New Approach for Measuring Properties of *rp*-Process Nuclei

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A new experimental approach was developed that can reduce the uncertainties in astrophysical rapid proton capture (*rp*) process calculations due to nuclear data. This approach utilizes neutron removal from a radioactive ion beam to populate the nuclear states of interest. Excited states were deduced by the γ-decay spectra measured in a semiconductor Ge-detector array. In the first case studied, ^{33}Ar, excited states were measured with uncertainties of several keV. The 2 orders of magnitude improvement in the uncertainty of the level energies resulted in a 3 orders of magnitude improvement in the uncertainty of the calculated ^{32}Cl$(p, \gamma)^{33}$Ar rate that is critical to the modeling of the *rp* process. This approach has the potential to measure key properties of almost all interesting nuclei on the *rp*-process path.

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Type I x-ray bursts are thermonuclear explosions on the surface of a neutron star accreting matter from a companion in a stellar binary system. The fuel, H and He, accretes onto the neutron star surface for hours to days and then ignites in a thermonuclear runaway releasing 10^{39}–10^{40} ergs in 10–100 s [1,2]. Recent observations by the Beppo SAX, RXTE, and CHANDRA satellites have provided a wealth of new data on x-ray bursters [3]. Interpretation of this observational information requires detailed understanding of the underlying nuclear physics.

The bursts are driven by the rapid proton capture process (*rp* process) [4] fusing H and He into heavier elements up to Te. Recent progress in modeling these bursts allows 1D simulations with the full nuclear physics of the *rp* process [5,6]. The predictions of these models depend on accurate nuclear reaction rates [4,7–11]. With accurate nuclear data, the new observations could be the beginning of a precision era in the study of x-ray bursts.

Many rates in the *rp* process are uncertain by several orders of magnitude. To reduce the uncertainties in the rates, experimental information is needed. Direct measurements require copious ($\geq 10^9$ ions/s) amounts of rare isotopes that are available for only a limited number of nuclei. This is particularly true for direct proton capture rate measurements that, despite a decade of research, have so far succeeded in only two cases: ^{21}Na$(p, \gamma)^{22}$Mg [12] and ^{13}N$(p, \gamma)^{14}$O [13]. Therefore, in general, indirect techniques must be used to determine reaction rates.

Transfer reactions with stable beams have been used to determine the level structure of unstable nuclei relevant for proton capture rates. However, transfer reactions with stable beams have limitations because they cannot reach nuclei that are far from stability, because of the difficulty to manufacture targets for certain elements, and because of their selectivity to only a subset of the relevant states. Therefore, most of the proton capture rates along the *rp*-process path are still highly uncertain, and in many cases no experimental information is available. Even in the cases where critical proton-unbound levels have been observed [14], the precision of the extracted resonance energy is on the order of 20 to 100 keV. Since the reaction rate depends exponentially on the resonance energy, such errors still lead to large uncertainties of several orders of magnitude.

In this Letter, we present a technique that allows determination of resonance energies to better than 10 keV leading to dramatic improvements in the accuracy of key reaction rates. We report the first application of our new approach to excited states in ^{33}Ar relevant for the ^{32}Cl$(p, \gamma)^{33}$Ar reaction rate.

X-ray burst simulations have been able to identify the reactions that form bottlenecks or waiting points along the *rp*-process path. These bottlenecks affect further nucleosynthesis leading to heavier nuclei [7]. The rate of ^{32}Cl$(p, \gamma)^{33}$Ar is one such example. Previously, there was no experimental information about the proton-unbound states in ^{33}Ar. The ^{32}Cl$(p, \gamma)^{33}$Ar reaction rate used in previous x-ray burst calculations was entirely based on shell-model calculations [7] with resonance energy uncertainties typically around 100 keV. This uncertainty corresponds to a 3 orders of magnitude variation in the calculated reaction rate at a temperature of 3×10^8 K.

States that dominate the reaction rates at temperatures found in the *rp* process are proton unbound. However, because of the Coulomb barrier unbound states can have lifetimes long enough to decay via γ-ray emission before

particle emission. Provided the proton-unbound states of interest can be populated with an appropriate reaction, the resulting γ rays can be measured yielding information about the level structure. Single neutron removal techniques are well suited to this kind of study since secondary beam rates are higher closer to stability, cross sections are large (several mb per state), and the reaction mechanisms are well understood [15]. A significant advantage of this technique is that its application to astrophysical reaction rates requires only beam intensities of approximately 1000 ions/s, and hence nearly all interesting nuclei can be studied at current facilities.

A secondary beam of typically 400 000 ^{34}Ar ions per second at 84 MeV/nucleon was produced by fragmentation of a 150 MeV/nucleon primary beam of ^{36}Ar by a 1030 mg/cm^2 ^{9}Be target and separated using the A1900 fragment separator [16] at the National Superconducting Cyclotron Laboratory (NSCL). To increase the beam purity an achromatic 240 mg/cm^2 aluminum degrader was placed in the intermediate image plane of the A1900. The ^{34}Ar beam was then transported to the target position of the S800 magnetic spectrograph [17]. The ^{34}Ar beam momentum spread was limited to $\Delta p/p = 0.5\%$.

The S800 was operated in energy-loss, dispersion-matched mode, and was used to measure kinematic properties of the ^{33}Ar nuclei resulting from neutron removal reactions in a 90 mg/cm^2 polypropylene target. Polypropylene has a relatively large areal density of hydrogen, which was used for neutron removal via the (p, d) reaction. In addition, the hydrogen as well as the carbon in the target removed neutrons via the ''knockout'' reaction mechanism [18]. In both reaction mechanisms the population of the final state of the A-nucleon system after neutron removal is proportional to the parentage of that state in the $A + n$ system; therefore, spectroscopic factors, shown in Table I, provided insight into what states are accessible.

The ^{33}Ar ions were detected in the S800 focal plane. Position sensitive detectors measured the position and angle of the ions. The ion momentum and angle after the target were reconstructed using the procedure described in Ref. [19]. A 16 segment ion chamber and a 5 mm plastic scintillator measured energy loss while a second 50 mm plastic scintillator measured total kinetic energy. The ^{33}Ar nuclei were identified in the focal plane of the S800 by their energy loss and time of flight through the spectrograph. Further isotopic separation was obtained by requiring the correct total energy-momentum relationship of ^{33}Ar.

The γ-ray energies and intensities were measured using the segmented germanium-detector array (SeGA) [20] in which the 32-fold segmented germanium detectors are arranged 20 cm from the target in two rings, with five detectors at 37° and nine at 90° with respect to the beam axis. The absolute γ-ray energies were determined by calibrated response of the detectors to known γ-ray energies from standard sources. The γ rays coincident with ^{33}Ar nuclei in the focal plane of the S800 were Doppler corrected into projectile frame decay energies. The γ-ray efficiency was determined using calibrated sources and GEANT simulations to account for the Doppler correction [21]. The in-beam energy resolution and efficiency for the SeGA array was, respectively, 2.5% and 2% at 1359 keV. The measured γ-ray spectrum coincident with ^{33}Ar ions is shown in Fig. 1 (upper part).

TABLE I. ^{33}Ar data and one neutron removal spectroscopic information from ^{34}Ar. The individual columns denote spin and parity J^π, measured energy E (MeV), the intensity I of the γ transitions relative to the 1359 keV level, and this intensity minus feeding F from higher lying states and spectroscopic factors, C^2S, calculated in this work using the USD shell model [23] for one neutron removal from ^{34}Ar. For excited states located above the proton separation energy S_p, the resonance energy E_R, $E - S_p$, (MeV) and single-particle width $\Gamma_{\text{s.p.}}$ (eV) are also shown.

J^π	E	I	$I - F$	C^2S	E_R	$\Gamma_{\text{s.p.}}$
$3/2^+$	1.359(2)	100(14)	46(24)	0.53		
$5/2^+$	1.798(2)	82(12)	77(13)	1.09		
$3/2^+$	2.439(7)	1.4(5)	1.4(5)	<0.01		
$3/2^+$	3.154(9)	2.0(3)	2.0(3)	0.02		
$5/2^+$	3.364(6)	8(3)	8(3)	0.69	0.024	4.28×10^{-39}
$7/2^+$	3.456(6)	2(1)	2(1)	0	0.116	5.72×10^{-15}
$5/2^+$	3.819(4)	47(7)	47(7)	1.31	0.479	1.13×10^{-3}

The energies of the γ-ray transitions were extracted from the measured spectra by least squares fitting of the spectrum using Gaussian shapes on top of a fitted background.

In order to establish the level structure of ^{33}Ar, γ-ray cascades were reconstructed by analyzing γ-γ coincidences. Figure 1 (lower part) shows a sample γ-γ coincidence spectrum. It demonstrates that the 2460 keV transition is in coincidence with the 1359 keV transition. The coincidence data, along with properties of the well-known ^{33}Ar analog nucleus, ^{33}P [14], were used to extract the level structure of ^{33}Ar. The analysis agrees with the previous measurement of the first two excited states by Nann *et al.* [22] who found excitation energies of 1340(20) and 1790(20) keV.

The deduced level diagram of ^{33}Ar is shown in Fig. 2.

The uncertainties in the γ-ray energies shown in Fig. 2 are based on systematic and statistical uncertainties added in quadrature. The systematic uncertainty was determined by measuring the energy of well-known states in nearby nuclei present in the secondary beam. The measured γ rays used for the systematic uncertainty determination were the 466.1(1) keV transition in ^{32}Cl, the 1248.9(2) keV transition in ^{31}S, and the 2090.9(3) keV state in ^{34}Ar. For these states, we obtained 465.7(6), 1249.2(10), and 2091.0(11) keV, respectively. The determination of the number of counts in a peak dominated the

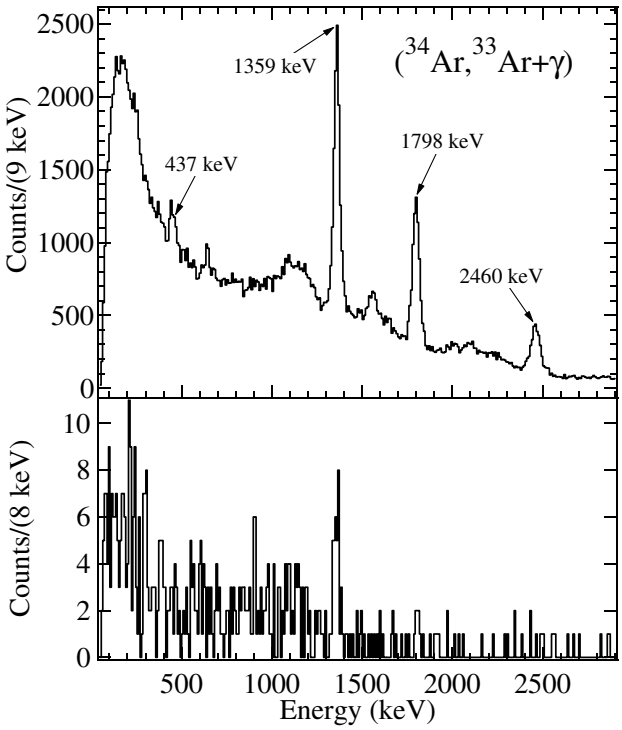

FIG. 1. The upper panel shows the Doppler-corrected γ-ray spectrum coincident with ^{33}Ar ions detected in the S800 focal plane. The lower panel shows the Doppler-corrected γ-ray spectrum in coincidence with γ rays at 2460 keV. Clear evidence for a coincidence between the 1359 and 2460 keV γ rays is seen.

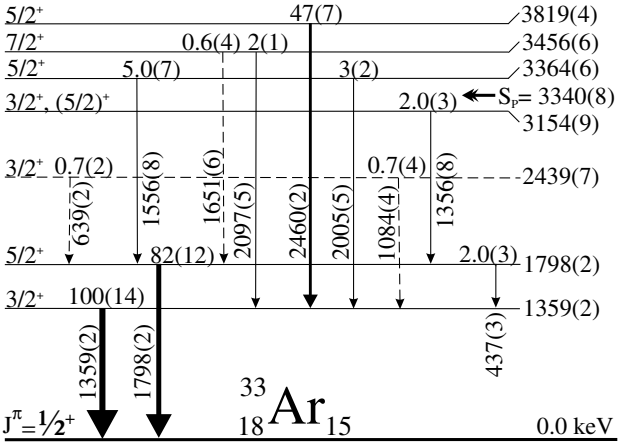

FIG. 2. The ^{33}Ar energy level diagram of this work. Vertical arrows represent observed electromagnetic transitions. Dashed lines and arrows denote weak evidence. Spin and parity (J^π) was determined by analogy with the ^{33}P analog nucleus. Intensities of the transitions relative to the 1359 keV transition are given by a percentage at the top of each arrow. Prior to this work only the 1359 and 1789 keV levels had been observed. S_p denotes the proton separation energy [25,26].

uncertainty in the intensity of the transition. A summary of the measured levels in ^{33}Ar is given in Table I. In addition to the deduced excitation energies Table I also shows the measured intensities relative to the γ decay of the 1359 keV state. The fourth column gives the relative population of the state by subtraction of feeding, F, from higher lying levels.

At the ^{34}Ar beam energy of this experiment, (p, d) transfer and knockout cross sections are expected to be proportional to neutron spectroscopic factors in ^{34}Ar. Column 5 in Table I gives the spectroscopic factors, C^2S, calculated with the Universal sd Hamiltonian (USD) shell model [23]. The trend between columns 4 and 5 suggests that the shell model is able to reasonably reproduce the structure of this nucleus. A measurement of the mirror nucleus, ^{33}P, C^2S values by Khan [24] shows good agreement with our shell-model calculations. The calculated 3.819 MeV state in ^{33}Ar C^2S value is 1.31 while the measured value [24] for the analog state in ^{33}P at 4.047 MeV is 1.48.

In this work, excitation energies of the states that dominate the astrophysical ^{32}Cl$(p, \gamma)^{33}$Ar rate were measured. The results allowed us to use accurate experimental excitation energies in theoretical calculations of the ^{32}Cl$(p, \gamma)^{33}$Ar reaction rate. The USD shell model was used to determine additional parameters such as the spectroscopic factors and gamma widths, Γ_γ [23]. These parameters entered the rate calculations linearly. Spectroscopic factors, single-particle widths, $\Gamma_{\text{s.p.}}$, and gamma widths were taken from [7]. The dependence of Γ_γ on excitation energy is negligible. Single-particle widths have been recalculated with the new excitation energies. The contributions of individual resonances to the reaction rate are shown in Fig. 3.

The total rate is dominated by the $J^\pi = \frac{5}{2}+$, $E_R = 0.479$ MeV resonance at rp-process temperatures, $(3\text{–}8) \times 10^8$ K.

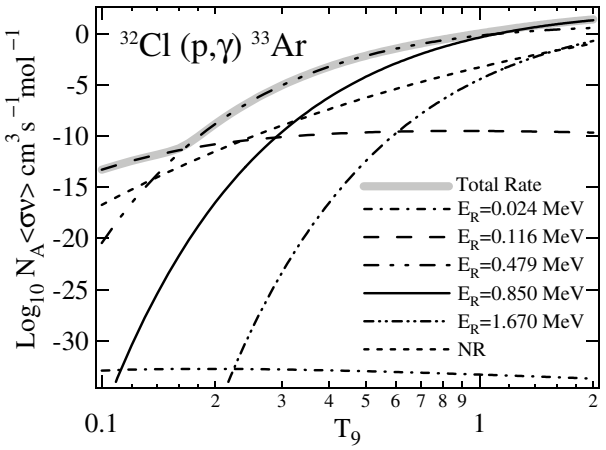

FIG. 3. The astrophysical ^{32}Cl$(p, \gamma)^{33}$Ar ground state capture reaction rates as a function of temperature, T_9, in GK. Contributions from individual resonances and the sum of all direct capture contributions (nonresonant) are shown.

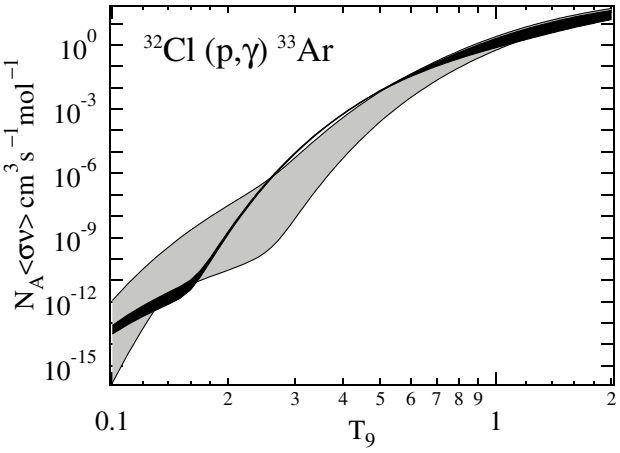

FIG. 4. The total astrophysical ^{32}Cl(p, γ)^{33}Ar ground state capture rate based on this work (black) and Ref. [7] (grey). Only uncertainties from excitation energies are shown. The grey shaded region shows the possible range of rates based solely on the shell model assuming a typical uncertainty in excitation energy of 100 keV. The region in black is the rate uncertainty based on the measured excitation energies presented in this Letter.

The new rate is an order of magnitude larger around 3×10^8 K compared to the shell-model rate in Ref. [7].

The 2 orders of magnitude improvement in the uncertainty in the energy of the levels yields a dramatic improvement in the accuracy of the reaction rate, Fig. 4. At the most relevant temperature of 0.3 GK, where the ^{32}Cl lifetime against proton capture at typical densities of 10^6 g/cm^3 becomes comparable to burst rise time scales and β-decay lifetimes (both 0.1–1 s), the accuracy of the rate was improved by 3 orders of magnitude. As a result of this work, the contribution of the uncertainty in the excitation energy is no longer the dominant contribution to the total uncertainty of the reaction rate for the temperature range of interest. The uncertainty in the Q value [25,26] is approximately 8 keV and contributes little to the total uncertainty. The remaining uncertainty in the rate is due to uncertainties in the calculated shell-model quantities and amounts to approximately a factor of 2 over the entire temperature range. Thus, the total new uncertainty of the ^{32}Cl(p, γ)^{33}Ar rate is now within a factor of 2–3 over the entire relevant temperature range.

Our discussion so far has been limited to improvements of the ground state capture rate given in [7]. However, at rp-process temperatures the first excited state in ^{32}Cl at 89.9 keV is significantly populated. We performed a calculation using our experimental results and found that the addition of the first excited state reduces the effective capture rate by no more than a factor of 2. Details and a complete discussion of the recommended stellar ^{32}Cl(p, γ) rate will be given in a forthcoming paper.

In summary, a new approach for measuring properties of neutron deficient rp-process nuclei has been reported. This approach has the potential to measure key properties of almost all interesting nuclei on the rp-process path. As a first measurement the astrophysically interesting nucleus ^{33}Ar was studied and a new, much more accurate ^{32}Cl(p, γ)^{33}Ar rate was determined. To measure astrophysically important states that decay by proton emission, a complementary technique detecting deuterons from the (p, d) reaction is being developed. These developments are an important step towards a reliable nuclear database for quantitative x-ray burst calculations. Such a database could form a starting point for systematic sensitivity studies to identify key reactions that need to be known with higher precision for follow-up studies.

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