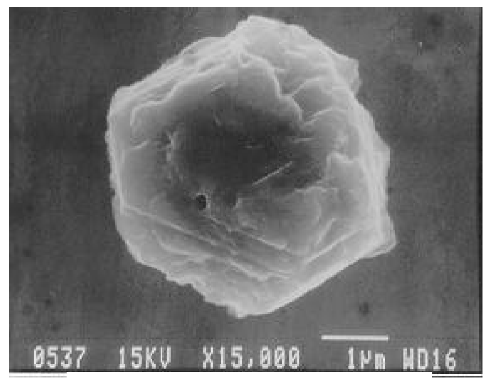
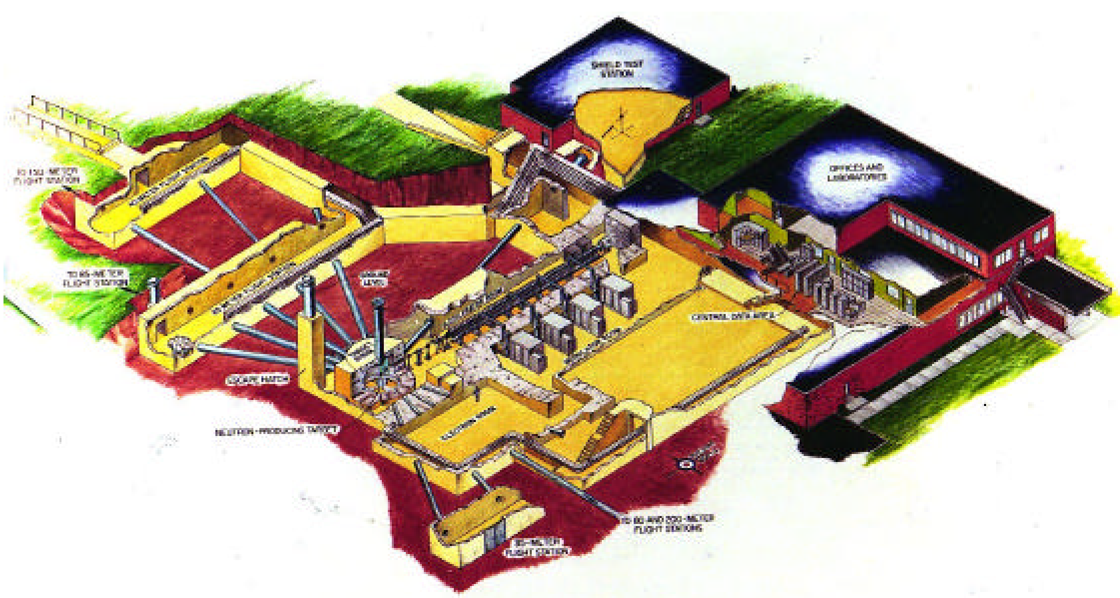
Opportunities
in
Nuclear Astrophysics
at the
Oak Ridge Electron Linear Accelerator

Nucleosynthesis in Stars and Supernovae



Isotopic Ratios in Stardust



The ORELA Facility

PREFACE

Recently, there has been a resurgence of interest in experimental neutron nuclear astrophysics. New precision abundance determinations, recent changes and improvements in stellar models, and the realization of new ways in which neutron experiments yield vital nuclear astrophysics data have all contributed to the need for new experiments. New neutron data are needed to test and improve models of astrophysical objects ranging from red giant stars to supernovae. The Oak Ridge Electron Linear Accelerator (ORELA) is the only facility in the United States capable of providing much of the needed neutron nuclear astrophysics data. Recent improvements in experimental techniques at ORELA have made it possible to make measurements with the precision and energy range needed to answer important astrophysical questions. In addition, ORELA is positioned to serve as an excellent test bed for developing instrumentation for astrophysics experiments at the new spallation neutron sources. This white paper surveys ways in which experiments at ORELA can contribute to a better understanding of several areas of astrophysics. An overview can be obtained by reading the first two short sections. The first section provides a brief summary of the important astrophysical questions that need to be addressed through neutron experiments. This is followed by a brief overview of recent results and possible future experiments at ORELA to address the astrophysics issues described in the first section. The third, and much longer section presents the astrophysics in more detail. Each subsection addresses a different astrophysics topic. A common theme is the fundamental quest to understand the origin of the chemical elements. A related unifying goal is to improve the input nuclear physics data so nucleosynthesis signatures of various astrophysical environments can be used to diagnose the inner workings of supernovae and stars. Measurements from ORELA will also impact related subjects such as the chemical evolution of the galaxy and the formation and age of our solar system. The final section presents a brief description of the ORELA facility.

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I. OUTSTANDING QUESTIONS IN NUCLEAR ASTROPHYSICS AND THE NEED FOR NEW NEUTRON DATA

Almost all elements heavier than iron were made in environments where neutrons play an important, if not dominant, role. The observed abundances of these elements and their isotopes in our solar system can be explained by three main models, the so-called *s*, *r*, and *p* processes, that took place at different time scales, temperatures, neutron densities, and sites. With nuclear physics measurements of sufficient breadth and accuracy, the observed abundances provide a fertile field for developing and testing models of stars, stellar explosions, and more exotic phenomena such as the merger of two neutron stars.

There are several important outstanding questions in nuclear astrophysics requiring new experiments for which ORELA is ideally suited.

- New (n,γ) reaction-rate measurements are urgently needed, especially for the *s*-only isotopes (isotopes produced solely by the *s* process) that are the most important calibration points for the models. The problem with most presently available reaction rates is that the cross-section measurements on which they are based did not extend to low enough neutron energies to determine the rates at the low temperatures (kT = 6-8 keV) needed by new stellar models. New measurements are also needed because many of the old rates are too imprecise to be used to differentiate between competing models of the *s* process.

- New, more precise (n,γ) rates are needed to allow exquisitely precise tests of stellar and galactic chemical evolution models made possible by new precise observational data from meteorites (presolar stardust). Most stardust grains appear to have been formed by red giant stars inside of which the *s* process had occurred. Very few (n,γ) rates have been determined with the precision and energy range needed to take advantage of the opportunities offered by this new, and growing, source of observational data.

- A series of low-energy (n,α) measurements across a broad range of masses is needed to obtain global improvement in rates for reactions involving α particles. These rates are the largest nuclear physics uncertainties in *p* process and other high-temperature environments inside supernovae and massive stars. Direct measurements of the needed (γ,α) and (α,p) rates are extremely difficult if not impossible, and currently are poorly constrained by theory. The calculated abundances can be proportional to these rates, so they need to be constrained much better than currently possible (~ factor of 10 or worse).

- New (n,n') measurements are needed to quantify enhancements in (n,γ) reaction rates inside the thermal plasma of a star due to reactions involving thermally populated excited states (stellar enhancement effects). Stellar enhancement effects for nuclides in the rare-earth region are calculated to be as large as 30%, but, at present, we must rely on largely unconstrained theoretical estimates for these effects. A program of (n,n') measurements is clearly needed to determine enhancements for *s*-only isotopes and to improve statistical models so reliable enhancements can be calculated for other nuclides of interest.

- Complicated mixing processes are thought to play an important role in a number of astrophysical environments. However, modeling mixing is computationally very difficult and few unambiguous constraints exist. Because *s*-process nucleosynthesis is intimately tied to mixing of internal layers in stars, and detailed *s*-process signatures have been observed in meteorites and in stars, the *s* process offers one of the best laboratories for obtaining a better understanding of mixing phenomena in astrophysics. More precise (n,γ) reaction rate measurements across the entire range of temperatures used in models as well as tighter constraints on the rates for the main neutron producing reactions are needed to better understand mixing in astrophysical environments.

- Measurements on radioactive samples and on stable samples having very small natural abundances or small cross sections are needed for several reasons. First, (n,γ) measurements for radioactive branching points along the *s*-process path could greatly aid in understanding dynamics of the *s* process. Second, at the end of the *r* process, (n,γ) reactions could help smooth out the abundance distribution. Such freeze-out effects are needed to improve agreement between the calculations and observed *r*-process abundances. Third, (n,γ) reaction rates on radioactive and very rare stable nuclides are calculated to play an important role during the *p* process. Almost none of these measurements have been made.

- New (n,γ) rates for the *s* process are also needed to better constrain *r*-process models. The *r*-process abundances (the main constraint on *r*-process models) are derived from the measured solar abundances by subtracting the calculated *s*-process contributions. Therefore, a reliable model for the *s* process is important for a better understanding of the *r* process. New observations of very old stars indicate that the nucleosynthesis yields from the *r* process have remained unchanged since the formation of our galaxy. Hence, it recently has become fashionable to refer to the "universal" *r* process. To obtain reliable residual *r*-process abundances using new stellar models of the *s* process, it is important to make new (n,γ) measurements so that accurate reaction rates can be determined across the expanded range of temperatures needed by the new stellar models.

II. RECENT AND POSSIBLE FUTURE ORELA CONTRIBUTIONS TO NUCLEAR ASTROPHYSICS

The combination of high flux, excellent resolution, and multiple beam lines for astrophysics experiments makes ORELA ideally, and in many cases uniquely, well suited for a number of high-priority nuclear astrophysics measurements. High reliability and cost-effective operation also make ORELA an attractive facility for these experiments. The next several subsections give brief descriptions of recent results and possible future experiments in nuclear astrophysics at ORELA.

The cool, new s-process models

In four out of five cases studied so far, new ORELA measurements indicate that extrapolations from previous data to obtain reaction rates at the low temperatures needed by new stellar models of the *s* process are in error by 2 to 3 times the estimated uncertainties. Therefore, extrapolated rates are not sufficiently accurate for meaningful tests of new stellar models. More measurements of cross sections to lower energies are needed, especially for the *s*-only isotopes that serve as the most important calibration points. Cross sections at low energies have been measured for only 4 of the 30 *s*-only isotopes.

Cracks in the classical s-process model

The competition between neutron capture and beta decay at several relatively long-lived radioactive nuclides along the *s*-process path can yield a very direct handle with which to estimate the average neutron density, temperature and matter density in the stellar plasma during the *s* process. Because we know assumptions of the classical *s*-process model are too simplistic for real stars, if (n,γ) cross-section data of sufficient accuracy exist, classical analyses of different branchings should eventually yield inconsistent results.

Thanks to precise new data from ORELA, cracks in classical model are beginning to show. Previous classical analyses of branchings in the *s*-process path had led to a temperature of $kT = 29\pm5$ keV. In contrast, recent precise reaction rate measurements from ORELA were used in a classical analysis of a different branching to deduce a mean *s*-process temperature of $kT = 15\pm5$ keV. This was the first time that clearly inconsistent temperatures were obtained from different *s*-process branchings. Even more recent ORELA measurements have yielded a second example of an inconsistency in results from classical analyses of different *s*-process branchings. Because stellar models are complicated, more precision measurements near other branching points (e.g., ^{85}Kr, ^{95}Zr, ^{151}Sm, ^{152}Eu, ^{153}Gd, ^{163}Ho, ^{170,171}Tm,..) will be needed to understand the crucial ingredients in the new stellar models.

Red Giant Stardust

Most of the microscopic grains of silicon carbide recovered from meteorites appear to be stardust from red giant stars inside of which the *s* process had occurred. The first precise test of the red giant stardust model recently was made possible when new ^{142,144}Nd(n,γ) cross sections were measured with good precision at ORELA. Stellar *s*-process model calculations made with previously accepted cross sections were in serious disagreement with the stardust data. The new ORELA measurements, which were made with an improved apparatus and over a wider energy range, showed that the old data were in error. With the new ORELA data, the agreement between the stellar model and the stardust data was excellent.

Subsequent ORELA measurements for isotopes of barium have revealed problems in the red giant stardust model. Stardust data for other elements exist (e.g., Sr, Mo, and Dy), but because many of the existing (n,γ) data are too imprecise or do not cover the entire energy range needed by the models, new measurements are needed to make use of these data to test and improve astrophysical models.

Improving Reaction Rates for Supernova Models

A new detector (a compensated ion chamber) pioneered at ORELA made possible the first measurements of (n,α) cross sections at astrophysically relevant energies. These data demonstrated that the latest nuclear models used to calculate astrophysical (α,γ) and (α,p) reaction rates for explosive nucleosynthesis studies (e.g. in supernovae) are in need of serious revision. More (n,α) data across a wide range of masses and energies are needed to obtain the necessary global improvement in rates for α-particle reactions. Counting-rate estimates based on these first experiments indicate that as many as 30 (n,α) measurements across the broad mass range from sulfur to hafnium should be possible.

Measurements to determine reaction rates for thermally populated excited states

The stellar enhancement factor (SEF) for one nuclide along the *s*-process path (^{187}Os) was determined via neutron inelastic scattering measurements at ORELA. There are four *s*-only isotopes (^{154}Gd, ^{160}Dy, ^{170}Yd, and ^{176}Hf) in addition to ^{187}O calculated to have SEFs greater than 10%, and 25 other nuclides along the *s*-process path calculated to have SEFs larger than 10%. Because there are substantial differences between the SEFs calculated by different statistical models, more (n,n') measurements are clearly needed.

Cross section measurements on light elements

There are several lighter nuclides whose abundances are modified by (n,γ), (n,α), and (n,p) reactions during the *s* process or during explosive nucleosynthesis. In some cases, these nuclides are of interest to γ-ray astronomy (e.g., ^{22}Na and ^{26}Al), to meteoric anomalies (e.g., Si, Cl, Ca, ^{50}V, and Ti), to the origin of rare isotopes of lighter nuclides (e.g., ^{36}Cl, ^{37,39}Ar), or to non-standard models of the big bang (e.g., ^{17}O, and possibly other neutron-rich lighter nuclides). Although measurements exist for many of these cases, the data from different measurements are in serious disagreement or of questionable quality, or cover too limited an energy range for astrophysics applications; hence, new measurements are needed.

Measurements of small cross sections and measurements using small and radioactive samples

The excellent time-of-flight resolution at ORELA makes it the ideal facility for measurements of very small, resonance-dominated cross sections. With the improved apparatus and excellent resolution, ORELA is the only facility in the U.S. capable of measuring small, resonance-dominated (n,γ) cross sections. Our recent ^{88}Sr(n,γ) measurements demonstrated that the backgrounds for these difficult measurements have been substantially reduced and are now at least a factor of 10 lower than at any other facility in the world. More such data are needed for a better understanding of meteoric anomalies (Si, Ca, Ti, Sr) and of abundance ratios in stars (Cl, Sr, Rb).

Recent proof-of-principle experiments with a 4π BaF_2 detector have demonstrated, contrary to published expectations, that such a detector should be very useful for (n,γ) measurements at ORELA. Because of its larger efficiency and shorter flight path, it should be possible to use this detector to make measurements on samples 50 to 100 times smaller than possible with our current apparatus. Such a system would be very useful for measuring (n,γ) reaction rates for *p*-process nuclides and for long-lived radioactive branching points in the *s* process.

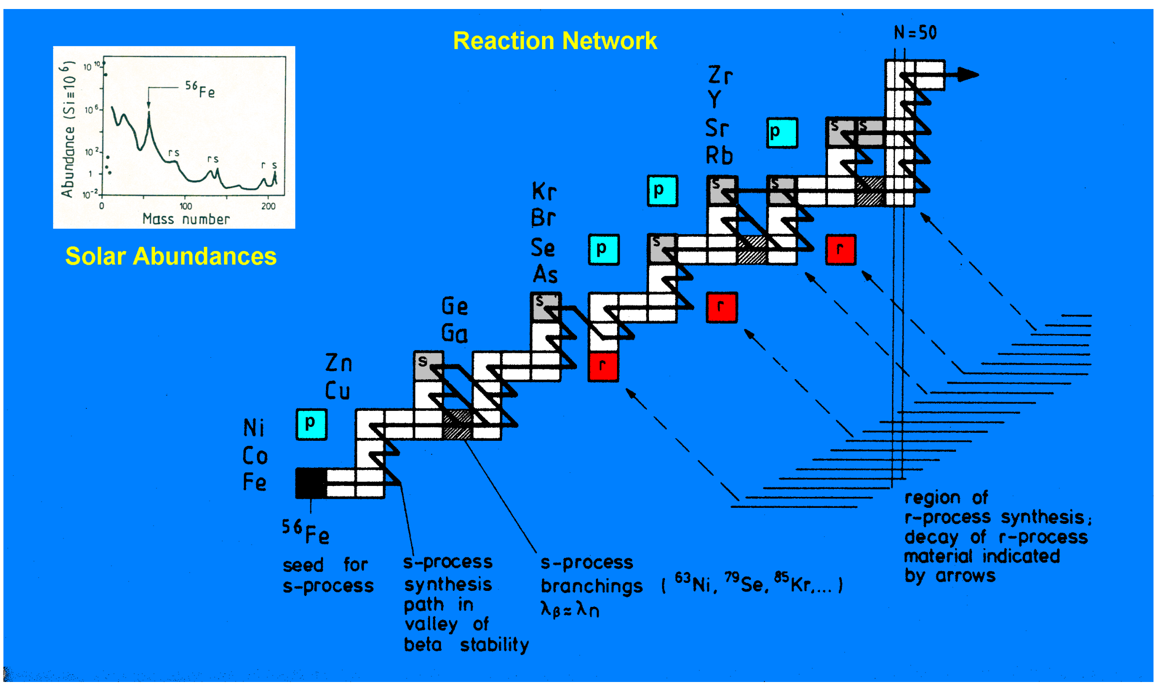
The high flux at the new Oak Ridge Spallation Neutron Source (SNS) will allow measurements to be made with smaller samples. Therefore, the SNS and the similar but less intense neutron source at the Manuel Lujan Neutron Scattering Center (MLNSC) at Los Alamos are the favored sites for measurements on short-lived radioactive samples. ORELA would be an excellent facility for developing detectors for experiments at the SNS. ORELA and the spallation sources are complementary facilities and both will be essential to cover the wide range of measurements needed for nuclear astrophysics.

III. NUCLEOSYNTHESIS OF THE HEAVY ELEMENTS

Almost all elements heavier than iron were made in environments where neutrons play an important, if not dominant, role. The observed abundances of these elements and their isotopes in our solar system can be explained by three main models, the so-called *s*, *r*, and *p* processes, that took place at different time scales, temperatures, neutron densities, and sites. With nuclear physics measurements of sufficient breadth and accuracy, the observed abundances provide a fertile field for developing and testing models of stars, stellar explosions, and more exotic phenomena such as the merger of two neutron stars.

The *s* process

Roughly half of the isotopes of elements heavier than iron are thought to be made in the slow neutron capture, or *s* process. In this process, heavier elements are built from lighter elements via a chain of successive neutron capture reactions and beta decays. The general pattern of elements in our solar system indicates the *s* process takes place under conditions where the time between neutron captures is longer than the average lifetime for beta decay. As a result, the *s* process proceeds through nuclides near the valley of beta



Schematic diagram of reaction network for the *s* process. A small section of stable nuclides heavier than iron is shown. The boxes labeled "s", "p", and "r" represent nuclides produced solely or at least predominantly by the *s*, *p*, and *r* processes, respectively. The inset depicts the measured solar abundances showing the characteristics *s*- and *r*-process peaks.

stability and the resulting isotopic abundances are typically inversely proportional to the neutron capture reaction rates. Neutron capture rates on closed neutron shell isotopes are small, resulting in an enrichment of these isotopes and the characteristic *s*-process peaks in the solar-system abundance distribution. A reliable model of the *s* process is also important for a better understanding of the *r* process because many heavy nuclides are made via both the *s* and *r* processes. Because the *s* process is better understood, the *r*-process abundances (the most important constraint on *r*-process models) are obtained from the measured solar abundances by subtracting the calculated *s*-process contributions.

It appears as if two *s*-process components are needed to explain observed solar-system abundances. The main component dominates nucleosynthesis in the region between Sr and Pb, and is associated with He-shell flashes in low mass (~1.5 M_{sun}) asymptotic giant branch (AGB, or, more commonly "red giant") stars.

Red giant stars are inherently interesting as well as potentially rich physics laboratories for a number of reasons. First, they synthesize roughly half of the elements heavier than iron. Second, through a complicated mixing process known as third dredge up, newly synthesized elements are carried from inner regions of the star out to its atmosphere where they are visible to astronomical observations. In fact, it was the observation of the radioactive element technetium (which has no stable isotopes) in the atmosphere of a red giant star that provided the first direct proof that nucleosynthesis occurs in stars. Also, the recurrent He-shell flashes which drive the nucleosynthesis and power the dredge up mechanism are complicated mixing phenomena. There are many mixing problems in astrophysics that computationally are very difficult, and hence poorly understood. Because *s*-process nucleosynthesis is intimately tied to mixing, and because detailed signatures have been observed, there is hope that red giant stars offer one of the best laboratories for obtaining a better understanding of mixing phenomena in astrophysics. Third, strong stellar winds from red giant stars disperse products of nucleosynthesis throughout the galaxy. In cooler outer regions of red giant stars, microscopic grains of refractory materials such as SiC form. As they form, trace amounts of heavy products of nucleosynthesis are trapped within them. Some of these grains from a red giant star (or stars) of a previous generation have apparently found their way to our own solar system. These grains have been recovered from primitive meteorites and detailed isotopic signatures being coaxed from them are providing a rich new set of observational data with which to test astrophysical models of these stars, of galactic chemical evolution, and of the formation of the solar system. Finally, as they die, red giant stars create a seemingly endless variety of so-called planetary nebula containing

Image of planetary nebula NGC3242b taken by the Hubble Space Telescope. These objects are born from the death of a red giant star inside of which the *s* process had occurred. In about 5 billion years our sun may form such an object.

many of the products of nucleosynthesis. In fact, in about 5 billion years our own sun will likely spawn a planetary nebula of its own as it shrinks and cools to a white dwarf star.

The second, or weak *s*-process component is responsible for nucleosynthesis up to the $A = 90$ range. It is thought to take place in massive stars (10-30 M_{sun}) during their He and C burning phases. In addition to synthesis of these heavier elements, the *s* process can modify isotopic patterns of many lighter elements and can create seed nuclides for later nucleosynthesis during the *p* process.

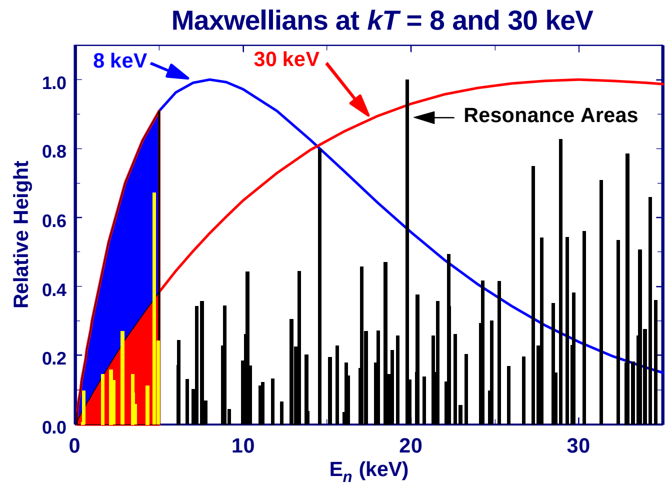
Research on the *s* process has undergone a renaissance in recent years, thanks to new more realistic stellar models, new extremely precise observational data, and improved experimental nuclear physics techniques and data. Until recently, even rather schematic *s*-process models reproduced the observed abundances rather well. However, as the precision of both observations and neutron capture cross section data has improved, it has become clear that more sophisticated models are needed.

Cracks in the classical s-process model

The so-called classical model of the *s* process as it was first outlined by Burbidge *et al*. in 1957 represents a purely phenomenological approach to neutron capture nucleosynthesis. It has been used for years in an attempt to understand the average properties of the *s*-process environment in stars. The main reasons for the popularity of the classical model are its simplicity and the fact that until recently it was successful in reproducing observed abundances of the *s*-only isotopes (isotopes produced solely or at least predominantly by the *s* process). In the classical model, it is assumed that properties of the *s*-process environment such as temperature, neutron density, and matter density are constant during each He-shell flash in the star. By making these assumptions, time is removed as a variable and the set of coupled differential equations describing the isotopic abundances can be solved analytically. It was shown early on that these equations can be solved by assuming an exponential distribution of neutron exposures, and furthermore that such a distribution was in at least rough agreement with stellar models for the *s* process. By adjusting parameters of the classical model, it was possible to obtain a good fit to all of the *s*-only isotopes at the same time. However, as neutron capture reaction rate measurements became more precise, disagreements began to emerge. First, it was shown that the classical model overproduced the *s*-only isotopes ^{134}Ba and ^{136}Ba and underproduced *s*-only ^{116}Sn. However, at the time, the solar abundance data for these isotopes was thought to be too uncertain to draw a firm conclusion. More recently, with precise new neutron capture data, it has been shown that the classical model clearly overproduces the *s*-only isotope ^{142}Nd. Because solar abundances are well determined in the rare earth region, there seems little doubt of the failure of the classical model in this case. Subsequent measurements of solar barium and tin abundances have verified the old data and hence solidified the failure of the classical model in these cases as well. In contrast, the new stellar models of the *s* process successfully reproduce the *s*-only isotopes ^{136}Ba and ^{142}Nd. The stellar models still overproduce *s*-only ^{134}Ba by a small amount, but a complicated branching in the *s*-process flow at radioactive ^{134}Cs obscures any firm conclusions in this case. With so few *s*-only isotopes having reaction rates measured to the required precision, it is not possible to draw any firm insights into reasons for the success of the new stellar models over the classical model. There are approximately 20 more *s*-only isotopes. Precise reaction rate measurements for these nuclides across the entire range of temperatures needed would go a long way in delineating essential ingredients of new stellar models.

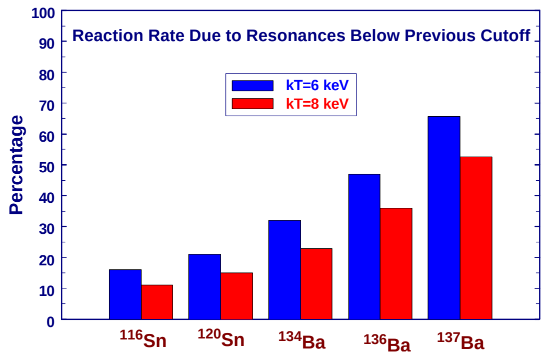
The cool new stellar s-process model

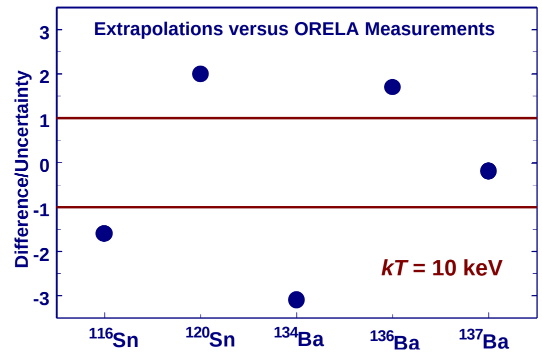
One major difference between classical and new stellar models of the *s* process is the temperature at which most of the neutron exposure occurs. Classical *s*-process analyses have indicated that the average temperature is about kT = 30 keV. However, recent calculations indicate that in low-mass red giant stars most of the neutron exposure occurs at much lower temperatures (kT = 6-8 keV), under radiative conditions between He-shell pulses. This lower average temperature requires extending many previous neutron capture cross section measurements to lower energies. Most previous measurements, as well as many new measurements made at other facilities, had a lower energy cutoff that was too high (E_n = 2.5 - 10 keV). Although such a high cutoff energy is sufficient for obtaining the reaction rate at 30 keV, to obtain the rate at kT = 6 - 8 keV to the required precision (~3%), it is necessary to make cross section measurements down to about 100 eV.



Portions of the Maxwell-Boltzman (M-B) distributions at kT=8 (blue curve) and 30 keV (red curve) for neutron energies below 35 keV. The neutron capture reaction rate at a given temperature is calculated by summing up the products of the resonance areas (depicted by vertical bars) times the heights of the M-B function at the resonance energy. For a temperature of 30 keV, only a small part of the reaction rate is missed (red region) if the measurements have a low energy cutoff of 5 keV. However, for a temperature of 8 keV, a sizeable portion of the reaction rate is unmeasured (blue region) if the low energy cutoff is 5 keV. Many previous measurements had cutoffs of 2.5 to 10 keV.

Recent ORELA measurements have demonstrated that extrapolations to estimate the contribution of low-energy resonances below energy cutoffs of previous measurements are not reliable. In 4 out of 5 cases studied so far, new ORELA data indicates that extrapolations are in error by 2 to 3 times the estimated uncertainties; hence, extrapolated rates do not provide reaction rates with sufficient accuracy for meaningful tests of the new stellar models. Therefore, direct measurements of cross sections to lower energies are needed. New low-energy measurements are especially important for *s*-only isotopes, for isotopes near





ORELA measurements of the contributions to reaction rates at temperatures of 6 and 8 keV due to resonances below the cutoffs of previous experiments. Low-energy resonances can account for as much as 70% of the reaction rate at these low temperatures.

Tests of the reliability of extrapolations to obtain the contribution of low-energy resonances to the reaction rate at 10 keV. The data points depict the difference between the ORELA data and the extrapolations, divided by the estimated uncertainty in the extrapolations. If the extrapolations were reliable, the data points should lie between ±1. However, all but one of the cases tested so far lie outside this range.

branchings in the *s* process, and for isotopes where precise new abundance ratios have been measured in grains from meteorites.

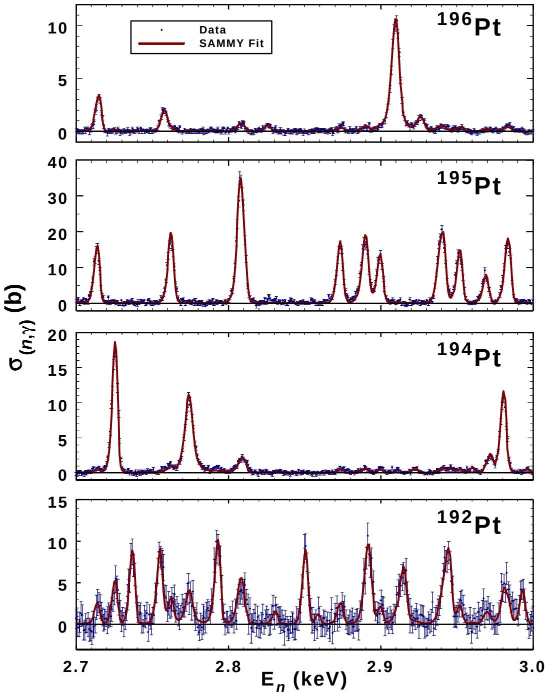
Branchings in the s-process flow

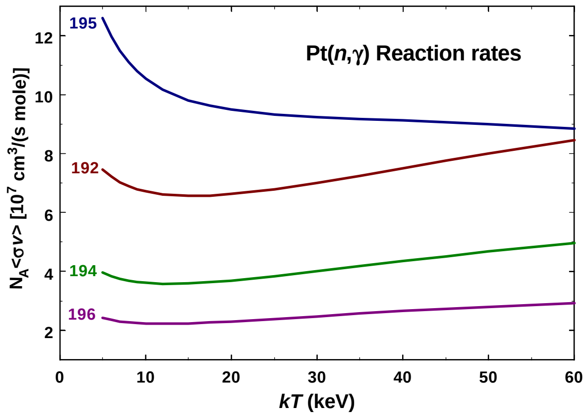
Occasionally, the nucleosynthesis path of the *s* process encounters a radioactive isotope having a beta decay lifetime comparable to its lifetime against neutron capture. The competition between neutron capture and beta decay causes the *s*-process flow to branch at these nuclides. The *s*-only isotopes near these branchings can serve as valuable diagnostics of both the average properties as well as the "dynamics" of the *s*-process environment. The competition between neutron capture and beta decay at the branching points yields a very direct handle with which to estimate the average neutron density during the *s* process. Because half lives of some *s*-process branching points depend on temperature or electron density, they can be used to estimate the temperature or matter density in the stellar plasma during the *s* process. Different branchings are sensitive to the temporal characteristics (i.e. the dynamics) of the *s*-process environment because (n,γ) reaction rates of the involved isotopes as well as half lives of the branching points vary considerably. Because we know that classical model assumptions of constant temperature, neutron density, and matter density are too simplistic for real red giant stars, if (n,γ) cross-section data of sufficient accuracy exist, classical analyses of different branchings should eventually yield inconsistent results.

For example, classical analyses of branchings at ^{151}Sm, ^{154}Eu, and ^{175}Lu had led to a temperature of $kT = 29\pm5$ keV. In contrast, recent precise reaction rate measurements for ^{134}Ba and ^{136}Ba from ORELA were used in a classical analysis of the branching at

^{134}Cs to deduce a mean *s*-process temperature of kT = 15±5 keV. This was the first time that clearly inconsistent temperatures were obtained from different *s*-process branchings.

Even more recent ORELA measurements of ^{192,194,195,196}Pt(n,γ) reaction rates have yielded a second example of an inconsistency in results from classical analyses of different *s*-process branchings. With the new ORELA reaction rate for the *s*-only isotope ^{192}Pt, a branching at ^{192}Ir can be used to estimate the neutron density during *s*-process.





A small part of the ORELA neutron capture cross sections (left) and reaction rates (above) for isotopes of platinum. The measurements spanned the range from 10 eV to 400 keV. The R-matrix program SAMMY was used to fit the data to obtain resonance parameters.

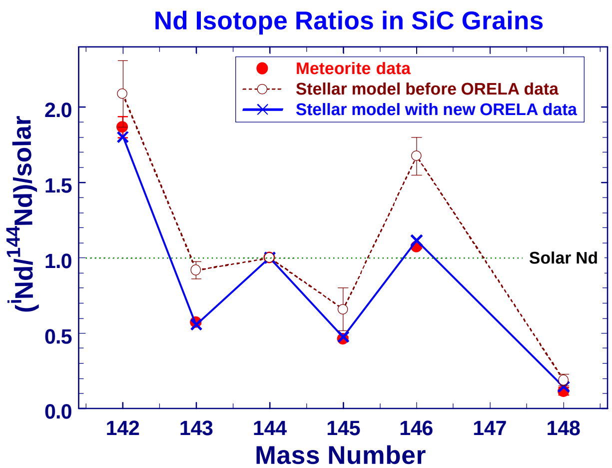
Previous classical analysis of a different *s*-process branching (at ^{147}Pm) had yielded a mean neutron density of n_n = (4.1±0.6)x10^8 cm^{-3}. The analysis of our new platinum data yielded n_n = (7±4)x10^7 cm^{-3}, clearly inconsistent with the ^{147}Pm result.

These relatively simple analyses using the classical model are starting to shed light on the crucial ingredients of the much more complicated stellar models of the *s* process. For example, the two different neutron densities and temperatures resulting from the different branching analyses discussed above indicate the need for a time dependence of the neutron density and temperature. Although it has been known for some time that any realistic stellar model would include such "dynamics", until recently, the neutron capture data were too imprecise to demonstrate it conclusively. More precise neutron capture data near other *s*-process branchings (e.g. ^{85}Kr, ^{95}Zr, ^{151}Sm, ^{152}Eu, ^{153}Gd, ^{163}Ho, ^{170,171}Tm,..) are needed to provide further constraints on the many "knobs" in current stellar models.

Stardust from the s process

One example of precise new observational data is the discovery in certain meteorites of presolar grains. These micron size pieces of silicon carbide and other refractory materials are quite literally stardust. They are called presolar because they apparently originated in an older generation of stars and supernovae before the birth of our solar system. As grains formed, they trapped within them small amounts of various heavy elements, thus preserving the nucleosynthesis signature of the parent star or supernova. Some of these grains survived formation of our solar system and were transported to earth intact inside meteorites. In recent years, it has become possible to measure isotopic ratios of the trace elements such as strontium, neodymium, and barium trapped inside these grains with part-per-thousand precision. The measured ratios are very non-solar and indicate that most grains are red giant stardust. For example, barium found in these grains is depleted (relative to the *s*-only isotopes ^{134,136}Ba) both in the lighter isotopes ^{130,132}Ba that are bypassed by the *s* process, and in the isotopes ^{135,137,138}Ba that are made in part by the *r* process,. To make use of these precise new data from meteorites to improve *s*-process models, it is necessary to have precise neutron capture data.

The first precise test of the red giant stardust model recently was made possible when new ^{142,144}Nd(n,γ) cross sections were measured with good precision at ORELA. Stellar *s*-process model calculations made with previously accepted cross sections were in serious disagreement with the stardust data. The new ORELA measurements were made over a wider energy range and showed that the old data were in error. With the new ORELA data, the agreement between the stellar model and the stardust data was excellent.



Isotopic ratios for neodymium found in silicon carbide grains from the Murchison meteorite. The stellar *s*-process calculations made using the new ORELA reaction rates for ^{142,144}Nd(n,γ) are in precise agreement with the meteorite data. In contrast, calculations made using the old reaction rates are in serious disagreement with the meteorite data.

Isotopic ratios for barium have also been measured in SiC stardust with good precision. They were found to be in good agreement with predictions of the *s*-process stellar model, with the exception of the isotope ^{137}Ba. The parameters of the stellar model were varied in an attempt to fit ^{137}Ba with no success; hence, it was suggested that the ^{137}Ba(n,γ) reaction rate was in error. Because the best previous measurement of this rate had a rather high low-energy cutoff of 10 keV, the reaction rate at the required temperature of 6-8 keV was mostly due to extrapolation. Therefore, it was reasonable to expect that the rate could be in error by as much as the 20% needed to reconcile the stellar model with the stardust data. New ^{137}Ba(n,γ) measurements at ORELA, across the entire energy range needed, resulted in a reaction rate in agreement with the previous rate to within 3% - far too small a difference to solve the difference between the stellar model and the stardust data. Hence, the difference between the *s*-process stellar model and the stardust data for ^{137}Ba remains an unsolved mystery.

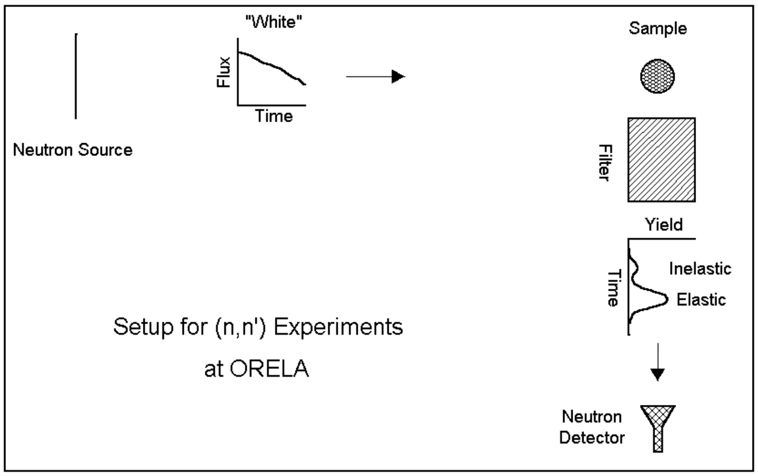
One interesting result from these first studies of red giant stardust is that stellar models of different ages are needed to reproduce the two types of *s*-process abundances. The stardust data require a younger stellar model than is needed to fit the solar abundances. A reasonable explanation is that stardust grains were made by a fairly recent generation of stars (perhaps by a star that helped trigger the formation of the solar system) that seeded the nascent solar system with grains as they died. In contrast, average solar system material is a mixture from all previous generations of stars since the beginning of the galaxy, so the average age of stars contributing to the solar abundances is older. This finding was not anticipated, but is in agreement with the expectations of galactic chemical evolution; hence, the study of stardust is not only testing and improving models of the *s* process, but is impacting other areas of astrophysics.

Isotopic ratios have been measured for many other trace elements found in stardust. New (n,γ) data are needed to make use of these data to test and improve astrophysical models. We have recently made high precision measurements of the ^{88}Sr(n,γ) reaction rate that have led to better agreement between the stellar models and the stardust data. However, important differences remain, and new high-precision measurements of the ^{86,87}Sr(n,γ) are urgently needed. Similarly, precise ratios for molybdenum and dysprosium isotopes in stardust exist, but high-precision (n,γ) data across the entire range of energies needed by the stellar *s*-process models are lacking. Finally, the experimenters making isotopic measurements on stardust have recently begun commissioning new, more sensitive instruments. It is expected that in the near future precise isotopic ratios will be measured for many more *s*-process elements. New (n,γ) data will be needed to be able to use these new stardust data to test and improve the astrophysical models.

Reactions on thermally populated excited states

The (n,γ) reaction rates inside the thermal plasma of a star can be significantly different from the rates measured in the laboratory due to reactions involving thermally populated excited states. These stellar enhancement effects cannot be directly measured, but can be determined by measuring neutron inelastic cross sections to the same levels populated in the stellar environment. The enhancement of stellar reaction rates due to this effect can be as large as 30%, while enhancements calculated by various nuclear statistical models can differ by substantial amounts. Such large and uncertain effects are particularly troublesome for *s*-only isotopes because they are the main calibration points for *s*-process models. Five *s*-only isotopes are calculated to have enhancements in excess of 10%. In contrast, current techniques can determine laboratory reaction rates to 1-3% accuracy and isotopic abundances can often be measured with part-per-thousand accuracy. A program of (n,n') measurements for these isotopes is clearly needed to determine enhancements for *s*-only isotopes and to improve statistical models so reliable enhancements can be calculated for other nuclides of interest.

The stellar enhancement factor (SEF) for one nuclide along the *s*-process path (^{187}Os) was determined through neutron inelastic scattering measurements at ORELA several years ago. This measurement was particularly difficult because the excitation energy of the first excited state in ^{187}Os is only 9.8 keV; hence, it was not possible to detect the de-excitation γ rays directly and it was difficult to resolve the inelastically scattered neutrons from the larger elastic group. However, by using a clever technique which exploits the excellent time-of-flight resolution available at ORELA, it was possible to measure this cross section. There are four *s*-only isotopes (^{154}Gd, ^{160}Dy, ^{170}Yd, and ^{176}Hf) in addition to ^{187}O calculated to have SEFs greater than 10%, and there are substantial differences



Schematic diagram of ^{187}Os(*n*,*n*') experiment at ORELA. An iron filter was placed after the sample to remove all but the neutrons in the "window" at 24.5 keV due to the large *s*-wave resonance near 26 keV. This filter, together with the excellent time-of-flight resolution at ORELA allowed the 9.8-keV inelastic group to be resolved from the larger elastic group. A similar technique, or direct detection of the de-excitation γ rays could be used to measure the (*n*,*n*') cross sections, and hence determine the SEFs for many other *s*-process nuclides.

between the SEFs calculated by different statistical models. Measurements should be easier for these four *s*-only isotopes than for ^{187}Os because both excitation energies and natural abundances are higher. Given advances in detector technology since the ^{187}Os experiment, it may even be possible to measure the de-excitation γ rays directly. There are about 25 other nuclides along the *s*-process path calculated to have SEFs larger than 10%. First excited state energies range from 8.4 keV (^{169}Tm) to 100.106 keV (^{182}W). For those with the smallest excitation energies it appears as if a technique similar to that used in the ^{187}Os experiment will be necessary. However, it should be possible to use a flight path about a factor of 4 shorter (and hence have a higher counting rate or use smaller samples) and still obtain resolution sufficient to separate the elastic and inelastic groups.

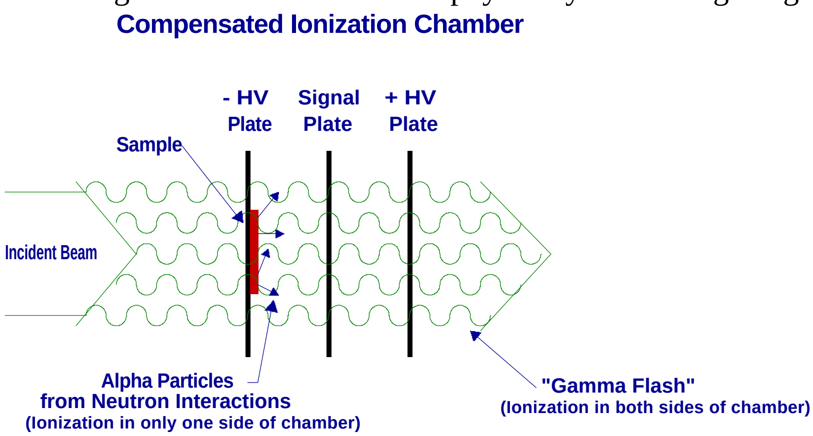
The *p* process

The *p* process is the name given to the mechanism by which low-abundance, proton-rich isotopes of intermediate to heavy elements were synthesized. Little is known about the details, but is seems certain that the *p* isotopes originated in a high-temperature environment (perhaps in supernovae or in the later burning stages in massive stars) where seed nuclides built up by a previous *s* process were "photo-eroded" via (γ,*n*), (γ,α), and (γ,*p*) reactions towards more proton-rich isotopes. At present, *p*-process calculations must rely on theoretical rates for most of the reactions in the nucleosynthesis flow.

Improving explosive nucleosynthesis reaction rates via (n,α) measurements

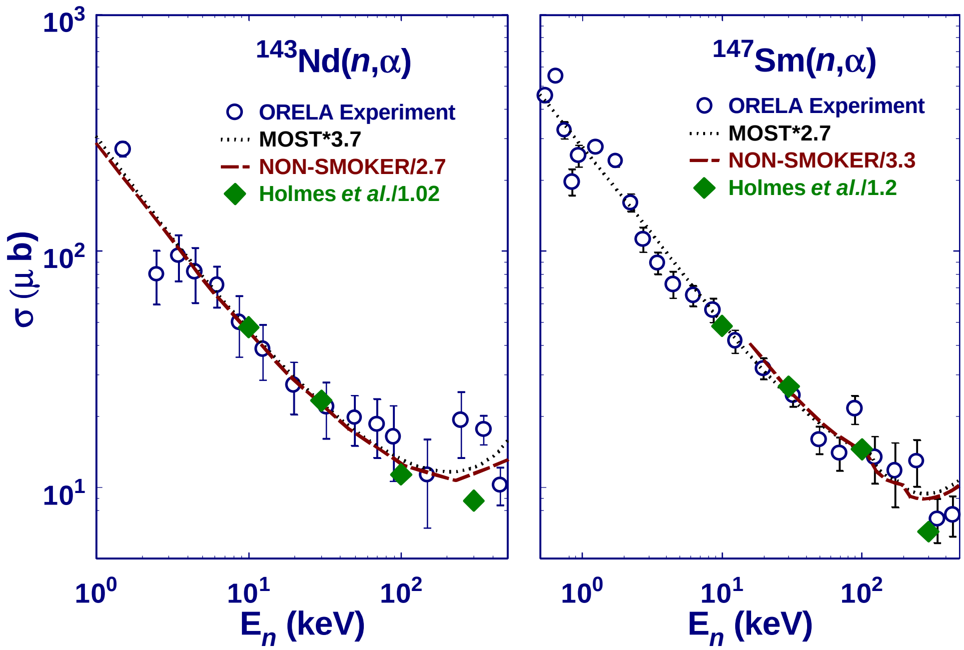
The largest nuclear physics uncertainties in the *p* process and other high-temperature environments are rates for reactions involving α particles. Direct (γ,α) measurements are extremely difficult (even via the inverse reaction) and it is very unlikely that rates for most of the needed reactions will be determined by direct experiments. Although the nuclear statistical model should be applicable to calculation of these rates, theoretical calculations are hampered by large uncertainties in the α+nucleus optical potential in the astrophysically relevant energy range. In contrast to (γ,*n*) and (γ,*p*) rates, which can be predicted to a factor of two or better, theoretical rates for (γ,α) reactions appear to be uncertain by a factor of ten or more. In addition, predicted abundances from *p*-process calculations can be linearly proportional to the (γ,α) rates.

Traditional methods for improving optical potentials, such as elastic scattering of α particles, have been of limited usefulness because the potentials must be extrapolated from measurements made at energies well above the astrophysically interesting range. Recent work at ORELA has shown that a series of low-energy (*n*,α) measurements, across a wide range of masses, appears to be the best means of constraining the α+nucleus potential and thus improving the calculation of these rates. The Q values for these (*n*,α) reactions are such that the relative energy between the α particle and the residual nucleus are in the astrophysically interesting energy range, so no extrapolation is necessary. Also, scaling the sample size to that employed in a previous measurement, using predicted cross sections, we calculate that as many as 30 nuclides across a wide range of masses should be accessible to measurements; hence, the needed global improvement in the α potential should be possible.



Schematic diagram of a compensated ion chamber (CIC). In this parallel-plate version, two plates at equal but opposite high voltages are equally spaced on either side of the signal plate. The large number of γ rays at the start of each pulse from the neutron source penetrate both sides of the CIC; hence the signal they induce on the central plate cancels out. In contrast, α particles from (*n*,α) reactions cause ionization in only one side of the chamber, so that a measurable signal is induced on the central plate.

At ORELA, the first application of this idea was to the ^{143}Nd and ^{147}Sm(n,α) cross sections, where measurements were made across the range of energies needed for astrophysics applications. Previous measurements of this type were limited to energies below a few keV (which is too small of an energy range to be useful for comparison to statistical models) due to overload problems in the detectors and associated electronics resulting from the γ flash at the start of each neutron pulse. In the new experiments, this problem was overcome by employing a compensated ion chamber (CIC) as the detector. The concept of using a CIC for measurements at a pulsed white neutron source was



Cross sections for the ^{143}Nd and ^{147}Sm(n,α) reactions in the unresolved region. Shown are the recent ORELA measurements and the calculations of Holmes et al., as well as calculations made with the newer statistical model codes NON-SMOKER and MOST. <u>Note that the theoretical calculations have been normalized by factors given in the legends</u>.

pioneered earlier at ORELA. Although a CIC can have poorer pulse-height resolution than, for example, a gridded ion chamber, it allows the γ-flash background to be reduced to the point where measurements are possible to much higher energies (500 keV in the cases of ^{143}Nd and ^{147}Sm).

The older calculations of Holmes *et al*. are much closer to our ^{143}Nd and ^{147}Sm(n,α) data than the newer NON-SMOKER or MOST calculations, which differ from the data by about a factor of 3 in opposite directions. The better agreement of the older model may be due to a fortuitous cancellation of effects. The newer models employ a neutron potential that is known to be more reliable in this mass region. In addition, the authors of the newer models have attempted to reduce the reliance on empirical fine tuning and to take advantage of the latest physics knowledge in an effort to increase the reliability of the models away from the valley of stability. In the case of the α potential, several parameters are needed to account for the mass, energy, and nuclear structure effects. At present, the values of these parameters in the astrophysically relevant range are poorly constrained by experiment.

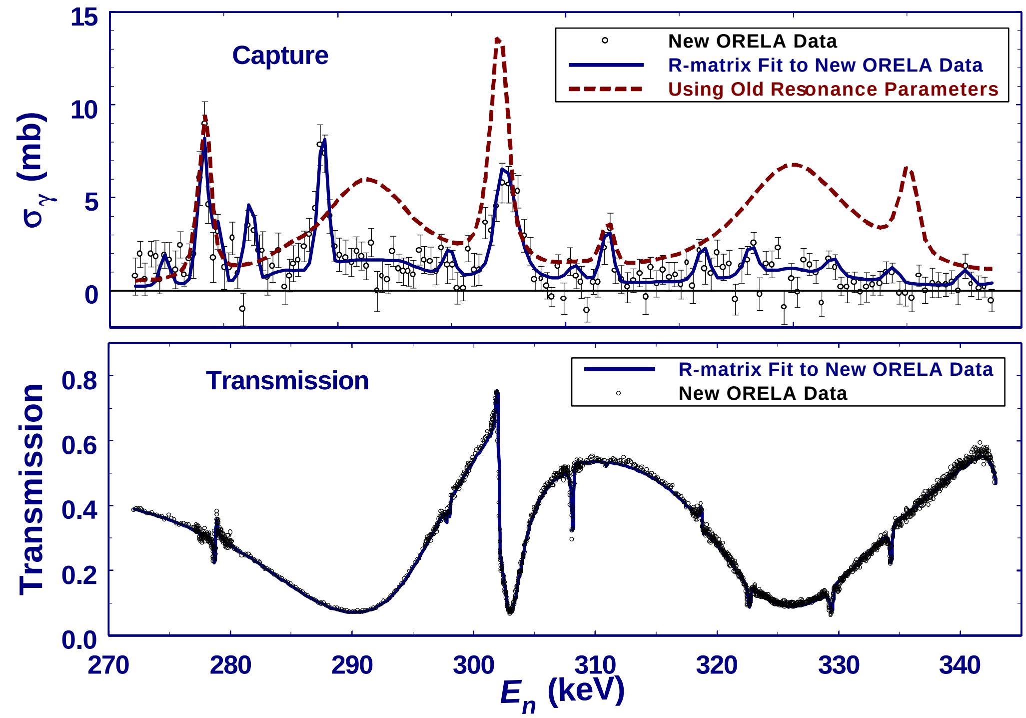
We have studied the sensitivity of calculated (n,α) cross sections to the α potential and level densities employed in the model. We found that differences of about a factor of 30 could be accounted for in the variation of the potential alone. The different level density prescriptions changed the cross section by a factor of about 1.5, far smaller than the effect of the α potential. More (n,α) data across as wide a range of masses and energies as possible are needed to constrain the several parameters thought to be necessary to define the global α potential needed for astrophysics applications. Counting rate estimates based on these initial experiments indicate that as many as 30 measurements should be possible across the mass range from S to Hf. However, a new detector that allows higher pressures and voltages, as well as more sample plates will be required for most of these measurements.

Measurements of small cross sections and measurements using small samples

Measurements on radioactive samples and on stable samples having very small natural abundances or small cross sections are needed for several reasons. First, (n,γ) measurements for radioactive branching points along the *s*-process path could greatly aid in understanding dynamics of the *s* process. Second, at the end of the *r* process, when reactions freeze out as the temperature and neutron density decline, (n,γ) reactions could help smooth out the abundance distribution and improve agreement between the calculations and observed *r*-process abundances. Third, very few measurements of (n,γ) reaction rates for nuclides involved in the *p* process have been made, so theoretical rates are used in *p*-process calculations. From measurements made near the valley of stability, it is known that (n,γ) rates can be predicted to within a factor of two. However, it is not known how reliable the theoretical rates are when extrapolated away from the valley of stability. Measurements on both radioactive samples and on the very rare *p*-isotopes themselves are needed to improve reliability of theoretical rates that must still be used for the many unmeasurable cases. Finally, there are several lighter nuclides whose abundances are modified by (n,γ), (n,α), and (n,p) reactions during the *s* process or during explosive nucleosynthesis. In some cases, these nuclides are of interest to γ-ray astronomy (e.g., ^{22}Na and ^{26}Al), to meteoric anomalies (e.g., Si, Cl, Ca, ^{50}V, and Ti), to the origin of rare isotopes of lighter nuclides (e.g., ^{36}Cl, ^{37,39}Ar), or to non-standard models of the big bang (e.g., ^{17}O, and possibly other neutron-rich lighter nuclides). Although measurements exist for many of these cases, the data from different measurements are in serious disagreement or of questionable quality, or cover too limited an energy range for astrophysics applications; hence, new measurements are needed.

The excellent time-of-flight resolution at ORELA makes it the ideal facility for measurements of very small, resonance-dominated cross sections. With excellent resolution, the signal-to-noise ratio of the measurements is greatly improved because the widely spaced resonance peaks stand well above the background. In addition, recent improvements in the (n,γ) apparatus at ORELA have resulted in a considerable reduction in sample-dependent backgrounds. Our recent measurements indicate that many older

(n,γ) cross section data on samples with small, resonance-dominated cross sections are in error due to underestimation of these backgrounds in past measurements. This sample-dependent background is due to neutrons scattered from the sample that subsequently capture in the detector and its surroundings, yielding a signal indistinguishable from (n,γ) reactions in the sample. In the old ORELA apparatus, this so-called neutron sensitivity background was sizeable for resonances having large neutron widths. The affected resonances had a measured radiation width much larger than the true width and hence the measured cross section was much larger than the true cross section and corrections had to be applied. With the new ORELA apparatus, this background has been reduced to the point of being unmeasurable, and the resultant average radiation widths and cross



Demonstration of the greatly reduced neutron sensitivity background in the new ORELA (n,γ) apparatus. Shown are (n,γ) and total cross section (transmission) data for ^{88}Sr from our new measurements at ORELA (points) as well as new R-matrix fits to the new data (solid blue curves). Also shown is a calculation of the (n,γ) cross section using the previous resonance parameters. Neither the new ORELA data nor the new resonance analysis included corrections for the neutron sensitivity background (which would cause the measured cross section to be too large). Although the old resonance parameters received substantial corrections for the neutron sensitivity background, it is clear that the size of the background in the old data has been underestimated. As a result, the old cross sections are too large, especially near 290 and 325 keV where there are resonances with large neutron widths.

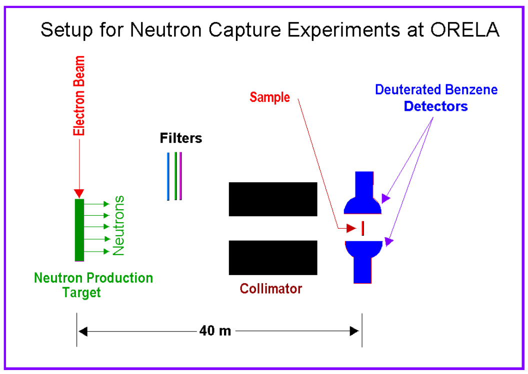
sections can be much smaller than previously reported. For example, in our recent ^{88}Sr(n,γ) experiment, we measured an average p-wave radiation width of 250 meV, which is over a factor of two smaller than the previously measured 670 meV. With this improved apparatus and excellent resolution, ORELA is the only facility in the U.S. capable of measuring the small, resonance-dominated (n,γ) cross section needed for a better understanding of meteoric anomalies (Si, Ca, Ti, Sr) and of abundance ratios in stars (Cl, Sr, Rb).

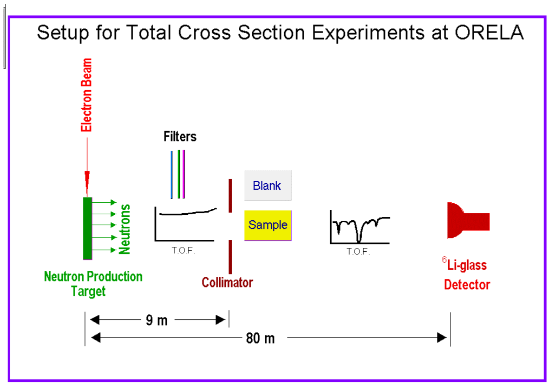
Recent proof-of-principle experiments with the 4π BaF_2 detector at ORELA have demonstrated, contrary to published expectations, that such a detector should be very useful for (n,γ) measurements at ORELA. Because of its larger efficiency and shorter flight path, it should be possible to use this detector to make measurements on samples 50 to 100 times smaller than possible with our current apparatus. This development would allow measurements to be made on some of the *p* isotopes as well as some long-lived radioactive isotopes of interest to the *s*, *p*, and *r* processes. Although proof-of-principle experiments were successful, work remains to be done to turn this into a "production" facility.

The high flux at the new Oak Ridge Spallation Neutron Source (SNS) will allow measurements to be made with smaller samples. Therefore, the SNS and the similar but less intense neutron source at the Manuel Lujan Neutron Scattering Center (MLNSC) at Los Alamos are the favored sites for measurements on short-lived radioactive samples and on stable samples of very low natural abundance. ORELA would be an excellent facility for developing detectors for experiments at the SNS. High flux, however, is not a panacea. It will not be possible to make many of the measurements of astrophysical interest at spallation sources because of their modest resolution. ORELA and the spallation sources are complementary facilities and both will be needed to cover the wide range of measurements needed for nuclear astrophysics.

IV. BRIEF DESCRIPTION OF THE ORELA FACILITY

An intense, pulsed source of neutrons is produced at ORELA when bursts of electrons from the linac stop inside a tantalum target. As the electrons slow down in the tantalum, they generate an intense flux of γ rays. These γ rays in turn produce neutrons via (γ,*xn*) reactions on the tantalum. The neutrons are moderated in the cooling water surrounding the target and then travel to the various experimental stations through evacuated flight tubes. The resulting neutron spectrum is "white" in the sense that the covered energy range is relatively broad (from sub-thermal to approximately 50 MeV) and the flux is roughly proportional to $E^{-0.7}$ where E is the neutron energy. The integrated flux is about 0.8×10^{14} neutrons/s at a power of 50 kW.





Schematic diagrams of neutron capture and total cross section experiments at ORELA.

The energy of an interacting neutron in an experiment is determined by its time of flight. The pulse width of the electron beam from the linac is adjustable from 4 to 30 ns. The pulse repetition rate is variable from 1 to 1000 Hz. At lower energies, the time-of-flight resolution is dominated by moderation effects. At a given energy, the resolution (in microseconds) due to the moderator is roughly given by, $\Delta t_m = 1.5E^{-0.5}$, where the neutron energy E is in units of eV. At higher energies, the resolution is dominated by the pulse width from the accelerator. Typical astrophysics experiments have been run with a pulse width of 7 ns. Under these conditions, the time spreads due to moderation and pulse width from the accelerator are equal at approximately 45 keV. In contrast, the pulse width at the MLNSC spallation source is 125 - 250 ns; hence, the resolution is about 18 - 36 times worse.

Typically, a set of (*n*,γ) and transmission experiments for astrophysics will be run with a pulse width of 7 ns, a power of 7 kW, and a repetition rate of 525 Hz. These operating conditions were chosen to give good resolution at a flux sufficient to complete the experiment in a reasonable time (2-3 weeks), and to ensure good accelerator reliability.

At ORELA, flight path lengths from 9 to 200 m are available. In addition, the beam lines and detector stations are underground to reduce backgrounds.

The very nature of white neutron sources make them ideal for running many simultaneous experiments - at ORELA, neutrons travel down all ten flight tubes where different experiments can be mounted. During typical operation for astrophysics, there are usually 3 different astrophysics measurements running simultaneously at ORELA. Neutron capture cross sections are measured using a pair of deuterated benzene scintillators on beam line 7, at a flight path length of 40 m. At the same time, the total cross section for another sample is measured on beam line 1 using a ^{6}Li-glass detector, at a flight path length of 80 m. In the third simultaneous experiment, the (n,α) cross section for another sample is measured on beam line 2 (or 11) at a flight path length of 9 m. In the future, an (n,n') measurement to determine the SEF for another sample and an (n,γ) measurement using the 4π BaF_2 detector could run as fourth and fifth simultaneous experiments on additional beam lines. All these experiments require the same ORELA operating conditions.

V. SUMMARY

New neutron data are urgently needed to test and improve models of astrophysical objects ranging from red giant stars to supernovae. Advances in precision abundance determinations, recent changes and improvements in stellar models, and the realization of new ways in which neutron experiments yield vital nuclear astrophysics data have all contributed to the need for new experiments. The Oak Ridge Electron Linear Accelerator (ORELA) is uniquely well suited for providing much of the needed neutron nuclear astrophysics data. Recent improvements in experimental techniques at ORELA have made it possible to make measurements with the precision and energy range needed. In addition, ORELA is positioned to serve as an excellent test bed for developing instrumentation for astrophysics experiments at the new spallation neutron sources. In this white paper we have surveyed ways in which experiments at ORELA can contribute to a better understanding of several areas of astrophysics. A common theme has been the fundamental quest to understand the origin of the chemical elements. A related unifying goal was the improvement of the input nuclear physics data so nucleosynthesis signatures of various astrophysical environments can be used to diagnose the inner workings of supernovae and stars.