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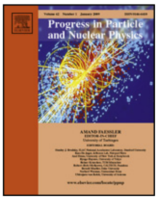

Review

Nova reaction rates and experiments

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ABSTRACT

Oxygen–neon novae form a subset of classical novae events known to freshly synthesize nuclei up to mass number $A \lesssim 40$. Because several gamma-ray emitters lie in this mass range, these novae are also interesting candidates for gamma-ray astronomy. The properties of excited states within those nuclei in this mass region play a critical role in determining the resonant (p, γ) reaction rates, themselves, largely unknown for the unstable nuclei. We describe herein a new Doppler shift lifetime facility at the Maier–Leibnitz tandem laboratory, Technische Universität München, with which we will map out important resonant (p, γ) nova reaction rates.

1. Introduction

Approximately 30% of main sequence (MS) stars in our galaxy are observed to be within binary star systems [1]. Main sequence stars obey the mass-luminosity relation $L \propto M^{\alpha}$, where L is the stellar luminosity, M is the stellar mass and α is a number crudely falling in the rage $3 \lesssim \alpha \lesssim 4$. For this reason, binary systems of disparate masses can evolve to a point where one star has become a white dwarf (WD), while the companion still lies on the main sequence (MS). When the MS companion enters its He burning phase and becomes a Red Giant (RG), hydrogen-rich material from the outer envelope of the RG can be captured into the WD's gravitational well and, losing angular momentum, spiral down on to the WD's surface; its kinetic energy thereby converted into heat. Here, it forms a dense, hot, mostly degenerate layer enveloping the WD. Under degenerate conditions, the proton–proton reaction sequence is able to increase the envelope's temperature without the envelope subsequently expanding and cooling. As the temperature at the base of the envelope increases, eventually proton capture on to the nuclei comprising the surface composition of the WD ensues. This results in a matter flow up the valley of stability (VoS) that passes through stable and unstable nuclei up to ≈2–3 neutrons removed from the VoS, on the proton-rich side of stability.

One particular class of novae, called oxygen–neon (ONe) novae, synthesize nuclei up to ^{40}Ca and are expected to produce long-lived β^+-unstable gamma-ray emitters ^{22}Na ($t_{1/2} = 2.6$ yr, $E_{\gamma} = 1.28$ MeV), ^{26}Al ($t_{1/2} = 7.2 \times 10^5$ yr, $E_{\gamma} = 1.8$ MeV), and shorter duration ^{34m}Cl ($t_{1/2} = 32$ min, $E_{\gamma} = 2.13$ MeV) [2,3]. A detection of any of these would provide the first open window through which to peer directly into the underlying nuclear physics of these explosions and, thereby, provide observational constraints on present theoretical nova models. For a review of nova nucleosynthesis see Refs. [4–6].

Concerted efforts to detect the ^{22}Na 1.28 MeV gamma-ray line from several ONe nova candidates, using the COMPTEL gamma-ray observatory, were able to only provide upper limits on the 1.28 MeV photon flux [7], serving to provoke theoretical studies [8] of critical reaction rates, on unstable nuclei, responsible for ^{22}Na production that have since been closed [9,10]. Recently, an observation of the ^{22}Na 1.28 MeV line has been reported [11] from Nova Cassiopeia 1995. This object is classified as a "very slow" nova and is therefore regarded as a carbon–oxygen nova. Prevailing opinion is that such carbon–oxygen novae are not expected to produce significant quantities of ^{22}Na [4], although this view has been challenged [12].

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The reactions that drive the nuclear mass flow up to the $A = 40$ region predominantly proceed via resonant $X(p,\gamma)Y$ capture into excited states of stable and proton-rich unstable nuclei ≈2–3 neutrons removed from stability. For this reason, those excited states above the proton threshold in the compound nucleus Y, lying within the Gamow window, play an essential role in the (p,γ) reaction rates. For the schematic reaction $p + X \rightarrow Y + \gamma$, the resonant (p,γ) reaction rate per (pX) particle pair is given by,

$$r_{pX} = \left(\frac{2\pi}{\mu k_B T}\right)^{3/2} \hbar^2\, N_p N_X \frac{2J_r + 1}{2(2J_X + 1)} (1 - B_p)\, \frac{\hbar}{\tau}\, \mathrm{e}^{-E_r/k_B T} \tag{1}$$

where $N_{p,X}$ are the respective number densities of protons or X; μ is the reduced mass of the pX entrance channel, $J_{X,r}$ are the respective spins of the ground state of X and resonant state in Y into which the proton is captured; k_B is Boltzmann's constant; T is the temperature; E_r is the resonance energy of the state into which the proton captures; B_p is the proton decay branching ratio of the resonant state, and τ is its lifetime. When more than one resonant state in Y is within the Gamow window, then the total (p,γ) reaction rate is the sum over these resonances with terms given by Eq. (1). From Eq. (1), the nuclear physics quantities that determine the resonant reaction rate are: the spin of the resonance level, the resonance energy, the proton decay branching ratio and the lifetime of the excited state.

Because the direct (p,γ) cross-sections themselves are very low at stellar energies, direct measurements of the resonant reaction is difficult. This is made additionally difficult when the nucleus X is unstable with a short half life; forming a sufficiently intense beam for a low cross-section measurement is, in fact, one of the greatest challenges in next generation facilities, such as ISAC, FAIR, RIKEN and FRIB. Nova reactions, typically taking place on nuclei only 2–3 neutrons removed from stability, are nicely within reach with stable beam tandem facilities, using indirect approaches. As Eq. (1) shows, the resonant (p,γ) rate depends inversely on the lifetime τ of the state into which the proton is captured. Thus, a measurement of τ is one valuable step towards eventually determining the reaction rate.

At the Maier–Leibnitz laboratory, we have begun a program to measure τ for key relevant states of importance to nova nucleosynthesis. Our new Doppler shift lifetime facility, to be used for this purpose, is described next.

2. Experimental facilities

The Maier–Leibnitz laboratory (MLL), operated by the Technische Universität München and Ludwig-Maximilians University, has a 14 MV MP tandem accelerator. There are presently two beam lines with experimental facilities used for experimental nuclear astrophysics. One such facility is a newly installed Doppler shift attenuation lifetime facility; the other is the high resolution Q3D momentum spectrometer. This article reports on the Doppler shift facility.

2.1. Doppler shift lifetime experimental facility

As discussed in Section 1, we desire the lifetimes of those astrophysically relevant excited states of the compound nucleus Y into which protons are captured from the reaction $p + X \rightarrow Y + \gamma$.

One experimental technique for obtaining τ is to populate the astrophysically relevant states in nucleus Y through suitably chosen transfer reactions (for example, a $(\alpha, {}^3\mathrm{He})$ reaction, to name one of many possibilities). Our Doppler shift lifetime facility is designed to exploit the principle of the Doppler shift attenuation method [13,14]. This method works on the principle that, when an excited nucleus decays while decelerating in a target material, the observed Doppler shifted gamma-ray spectrum is equivalent to the folding of the velocity distribution of Y at the moment of its decay with the exponential time probability for decay. Suppose an ensemble of N nuclei Y are produced in an excited state and decay while decelerating in a target material, with an instantaneous velocity function $\beta(t)$. In the non-relativistic limit, the Doppler shifted gamma-ray energy is given by

$$E_\gamma - E_0 \equiv \Delta E_\gamma = E_0 \beta(t) \cos\phi \tag{2}$$

where E_0 is the rest-frame gamma-ray energy, $\beta(t)$ is the velocity of nucleus Y at the moment of its decay, and ϕ is the direction of emission of the gamma-ray with respect to the velocity vector $\vec{\beta}$ of Y. Furthermore, the fraction $\mathrm{d}N/N$ of all nuclei in the ensemble that decay between t and $t + \mathrm{d}t$ giving rise to a Doppler shift ΔE_γ is just,

$$\frac{\mathrm{d}N}{N}\mathrm{d}t = \frac{1}{\tau}\exp(-t/\tau)\mathrm{d}t \tag{3}$$

if we assume that the state is formed directly (no feeding). Eq. (2) represents the distribution of energies measured by a gamma-ray detector observing the gamma-rays from the decay of Y; the run of values formed by Eq. (2) are the abscissae of the Doppler shift energy distribution. The values formed by Eq. (3), on the other hand, form the ordinate values of each ΔE_γ bin. They, thus, form a parametric system of equations, connected by parameter t that can be used to fit the line shape of the Doppler shifted gamma-ray spectrum, where the lifetime τ is a free parameter of the fit. Of course, a model of the velocity distribution $\beta(t)$ in the target material is required.

Fig. 1 shows the design of our Doppler shift lifetime facility, with the left panel showing a design rendering and the right side showing a photograph of the facility installed on a beam line at the MLL. The facility consists of a target chamber, of