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Proton capture cross section of ^{72}Ge and astrophysical implications

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This paper reports on the first cross section measurement of the ^{72}Ge(p,γ)^{73}As reaction. The proton capture reaction on ^{72}Ge is relevant for the astrophysical p-process and was identified in a sensitivity study as one of the important reactions required to estimate the abundances of the light p-nuclei. The γ-summing technique was employed using the Summing NaI(Tl) detector (SuN) from the National Superconducting Cyclotron Laboratory. The experiment was performed at the University of Notre Dame using a 1.8 to 3.6 MeV proton beam. In order to test the predictive power of different theoretical calculations in the region, experimental values are compared to the results given by the nuclear reaction code TALYS 1.6. The theoretical uncertainties in the cross section arising from different combinations of nuclear level densities, γ-ray strength functions and optical model potentials were reduced to $10-18\%$ by the experimental data. The recommended reaction rates from the standard astrophysical libraries, BRUSLIB and REACLIB, are found to be in good agreement with the experimental results.

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I. INTRODUCTION

Reaction rates constitute one of the main nuclear inputs required by astrophysical calculations in modeling the processes responsible for the synthesis of all the elements [1–4]. The main processes believed to produce most of the heavier nuclei are the rapid- [2] and slow- [3] neutron-induced capture processes. A third production mechanism, called the p-process, exists which creates proton-rich nuclei in the mass region between $Z = 28$ and $Z = 80$ [1, 4]. There are 35 stable isotopes called the p-nuclei which are produced only by the p-process. These isotopes are mainly formed by successive proton, neutron and α-particle photodisintegration reactions [1, 5]. At higher temperatures, particle captures also play an important role. The final abundances are sensitive to the γ-induced reaction and particle-capture rates because they determine the balance of production and destruction channels for each nucleus. Therefore, considerable effort has been devoted both on theoretically predicting and experimentally measuring the cross sections for reactions relevant for determining the path of all of these astrophysical processes [6–8].

To describe the synthesis of p-nuclei, different sites and mechanisms have been suggested. Potential settings like mass-accreting white dwarf stars [9], fast proton captures in the neutrino-driven winds in core-collapse Type II supernovae (SNII) [10, 11], and Type Ia SN explosions [12] are investigated to understand the underlying processes. However, the most widely studied location remains the shock front of SNII passing through the O-Ne burning zone of massive stars [5, 13, 14]. According to the proposed scenario, the intense photon flux initiates a series of (γ,n) disintegration reactions producing proton-rich nuclei until the high neutron binding energy makes removing any more neutrons difficult. For heavier nuclei, $Z > 50$, the reaction flow is then maintained by the (γ,p) and (γ,α) reaction channels. For $Z < 50$ nuclei single-particle captures contribute to the reaction series, due to the high neutron and proton binding energies [1, 5]. During this time, the respective inverse reactions also play an important role in balancing different branches. The suggested mechanism produces most of the heavy p-nuclei with $A > 100$. However, there are some anomalies in the predicted production rates of the light p-nuclei like ^{74}Se, ^{92,94}Mo, and ^{96,98}Ru. The ^{74}Se isotope is largely overestimated by simulations, while the latter are underproduced [15]. In the sensitivity study by Rapp *et al.* [15], a list of distinct reactions contributing towards the production of all the p-nuclei was provided. Calculations were performed for an 11 layer model incorporating initial seed abundances from the evolution of a 25 $M_\odot$ star before the SNII supernova explosion. The ^{72}Ge$(p,\gamma)^{73}$As reaction was identified as one of the dominant reactions in the p-process and could contribute to the formation of ^{74}Se through the reaction sequence ^{72}Ge$(p,\gamma)^{73}$As$(p,\gamma)^{74}$Se. None of these reactions have been measured before. An attempt was made by Kiss *et al.*, [16] to measure the (p,γ) reactions on all the stable Ge isotopes using the activation technique. Due to the low (p,n) threshold, the ^{73}Ge$(p,n)^{73}$As reaction contributed to the production of ^{73}As and could not be separated from the ^{72}Ge$(p,\gamma)^{73}$As

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channel in that work.

In an effort to minimize the uncertainty in the predicted production rates, particularly of Se, Mo and Ru isotopes, a series of experiments was performed to accurately measure the cross sections of relevant (p,γ) reactions in the mass region [17, 18]. The measurements were done using the SuN (Summing NaI(Tl)) detector of the National Superconducting Cyclotron Laboratory coupled to the FN Tandem Accelerator facility of the university of Notre Dame. We report on the first measurement of the ^{72}Ge$(p,\gamma)^{73}$As cross section in the energy range of 1.8 - 3.6 MeV. The Gamow window for this reaction at p-process temperatures of 1.5 - 3.3 GK is 1.1 - 3.7 MeV.

Details regarding the experimental technique are provided in Sec. II. Analysis methods and results obtained are presented in Sec. III. Section IV discusses the theoretical interpretation of the experimental data and the conclusions are given in Sec. V.

II. EXPERIMENTAL TECHNIQUE

The experiment was performed at the Nuclear Structure Laboratory at the university of Notre Dame using a 11 MV FN Tandem Van de Graff accelerator. A proton beam impinged on a 1.79 mg/cm^2 thick natural Ge (^{nat}Ge) target. The energy of incident beam was varied from 1.8 to 3.6 MeV in the steps of 0.2 MeV to cover the relevant Gamow window of the reaction. The energy loss of the beam through the Ge target was 150 keV at 1.8 MeV and 100 keV at 3.6 MeV. A Faraday cup mounted at the end of the beam line monitored the amount of charge collected for each energy setting. The experimental setup for measuring the γ rays emitted after the reaction consisted of the SuN detector, an array of eight NaI crystals, each read by 3 photomultiplier tubes [19]. The eight crystals are optically isolated. The target was produced by evaporating ^{nat}Ge on a Ta backing at the Notre Dame target lab and was placed in the center of the SuN detector in a 1.7 in. hole. The closely packed geometry of SuN's crystals provides an efficient array to apply the γ-summing technique [19, 20]. All the γ rays emitted during the decay of the excited state populated in a reaction are added up on an event-by-event basis. Consequently, instead of the individual γ lines, a single *"sum peak"* is observed whose energy is equal to the sum of the incident beam energy in the centre-of-mass frame and the Q-value of the reaction. The advantage of such a technique is that high-energy, low intensity γ rays which are otherwise difficult to observe, get added up in an event and show up in the sum peak, in a low-background energy region of the γ spectra.

For extracting the cross section, σ, the following expression was used,

$$\sigma = \frac{N_\Sigma}{N_t \epsilon_\Sigma N_p} \tag{1}$$

where, N_Σ is the total number of counts observed in the sum peak, N_p is the number of protons impinging on the target, N_t is the number of target nuclei and ϵ_Σ is the summing efficiency of the SuN detector, which depends on the sum peak energy and the number of gamma rays emitted in the decay. To estimate the average multiplicity of the decay, the *"hit pattern"* of the sum peak was obtained by counting the number of segments that detected energy in an event. A Gaussian fit provided the centroid of the hit pattern which is governed by the multiplicity and the energy of sum peak. The summing efficiency was then determined by the hit-pattern centroid and the sum peak energy. This technique of extracting the efficiency is referred as the hit-pattern method and was optimized for the SuN detector. A detailed study of the efficiency of SuN detector as a function of hit pattern for different sum peak energies is presented in Ref. [19]. N_Σ was obtained by integrating the sum peak following the method presented in [19]. The limits of integration were kept between (E$_\gamma$ - 3σ) and (E$_\gamma$ + 3σ) and a linear background was subtracted. The energy of the sum peak, E$_\gamma$, and its standard deviation, σ, were determined by fitting only the high energy part of the peak with a Gaussian distribution. N_p was calculated from the total charge collected in the Faraday cup. To measure the thickness of the target, Rutherford Backscattering Spectrometry was performed at the Hope College Ion beam Analysis Lab (HIBAL) [21]. A detailed description of the technique and the methods adopted are presented in Ref. [18].

III. RESULTS

The Ge target consisted of five naturally occurring Ge isotopes, namely, ^{70}Ge, $^{72-74}$Ge, and ^{76}Ge. The natural abundances of each of these isotopes are given in Table I. The same table also includes the Q-values of the relevant (p,γ) and (p,n) reactions. A γ ray spectrum obtained for an incident beam energy of 3.6 MeV in the centre-of-mass frame is shown in Fig. 1. The sum peaks observed for the proton capture on different Ge isotopes are marked. The energy of each peak corresponds to the respective Q-value of the (p,γ) reaction (see Table I) added to the beam energy in the centre-of-mass frame. An additional peak at $\sim$6.8 MeV is due to the capture of the free neutrons by the detector material. These neutrons are created by competing (p,n) reactions on all five Ge isotopes.

The predicted (p,γ) cross section for the ^{70}Ge isotope is almost half that for ^{72}Ge [22]. Although the ^{70}Ge$(p,\gamma)^{71}$As sum peak is visible in the spectrum (with low statistics), no cross section for the reaction was extracted due to the expected neutron contamination. Similarly, low statistics in the ^{77}As peak populated in the proton capture on ^{76}Ge did not allow a reliable cross-section determination for that case either.

Therefore, the present work obtained cross sections for the ^{72}Ge$(p,\gamma)^{73}$As and ^{74}Ge$(p,\gamma)^{75}$As reactions only. The latter was also measured in a dedicated experiment with

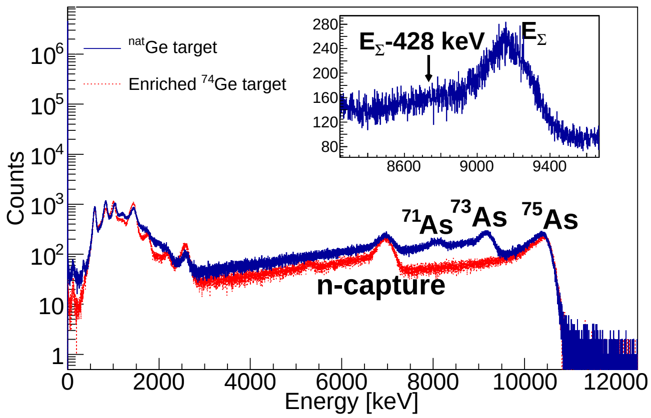

FIG. 1: (Color online) Gamma spectrum obtained for an incident beam energy of 3.6 MeV for a ^{nat}Ge target is shown in solid line. In total, four sum peaks are observed. The peak marked as n-capture originates from the capture of free neutrons by the detector material, while ^{71}As, ^{73}As, and ^{75}As are from ^{70}Ge(p,γ)^{71}As, ^{72}Ge(p,γ)^{73}As, and ^{74}Ge(p,γ)^{75}As reactions, respectively. Due to low cross sections and isotopic abundances, neither ^{74}As or ^{77}As sum peaks are visible in the spectrum (see text). The inset shows the zoomed in region of the spectrum with the sum peak of ^{73}As and the expected energy of γ rays originating from the 428 keV isomeric state. For comparison, a γ spectrum obtained with an enriched ^{74}Ge target is shown in dashed line. The spectrum consists of neutron capture peak and a sum peak for the production of ^{75}As at an incident beam energy of 3.6 MeV. The experiment with enriched ^{74}Ge target was performed using the same setup and experimental technique. A detailed description of that analysis and the results are given in Ref. [18].

the same setup [18]. A γ spectrum from that work is shown for reference in Fig. 1. The spectrum from Ref. [18] is normalized to the yield of the ^{75}As sum peak from the current measurement. The ^{73}Ge(p,γ)^{74}As reaction has a comparable Q-value as the ^{74}Ge(p,γ)^{75}As, therefore the sum peak for the former is hidden underneath the ^{75}As peak. However, its predicted cross section is much smaller [22]. Folding in the lower abundance of ^{73}Ge, the contribution from the ^{73}Ge(p,γ)^{74}As reaction in the ^{75}As sum peak amounts to $\sim$ 0.7 - 1.5%. A comparison of the results of the present work for the ^{74}Ge(p,γ)^{75}As reaction to those obtained with an enriched target in Ref. [18] are shown in Fig. 2. The two measurements are in excellent agreement and their comparison provides a cross check for the experimental methods used in the present work.

The experimentally deduced values for the ^{72}Ge$(p,\gamma)^{73}$As cross section are given in Table II. In this analysis, all the γ rays observed within a time interval of 300 ns with respect to the trigger were grouped as single event. Therefore, the γ rays from a 427.9 keV state in ^{73}As with a half-life of 5.7(2) μs are not included in the sum and appear at an energy of 428 keV less than the sum peak. To account for

TABLE I: Summary of the natural abundance of Ge isotopes present in the ^{nat}Ge target and their respective Q-values for the (p,γ) and (p,n) reactions.

Isotope	Natural abundance[a] [%]	Q-value[b] [keV] (p,γ)	Q-value[b] [keV] (p,n)
^{70}Ge	20.57(27)	4620.8(47)	-7002.4(506)
^{72}Ge	27.45(32)	5659.7(42)	-5138.5(46)
^{73}Ge	7.75(12)	6851.4(27)	-1123.2(41)
^{74}Ge	36.50(20)	6899.4(23)	-3344.8(27)
^{76}Ge	7.73(12)	7992.2(26)	-1705.7(22)

[a] Values taken from [23].
[b] Values calculated from [24].

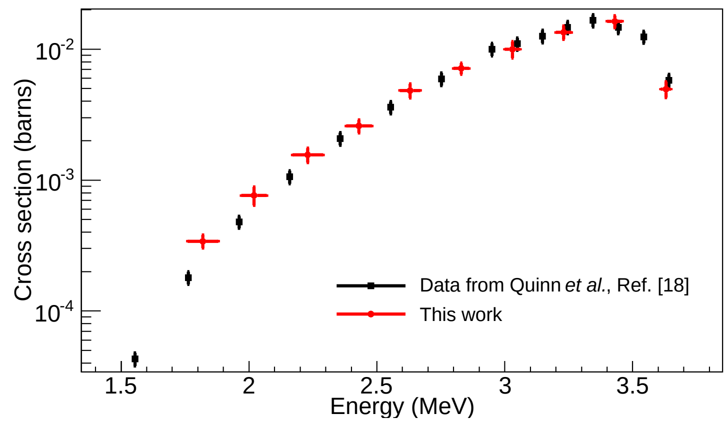

FIG. 2: (Color online) Comparison of values obtained in the present work (solid squares) and in a previous experiment aimed at measuring the ^{74}Ge$(p,\gamma)^{75}$As cross sections. Reference data (solid circles) is taken from [18].

them, the integration bounds can be kept between $E_\Sigma - 3\sigma - 428$ keV and $E_\Sigma + 3\sigma$. However, since no obvious signature of the isomeric state is present in the experimental spectra (see Fig. 1) and to avoid any additional background contributions, the cross section for ^{72}Ge$(p,\gamma)^{73}$As was calculated by integrating only the main sum peak excluding the γ rays from the isomeric state. The values presented in Table II and in Fig. 3 include only the ground state component of the cross section. The error on the experimental value is inherited from the uncertainty in the number of counts in sum peak (3%), sum-peak efficiency ($10-15\%$), the error in the beam-current measurement ($5-14\%$), and the target thickness (5%).

IV. DISCUSSION

There are no previous proton capture cross section measurements reported on ^{72}Ge. The results of the

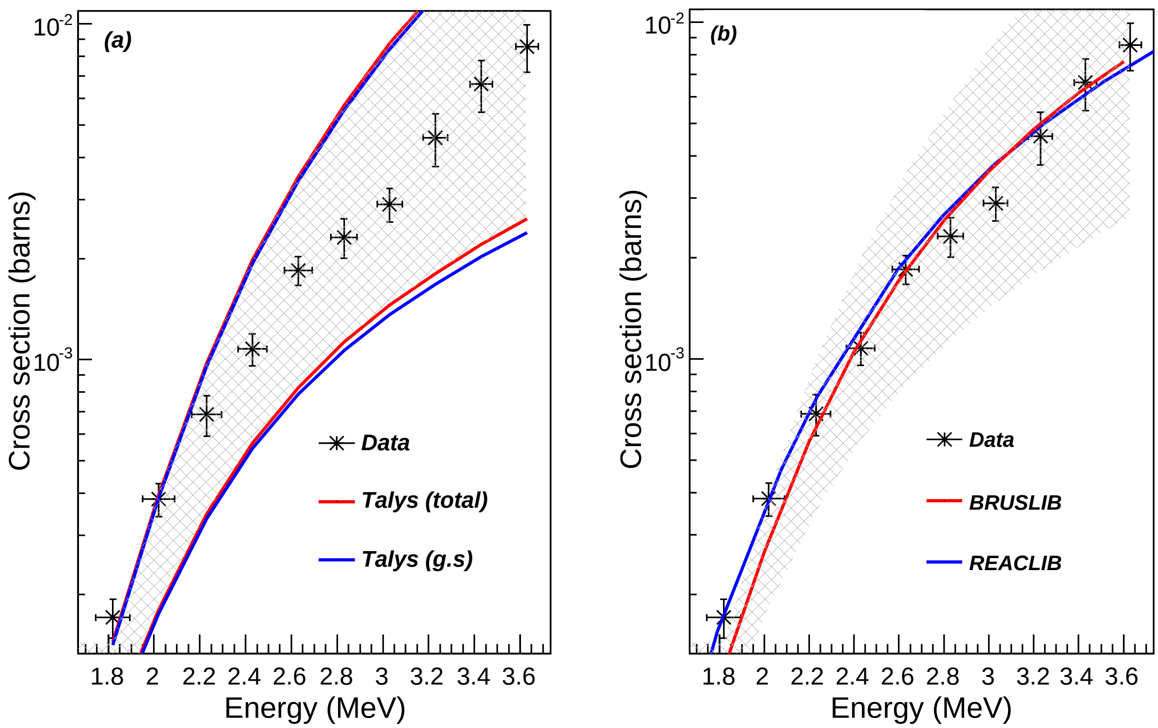

FIG. 3: (Color online) The experimentally measured cross section of the ^{72}Ge(p,γ) reaction. (a) Solid line shows the total cross section calculated using TALYS 1.6 and dashed line represents the production of only the ground state excluding the isomeric state at 427.9 keV. Results of the calculations done with different combinations of nuclear level densities, γ-ray strength functions and nuclear optical potentials lie within the grey shaded area. (b) Same as (a) with the recommended values for the reaction by BRUSLIB (solid line) and REACLIB (dashed line).

present work are compared with different theoretical calculations performed using TALYS 1.6 [25] nuclear reaction code. The grey band shown in Fig. 3(a) corresponds to calculations using different combinations of optical model potentials (OMP), nuclear level densities (NLD), and γ-ray strength functions available in TALYS 1.6. The two kinds of OMP used are the semi-empirical microscopic spherical nucleon-nucleon potential as described in [26] and the parametrization of Koning and Delaroche [27]. Nuclear level densities are derived both from phenomenological expressions and microscopic models. Approaches like the Fermi gas model [28], the constant temperature model [29], the back-shifted Fermi gas model [30], and the generalized superfluid model [31, 32] constitute the phenomenological expressions. For microscopic calculations, Hartree-Fock [33], Skyrme-Hartree-Fock-Bogolyubov framework [34], and temperature-dependent Hartree-Fock-Bogolyubov methods [35] are used. More details can be found in Ref. [36]. For γ-ray strength functions, the standard five options provided by the TALYS 1.6 software are employed. These options consist of models describing mainly the E1 strengths and include the Kopecky-Uhl generalized Lorentzian [37], the Brink-Axel Lorentzian [38, 39], the Hartree-Fock BCS model [36], the Hartree-Fock-Bogolyubov model [36], and Goriely's hybrid model [40, 41].

The cross section values obtained with the above mentioned nuclear potentials are consistent with each other. The constant temperature model for level densities predicts cross sections 3 times higher than the ones estimated by the Fermi gas model. All other options give values within this range. Changing the γ-strength functions alter the output by a factor of 5. However, different combinations of nuclear level densities and γ-ray strength functions vary the predicted cross section values by a factor of 2 at low energies and by almost an order of magnitude for energies around 3.6 MeV. The current measurement excludes some of the phase space of the parameter combinations and reduces this uncertainty to at most 18%. Here, 18% is the largest size of the experimental uncertainty in the present measurement and the smallest value is 10%.

Calculations predict less than 2% cross section for the production of the 427.9 keV isomeric state in ^{73}As at 1.8 MeV while it rises to $\sim$ 9% at higher energies. The upper- and lower limits of the calculated cross section

TABLE II: Summary of proton capture cross section obtained for ^{72}Ge isotope in an energy range of 1.8 to 3.6 MeV. The beam energy is given in the centre-of-mass frame at the center of the target.

$E_{c.m.}$ [MeV]	Cross section^{a} [mb]
1.82(8)	0.17(3)
2.02(7)	0.38(5)
2.23(7)	0.69(10)
2.43(7)	1.08(12)
2.63(6)	1.84(19)
2.83(6)	2.31(31)
3.03(6)	2.90(34)
3.23(6)	4.58(82)
3.43(5)	6.61(116)
3.63(5)	8.55(137)

[a] The cross section of producing 427.9 keV isomeric state in ^{73}As in not included.

with and without the production of the isomeric state are shown in Fig. 3(a). Experimentally, an upper limit of 6 % on the contribution from the isomeric state was assigned by integrating the area around $E_{\Sigma} - 428$ keV where the isomeric state signal is expected. Due to the small contribution of the isomeric state, comparing the data with the total cross sections corresponding to the recommended rates of BRUSLIB [42] and REACLIB [43] is meaningful and useful.

The REACLIB and BRUSLIB libraries are the databases of reaction rates prevalent in the stellar environment. The cross sections corresponding to the predicted reaction rate for each reaction can be calculated using the nuclear physics inputs highlighted on the web page of each of these libraries. The recommended rates in the REACLIB library correspond to the cross sections derived from the code NON-SMOKER [22]. The recommended rates in the BRUSLIB library correspond to TALYS calculations performed with the parametrized nuclear potential given in [26], NLD from the combinatorial model of Ref. [34] and γ-ray strengths calculated using the Hartree-Fock-Bogolyubov methods [44].

In Fig. 3(b) the values given by BRUSLIB and REACLIB are plotted. Both theoretical calculations are in excellent agreement with the experimental data.

The astrophysical implications of the measured cross section are mainly reflected in the abundance of the ^{74}Se p-nucleus. To study the impact of the reduced uncertainty, a p-process calculation was performed using the post-processing NucNet code [45]. The reaction rates incorporated in this code are from the REACLIB database and the initial seed abundances, temperature, and density profiles for the $25M_{\odot}$ star are the same as the ones used in Rapp *et al.* [15]. The final abundances of the p-nuclei are calculated for 11 separate mass layers. Each layer is characterized by a different temperature ranging from 1.8 - 3.4 GK. Since the REACLIB cross sections are in excellent agreement with the present measurement, the recommended rates were not modified for the calculation. To estimate the uncertainty in the predicted ^{74}Se abundance, the reaction rates were first increased and then decreased by a factor of 0.18 corresponding to the 18 % error in the experimental cross sections. Following this procedure, the predicted uncertainty in the abundance of ^{74}Se arising from the ^{72}Ge(p,γ)^{73}As reaction was confined to 1%.

V. CONCLUSIONS

The γ-summing technique was utilized to measure the ^{72}Ge(p,γ)^{73}As cross section in the energy range of 1.8 - 3.6 MeV. The present work reports on the first such measurement on the ^{72}Ge isotope. As a ^{nat}Ge target was used in the experiment, a similar measurement could be performed on the ^{74}Ge isotope. The ^{74}Ge(p,γ)^{75}As reaction has been studied previously using the same experimental setup and analysis methods but with an isotopically enriched target. The cross section values extracted in this work are consistent with the old data. The new experimental results on the ^{72}Ge(p,γ)^{73}As reaction are compared to the theoretical calculations done using the TALYS nuclear reaction code. Theoretical uncertainty in predicting the cross sections using different combinations of nuclear level densities, optical model potentials and γ-ray strength functions are reduced to at most 18% with this measurement. The cross sections corresponding to the recommended rates from the standard astrophysical libraries, BRUSLIB and REACLIB, are compared to the experimental data. Both sets of values reproduce the experimentally deduced reaction cross sections well with a slightly better agreement with REACLIB at low energies.

VI. ACKNOWLEDGEMENT

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