to improve the existing uncertainty in the reduced transition probability value for this nucleus. By comparing the reduced transition probabilities in this $T = 1$ triplet, it will become possible to disentangle both, the isoscalar and the isovector components of the Hamiltonian.

2 Experimental approach

Because of the proximity of ^{58}Zn to the proton dripline, this nucleus can be best accessed by means of fragmentation of a primary Krypton beam. Thanks to the high intensity ($\sim 3\times10^{10}$ particles/spill before SIS extraction) available at GSI for an enriched ^{78}Kr beam, a secondary beam of ^{59}Zn can be produced with high intensity ($\sim 4.2\times10^3$ Hz) for inducing neutron knockout reactions on a Beryllium target (400 mg/cm^2) placed at the final focal plane of the FRS. To this aim, the primary ^{78}Kr beam impinges at 580 MeV/u onto a 4 g/cm^2 Beryllium target with an intensity of 1×10^{10} Hz (here we assume 30% loss due to the SIS extraction efficiency). Enriched ^{78}Kr gas can be purchased for this experiment with a rather low cost of ∼2000 Euro/liter, being 200 ml/day requested for the ion source. A secondary RIB of ^{59}Zn is selected and transtmitted through the FRS with an efficiency of more than 11%.

The total particle rate at the second focal plane S2, with the slits completely open, amounts to 1 MHz and is dominated by ^{79}Rb, ^{69}Se and ^{65}Ge. For this reason the new finger scintillator at S2 should be preferably used (see technical proposal). Alternatively this rate can be reduced efficiently by partially closing the S2 slits. The ^{59}Zn rate at the final focal plane S4 is of 4.23×10^3 ions/s. The latter dominates the total particle intensity at S4, which is of 7.7×10^3 Hz.

The secondary RIB of ^{59}Zn will be focussed at S4 onto a 400 mg/cm^2 Beryllium target for inducing knockout reactions. The energy of the ^{59}Zn fragments before the secondary Be-target is of 160 MeV/u, and after it this energy is reduced down to 130 MeV/u. In particular, the one-neutron removal channel will lead to excited states of the nucleus of interest, ^{58}Zn, with a probability given by the cross sections listed in the last column of Table 1.

De-excitation γ-rays from ^{58}Zn will be detected via the AGATA array consisting of 5 double and 5 triple clusters. Particle-gamma detection rates have been realistically estimated on the basis of the aforementioned cross-section calculations (see Table 1) and the corresponding AGATA response obtained via Monte Carlo simulations (see Fig. 2). These rates are listed in Table 2.

Table 2: Expected particle-gamma rates for the transitions of interest in ^{58}Zn. The states which are expected to contribute most to the stellar rate are highlighted in bold.

Transition			$\sim$E$_\gamma$ (keV)	σ (mb)	pγ-rate (Counts/day) for 400mg/cm^2 at 23cm
4^+	$\rightarrow$	2_1^+	1179	0.53	342
0^+	$\rightarrow$	2_1^+	1253	0.12	78
2_1^+	$\rightarrow$	0^+ (G.S.)	1642	3.11	1435
3^+	$\rightarrow$	2_1^+	1891	0.12	55
$\mathbf{2_2^+}$	$\rightarrow$	$\mathbf{0^+}$ **(G.S.)**	**2790**	**0.23**	**85**
1_1^+	$\rightarrow$	0^+ (G.S.)	3026	0.04	15
$\mathbf{2_3^+}$	$\rightarrow$	$\mathbf{0^+}$ **(G.S.)**	**3290**	**0.25**	**92**
1_2^+	$\rightarrow$	0^+ (G.S.)	3549	0.04	14

After interactions in the 400 mg/cm^2 Be-target, the outgoing ^{58}Zn fragments will be identified via the LYCCA calorimeter for an unambiguous correlation of gamma-rays and the selected reaction channel. A precise particle tracking, in addition, allows for the best possible Doppler-correction. The 1-neutron knockout mechanism proposed for this measurement shows the advantage of a reduced gamma-ray background because using LYCCA one can gate on one specific outgoing fragment.

The lifetime of the 2^+ state in ^{58}Zn will be obtained by applying the peak-shift method [21]. The target thickness and the beam energy have been optimized in order to exploit this feature. The sensitivity of the method is illustrated in Fig. 3. Error bars are purely statistical, and the number of counts correspond to the requested beam time of 8 days. From Eq. (3), for ^{58}Zn one expects to measure a lifetime smaller than the lifetime of ^{58}Ni, which is precisely known as $\tau = 0.94(3)$ ps [19]. Figure 3 shows the effect expected on the line-shape and in particular on the centroid of the measured (simulated) gamma-ray distribution, for sensitive variations of the lifetime. For this kind of analysis the position sensitivity of the AGATA

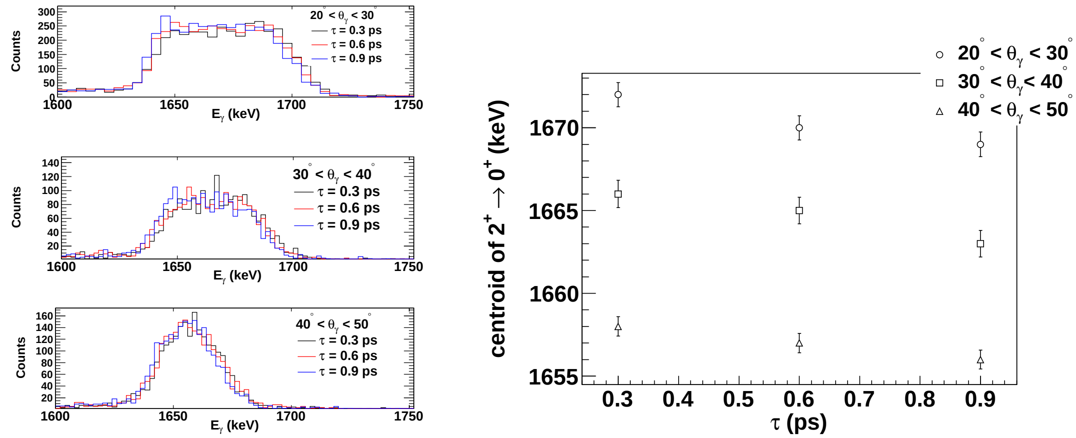

Figure 3: (Left) Simulation of the $2_1^+ \rightarrow 0^+$ transition in ^{58}Zn for different assumptions on the lifetime of the state, and for several angular cuts on the emitted γ-ray direction. (Right) Dependence of the γ-peak position with the lifetime for the three angular cuts shown on the left-hand side.

tracking array will be of great advantage. The lifetime of the 2^+ state in ^{58}Cu, which is also expected to be around 0.9 ps, will be measured in a similar way as the one in ^{58}Zn. In this case, the ^{59}Zn one-proton knockout channel will be selected, by putting a gate in LYCCA in the outgoing ^{58}Cu fragments.

The estimated rates of table 2 include the transmission of ^{59}Zn through the FRS, which is of 11%. They correspond to a setup described above, consisting of a 400 mg/cm^2 Be target and AGATA (with 5 double and 5 triple clusters) at the nominal distance of 23 cm from the Be-target.

In total we request **8 days (24 shifts) of dedicated beam time**. This is needed in order to acquire sufficient statistics in the high excitation energy transitions, which are extremely important for the proposed *rp*-process study. The requested beam time is also needed to perform a reliable lifetime analysis of the 2^+ level in ^{58}Zn. In addition, **2 days of parasitic beam time** are requested for FRS and LYCCA calibrations. In case of technical compatibility, the latter beam tuning can be shared with other AGATA experiments.

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