Nuclear Structure Aspects in Nuclear Astrophysics

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Abstract Nuclear structure information plays an extremely important role in studies of the evolution and explosion of stars and the cosmic synthesis of the elements. Properties of nuclear ground states (e.g., masses, lifetimes, decay branches) and low-lying resonances (excitation energies, spins, parities, decay widths, spectroscopic factors), especially on unstable nuclei, can quantitatively and qualitatively change predictions of astrophysical simulations. The location of the particle driplines and shell structure far from stability also strongly influence our astrophysical predictions. A number of examples of the dramatic impact that new nuclear structure information has on simulations of nova explosions, X-ray bursts, and core collapse supernovae are given. Some of these are results of recent measurements with radioactive ^{18}F, ^{82}Ge, and ^{84}Se beams at ORNL's Holifield Radioactive Ion Beam Facility. A new suite of software tools to help determine the astrophysical impact of nuclear physics studies will also be presented.

Key words nuclear astrophysics, nucleosynthesis, radioactive beam, reaction rates, supernova

1 Introduction

This is an incredibly exciting time for astrophysics. New measurements of neutrinos emitted from the core of our sun have shown flavor oscillations[1]. A map of the entire galaxy in gamma rays emitted from the decay of ^{26}Al shows hotspots in "recent" element synthesis[2]. Detailed spectral analysis of material ejected from supernovae explosions such as the one in Cas A show anomalous abundances of ^{44}Ti[3] and the presence of iron in the outer ejected layers (showing the star turned itself inside out)[4]. Images and spectroscopy of a shell of material blown off nova explosions show isotopic anomalies and spatial density inhomogeneities[5].

A diverse set of nuclear structure information on a wide variety of nuclei serves as essential input for simulations that attempt to explain these, and many other, observations of astrophysical phenomena. Information on unstable nuclei is particularly important to understand the nuclear processes occurring in the extremely high temperature and density environments characteristic of exploding stars[6]. Some of the needed structure information, and the relevant astrophysical phenomena, include: resonance parameters (novae); positron decays, proton separation energies (X-ray bursts); level densities, alpha-nucleus potentials, decay lifetimes, masses, neutron separation energies (supernovae). Also needed are: optical model parameters, 2-particle separation energies, single particle energy levels, decay modes, branching ratios, and beta-delayed particle emission probabilities. The availability of beams of some of the nuclei involved in stellar explosions with reasonable purity, intensity, and emittance is now making it possible to begin building an empirical foundation for models of stellar explosions. This experimental work, in combination with theoretical estimates of unmeasured quantities, will enable nuclear structure science to make tremendous contributions to our understanding of how stars explode. Below I will give examples of the significant impact of nuclear structure studies

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– some made with radioactive beams at Oak Ridge National Laboratory (ORNL) – in our understanding of three types of stellar explosions – nova explosions, X-ray bursts, and supernovae.

2 Novae

Novae occur in binary star systems in which a main sequence or giant star expands and transfers material to its white dwarf companion star. The accreted material increases in temperature and density until thermonuclear reactions are triggered on the surface of the compact dwarf star, leading to a runaway explosion which generates up to 10^{45} ergs of energy in roughly 1000 seconds and increases the light output by up to a factor of a million. Nuclear reactions on unstable nuclei up to mass 40 are believed responsible for the nova outburst[7], but the rates of most of the relevant reactions are unmeasured. Theoretical estimates are particularly difficult to make because individual nuclear resonances can change reaction rates by factors of 10 — 10^7, dramatically changing predications of energy generation and element synthesis in these explosions. Therefore, searching for resonances and measuring their properties (resonance energy, spin, partial and total widths) is absolutely essential to understand novae. Nuclei in the sd-shell are the most important, as the burning rarely involves nuclei with mass greater than 40.

As an example, the structure of ^{18}Ne was investigated at ORNL to improve our estimate of the ^{17}F(p,γ)^{18}Ne reaction. This reaction, crucial in synthesis of ^{15}N, ^{17}O, ^{18}O, and ^{18}F in novae, is likely dominated by a 3^+ resonance (known in the mirror nucleus ^{18}O) not seen in nine stable beam studies of ^{18}Ne. By measuring the interference of resonant and elastic scattering using a radioactive ^{17}F beam produced at ORNL's Holifield Radioactive Ion Beam Facility (HRIBF)[8], we provided the first unambiguous evidence for this important resonance, confirmed its spin and parity, and precisely determined the resonance energy and total width (to ± 2keV)[9]. The now measured properties of this level changed the ^{17}F(p,γ)^{18}Ne rate calculations by up to a factor of 30 over previous estimates using older nuclear structure information. When utilized as input for a nova nucleosynthesis simulation, the rate based on the new ^{18}Ne level information changed the calculated production of ^{17}O in novae by factors of 5 when averaged over the entire exploding envelope, and by a factor of 15,000 in the hottest regions of the envelope[10].

3 X-ray bursts

A Type I X-ray burst (XRB) is a violent thermonuclear runaway explosion[11] which is similar to a nova, except transfer of material is onto surface of a neutron star – the exotic remnant of a supernova explosion. The resulting bursts of X-rays (10^{-8} erg·cm^{-2}·s^{-1}) can last for tens of seconds and can recur hourly or daily, and are driven by reactions [(α,p) and (p,γ)] on proton-rich nuclei with masses up to approximately $A = 100$ via the “alpha-p process” and “rp-process”[12, 13]. Large-scale nuclear burning calculations are required to determine the energy generation in XRBs that drives the observed X-ray luminosity. Nucleosynthesis calculations can also estimate the possible contribution of these explosions to the abundances of the rare, low-mass p-nuclides such as ^{74}Se, ^{78}Kr, ^{92,94}Mo, and ^{96,98}Ru that are difficult to synthesis in standard p-process scenarios[14].

The peak temperatures of XRBs can be as high as 10^9 K. The proton capture reactions driving the burst proceed through resonances above the proton threshold, which for high mass nuclei ($A > 40$) are at excitation energies where the level densities are quite high. For this reason, estimates of cross sections from a statistical model are used for the overwhelming majority of the hundreds of strong interaction rates used in XRB computer simulations. However, this approach is invalid for low level densities or near closed shells or subshells where individual resonances can significantly contribute to the capture rates[15]. Shell models can, however, be used to predict the levels, spectroscopic strengths, and reduced transition probabilities needed to calculate resonant reaction rates. One recent study[16] used the shell model ANTOINE to determine the properties of resonances in the fp shell. Excitation energies of previously measured states are calculated in this approach to typically within 1MeV of their known energy, and spectroscopic factors are calculated to within 40% of the known values. New rates based on this resonance information were then utilized in an XRB element synthesis simulation[16] and found to change the predictions of synthesized abundances of a number of fp shell nuclei by a factor of ∼10 compared to simulations using the older reaction rates based solely on a statistical model. Measurements of level structure, and improved shell model calculations, are needed for accurate predictions of XRB physics.

Furthermore, mass models and particle decay properties are also needed for XRB studies. The nuclear burning in XRBs proceeds by successive proton capture reactions until halted by photodissociation (γ, p) at the proton dripline. Nuclear masses determine the (p,γ) - (γ, p) detailed balance: the ratio of the rates at a temperature T is proportional to $\exp(-Q_{(\mathrm{p},\gamma)}/\mathrm{kT})$ where $Q_{(\mathrm{p},\gamma)}$ is the Q-value for the proton capture reaction. Recently, a comparison of XRB luminosity predictions using four different mass models[17] found significant qualitative (shape of initial and subsequent peaks) and quantitative (duration, amplitude) changes. Another XRB study of the highest masses synthesized – the endpoint of XRB nucleosynthesis[18] – illustrated the model sensitivity to alpha decays. Their calculations suggested that the synthesis of elements beyond Sn-Sb-Te is difficult because of photo-induced alpha emission. However, this relied on the assumption that Te isotopes are alpha-unbound by ∼4MeV. Experimental determination of the Q_α values and other properties are really needed to determine highest mass nuclides synthesized in XRBs.

4 Supernovae

Supernova explosions are powered not by nuclear reactions but by the gravitational collapse of the Fe core of a massive star. The collapse to densities greater than nuclear matter in the inner core is followed by a rebound, with inner core material moving outwards while the outer core materials is falling in. This sets up a shock wave which, with help from neutrino interactions[19] and convection, propagates outwards through the dense core and then to the lower density outer layers, completely disrupting the star and leaving behind either a neutron star or, for higher mass stars, a black hole.

In this scenario, there is a high-entropy bubble formed above the newly-born neutron star, and the conditions (temperature, free neutron density, number of heavy nuclei present) are just right to quickly form roughly half of all nuclei heavier than iron via the rapid neutron process (r-process)[20]. This sequence of nuclear reactions involves rapid neutron captures on neutron-rich unstable nuclei. Simulations of the r-process require nuclear structure information (masses, lifetimes, level structure, decay properties) on thousands of nuclei out to the neutron drip line. Additionally, nuclear reaction information is needed, especially near the N=50 and 82 closed neutron shells[21] where the abundances peak. Because the relevant nuclei have very short lifetimes, information on their structure are challenging to obtain experimentally.

These nuclei are also difficult to model theoretically because they are many mass units away from stability and there is a general lack of experimental information to constrain relevant theoretical models. Nevertheless, the structure information is crucial for understanding the r-process, and nuclear masses are particularly important. During the supernova cooling phase, the sequence of reactions followed in the r-process follows contours of constant neutron separation energy. The wide variety of available mass models – phenomenological, microscopic, semimicroscopic – predict significantly different r- process reaction paths, which give radically different predictions of the abundances of nuclei synthesized in the r-process[22]. Nuclear masses are also direct input into simplified r-process element abundance estimations that utilize the “waiting point” approximation[23]. Furthermore, masses are required to calculate thermonuclear energy released during r-process burning, and are direct input in calculations of neutron capture cross sections using a statistical reaction model.

Other structure information, such as beta-delayed neutron emission (βn), is also important for understanding r-process burning. The neutron-rich unstable nuclei that are in the r-process reaction path beta decay back to stability as explosion temperature drops; this decay changes the element, the Z, but not the mass value. Older r-process models (which did not include βn), however, almost always underpredict the observations of nuclei in the mass range 124—126 while overpredicting the abundances at the mass 130 peak[22]. The inclusion of βn can solve this problem because this decay branch lowers the mass value during decay. Significantly improved agreement between theory and observations is obtained when βn is included in the calculation[22]. However, more extensive measurements of this branch are needed, both near mass 130 and near the other r-process abundance peaks at mass 80 and 195. This branch may potentially also be important for light masses as well. There is one model[24] that suggests that the inclusion of reactions on light (Z <10) neutron-rich nuclei could modify predicted r - abundances by up to a factor of 10. This study utilizes an old calculation of beta-delayed neutron emission[25] which may need updating at these low mass nuclei. New experimental information on βn would help understand the necessity for neutron captures on light-element nuclei in the r-process.

Another exciting area of research is into the possible weakening or disappearance of the traditional nuclear shell structure for unstable nuclei approaching the neutron drip line. There are numerous theoretical models of shell gap evolution away from stability[22, 26], and the astrophysical implications of this are profound: r-process abundance predictions can be changed by up to a factor of 100 - 1000[22]. The current lack of measurements makes shell gap evolution difficult to study off stability. However, beams of neutron-rich unstable nuclei are now enabling an empirical foundation to be built for this work. ORNL's HRIBF has the capability – unique in world – to utilize transfer reactions to investigate the level structure of neutron-rich nuclei in and near the r-process path. For example, the first (d,p) measurements on nuclei at the N=50 closed shell, ^{82}Ge(d,p)^{83}Ge and ^{84}Se(d,p)^{85}Se, have been measured at HRIBF[27], with the result that a weaker shell closure in ^{83}Ge is measured than previously predicted[28]. Many more measurements needed to benchmark theory, however. Currently, (d,p) reactions on nuclei at the N=82 closed shell, ^{132}Sn and ^{130}Sn, are being measured at HRIBF, and many more studies are planned in the future.

5 Online nuclear astrophysics software tools

To examine the astrophysical impact of the latest nuclear measurements and theoretical calculations, it is essential to process the nuclear information into a format that astrophysical simulations can utilize. This work, and more, is now greatly streamlined by the **Computational Infrastructure for Nuclear Astrophysics**[29]. This is a unique suite of computer codes, freely available online at **nucastrodata.org**, that enables anyone to quickly – with a few mouse clicks – incorporate new nuclear physics results in astrophysical simulations, run the simulations, visualize the results, and compare new predictions to those based on older data. Furthermore, the suite enables users to share large datasets (reaction rate libraries, astrophysical simulations) with each other in an online community. The nucleosynthesis calculations utilized the reaction network code of Hix and Thielemann[30]. More features are continually being added to this suite, many on the basis of user recommendations. For example, tools to visualize theoretical mass models and compare them with each other and with experimental masses were recently added to our suite.

6 Summary

To understand the evolution and explosion of stars, and the accompanying synthesis of nuclei, it is necessary to determine the structure of subatomic nuclei. Information needed includes masses, lifetimes, decays, shell structure, resonance properties, and level densities. This is especially important for nuclei away from stability, where nuclear theories are the most uncertain and the measurements are the most difficult to make. As measurements and theoretical calculations in nuclear structure improve, significant quantitative and qualitative changes are sometimes made in our prediction of astrophysical phenomena. The availability of beams of radioactive nuclei are now making it possible to build an empirical foundation for studies of exploding stars, and the impact of recent can now be quickly estimated with some online software tools. Much future nuclear structure work, both experimental and theoretical, is however still needed to improve our understanding of the cosmos.

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核天体物理中的核结构问题

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摘要 核结构信息在星体的演化和爆炸以及宇宙元素生成的研究中起着极重要的作用. 原子核基态性质(如质量、寿命、衰变分支), 特别是不稳定核的性质, 可以定性地和定量地改变天体物理模拟的预言. 远离稳定线粒子滴线的位置和壳结构也会强烈地影响天体物理的预言. 举几个例子说明新的核结构信息对于新星、X射线爆和核芯塌缩超新星的戏剧性影响. 其中的某些方面来自于橡树岭实验室放射性离子束设备上的^{18}F, ^{82}Ge和^{84}Se放射核束的最新实验测量结果. 同时展示新一套软件工具如何帮助确定核物理研究对于天体物理的影响.

关键词 核天体物理 核合成 放射性核束 反应率 超新星

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