Halflife measurements of the rp-process nuclei $^{61}$Ga, $^{63}$Ge, and $^{65}$As

J.A. Winger $^a$, D.P. Bazin $^{a,1}$, W. Benenson $^{a,b}$, G.M. Crawley $^{a,b}$, D.J. Morrissey $^{a,c}$, N.A. Orr $^a$, R. Pfaff $^{a,b}$, B.M. Sherrill $^{a,b}$, M. Steiner $^{a,b}$, M. Thoennessen $^{a,b}$, S.J. Yennello $^a$ and B.M. Young $^{a,b}$

$^a$ National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, MI, 48824-1321, USA
$^b$ Department of Physics and Astronomy, Michigan State University, East Lansing, MI, 48824-1321, USA
$^c$ Department of Chemistry, Michigan State University, East Lansing, MI, 48824-1321, USA

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Using the A1200 beam analysis device at the National Superconducting Cyclotron Laboratory, we have measured the halflives of several nuclei along the rp-process path near the proton-drip line. Halflife results for $^{61}$Ga, $^{63}$Ge, and $^{65}$As ($0.15 \pm 0.03$ s, $95 \pm 23$ ms, and $0.19 \pm 0.01$ s, respectively) and their implications for the rp-process are presented.

A great deal of interest has been shown in proton-drip line nuclei in the $60<A<100$ mass range, in part due to their role in determining the astrophysical rapid proton capture (rp-) process path [1]. By measuring the halflives and binding energies of these nuclei, the path and extent of the process can be determined. Certain of these nuclei, $^{65}$As and $^{69}$Br, are particularly important since they are candidates for the rp-process termination point [2-6]. If these nuclei are stable to proton emission, then the rp-process, illustrated for this region in fig. 1, will proceed through them by proton capture followed by proton capture or beta decay. However, if they proton decay, the process will terminate, or at least be greatly hindered, due to the long halflife ($>60$ s) of their proton-capture precursor relative to the expected time scale ($\sim 10$ s) of the rp-process. This occurs because the slow beta-decay rate for the proton-capture precursor ($^{64}$Ge or $^{68}$Se) does not provide sufficient daughter nuclei ($^{64}$Ga or $^{68}$As) to be processed by proton capture, a fast process, to higher mass nuclei. Since various mass predictions [7] disagree on whether these nuclei are bound, experiments are necessary to determine their primary decay modes. A number of experiments have attempted to measure ground-state proton decay for $^{65}$As and $^{69}$Br [5,9,10], but each gave no result. The recent observation of six new nuclei, including $^{65}$As and $^{69}$Br, by Mohar et al. [6] did not require them to be proton bound, but only required the halflife to be on the order of the flight time of the ion through the experimental system. In the present experiment, we were able to produce, identify, and measure the beta-decay halflife of $^{65}$As as well as those of $^{61}$Ga and $^{63}$Ge.

Radioactive isotopes were produced by fragment-
ing an $E/A = 75$ MeV $^{78}$Kr beam by an enriched $^{58}$Ni target ($\sim 105$ mg/cm$^2$) with a $3$ mg/cm$^2$ aluminum backing to provide a higher percentage of fully stripped ions. Fragments within $\pm 1.5\%$ of the peak momentum for the $Z \approx 30$, $T_z = -\frac{1}{2}$ nuclei were selected in the first half of the A1200 using the high acceptance mode [11]. A curved plastic achronmatic degrader wedge [12] ($C_9H_{10}$, $\sim 100$ mg/cm$^2$), placed at the second dispersive image, reduced the number of different isotopes arriving at the A1200 focal plane from more than 150 to less than 30. Four settings for the second half of the A1200 were used successively to implant $^{61}$Ga, $^{62}$Ga, $^{63}$Ge, and $^{65}$As fragments into a Si detector telescope placed at the A1200 focal plane which was surrounded by a segmented plastic scintillator beta detector. Two position-sensitive parallel plate avalanche counters, one placed 37 cm upstream and one 5 cm downstream of the achronmatic degrader wedge at the second dispersive image, coupled with NMR measurements of the dipole fields provided a measure of the rigidity of each ion. Two thin plastic scintillators ($\sim 10$ mg/cm$^2$) separated by $\sim 14$ m provided a measure of the time-of-flight (TOF).

The Si detector telescope consisted for four detectors: $\Delta E_1$ and $\Delta E_2$, which provided redundant $Z$ identification; $E_v$, in which the ions were stopped and in which decay protons could be observed; and $E_s$, which was used to reject any ions not stopping in $E_v$. These detectors were calibrated with the primary beam as well as a range of known fragments from $Z=14$ to 36. Variation due to the large momentum acceptance of the system required the energy losses, total energy, and TOF of each ion to be compensated for rigidity, dispersive angles, pathlength, and final position. These compensations allowed unambiguous identification of individual particle groups on which software conditions could be set to insure selection of a single isotope.

The beta detector consisted of a hollow inner cylinder of plastic scintillator 17 cm long with a 5 cm inner diameter and a 3 mm wall thickness which was surrounded by a $16 \times 16 \times 19$ cm$^3$ plastic scintillator block with a 6.5 cm diameter hole cut along the major axis. The outer scintillator block was sectioned into quadrants along the major axis to create individual detectors of approximately $8\times8\times19$ cm$^3$ which acted both as beta-particle detectors and a cosmic-ray shield. The Si detector telescope was held inside the beta detector by means of a thin copper cylinder ($\sim 1$ mm thick) which provided detector cooling and acted as a filter for low-energy beta particles. Although filtering decreased the overall detection efficiency, it prevented the system from detecting beta particles arising from long-lived, low-$Q_p$ nuclei that accumulated in the detector. Background events in the beta detectors, for example from external cosmic rays and internal gamma rays, were reduced by a fast coincidence circuit that required any valid beta event to trigger the inner cylinder and only one of the outer quadrants, and by setting upper and lower software thresholds on each detector’s energy spectrum.

The implantation rate for the $T_z = -\frac{1}{2}$ nuclei of only a few per minute compared to an overall implantation rate of $\sim 1000$ ions/second required a beam-on/beam-off cycle [13] in which the beam was interrupted by the data acquisition computer only when a fragment’s energy loss ($\Delta E_1$) and TOF were within a specified software acceptance window. During the beam-off period, all events triggering the beta detector were accepted even though this resulted in multiple events, due to the presence of background, associated with each implantation. To measure the background rate, the acceptance window was set to include some $N=Z$ nuclei.

A measurement of the half-life of $^{62}$Ga ($116.12$ ms [14,15]) was used to test the system. Using a single setting of the system (spectrometer and acceptance window), data were obtained for $\sim 11000$ $^{62}$Ga and $\sim 7000$ $^{64}$Ge implanted ions with a beam-off period of 500 ms. The rate of background events within the beam-off period was constant independent of the nucleus which arrived within the acceptance window. Therefore the background rate could be determined from the ratio of decay to implantation events ($R_b$) associated with $^{64}$Ge ($Q_p=4.41$ MeV [16], $t_{1/2}=63.7$ s [17]) since decays from this nucleus should not trigger the beta detector. An estimate of the detection efficiency of the system ($\epsilon_d$) for beta particles emitted by $^{62}$Ga can be made by taking the ratio of decay to implantation events associated with $^{62}$Ga and subtracting the measured background ratio ($R_b$) from $^{64}$Ge. The software thresholds were then adjusted to optimize $\epsilon_d$ ($\sim 14\%$) relative to $R_b$ ($\sim 23\%$). Since the $T_z = -\frac{1}{2}$ nuclei studied will have similar beta spectra to $^{62}$Ga, ground-state to ground-state transitions with $Q_p \sim 9$–10 MeV, it is expected that they will
have similar detection efficiencies. The $^{62}$Ga decay spectrum obtained was analyzed using a maximum likelihood method in which the expected number of counts in each channel of the spectrum, given by a Poisson distribution, was obtained by integrating an exponential decay (with half-life $t_{1/2}$ and initial activity $A_0$) added to a constant background ($B_0$). All three parameters could be fit independently or held fixed, and the uncertainties ($\pm \sigma$) were determined from the value with which the likelihood value increased by one for variation of a given parameter with the others held fixed. The relatively high background level required that $B_0$ be held fixed in order to obtain a reasonable value for $t_{1/2}$. Consequently, the background level was first established using the measured Rb value from the $^{64}$Ge data then used to analyze the $^{62}$Ga decay spectrum giving a half-life of $113_{-6}^{+7}$ ms in good agreement with the literature value.

The background levels used for the other decay spectra were obtained by a weighted average of the Rb values from analysis of the $^{64}$Ge spectra and the $^{62}$Ga spectra in which $t_{1/2}$ was fixed to the literature value. The $R_b$ value, which varied depending on the field setting for the second half of the A1200 and/or the $\Delta E$/TOF acceptance window, was determined for each setting. Combining these $R_b$ values with the number of implantations for each isotope at a given setting and summing over all settings provided the total number of expected background events which was then divided by the beam-off time period to fix the $B_0$ value used in analyzing the decay spectra. Halflife values obtained for the $T_{1/2} = -\frac{1}{2}$ nuclei were $0.15\pm0.03$ s for $^{61}$Ga, $95_{-23}^{+23}$ ms for $^{63}$Ge, and $0.19_{-0.07}^{+0.1}$ s for $^{65}$As. These results, along with the total number of implantations, and derived $R_b$ and $\epsilon_d$ values for each isotope, are presented in table 1. The total $R_b$ values differ due to variation in the background for various settings of the system and the overall buildup in activity over the course of the experiment whereas the $\epsilon_d$ values are expected to depend only on the spectrum of emitted beta particles. The measurement for $^{66}$As provided a test of the validity of the method for a low statistics case with the halflife obtained ($0.10_{-0.07}^{+0.07}$ s) in good agreement with the literature value ($95.77\pm0.23$ ms [14,18]). Fig. 2a is the summed decay spectrum for $^{64}$Ge with the solid line showing the extracted background level. Within $2\sigma$ the background can be represented by a constant

<table>
<thead>
<tr>
<th>Nucleus</th>
<th>Total implants</th>
<th>$R_b$</th>
<th>$\epsilon_d$</th>
<th>$t_{1/2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{62}$Ge</td>
<td>22813</td>
<td>0.328$\pm$0.04</td>
<td>0.142$\pm$0.03</td>
<td>0.113$^{+0.03}_{-0.05}$</td>
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<td>$^{61}$Ga</td>
<td>972</td>
<td>0.180$\pm$0.02</td>
<td>0.134$\pm$0.02</td>
<td>0.153</td>
</tr>
<tr>
<td>$^{63}$Ge</td>
<td>1219</td>
<td>0.308$\pm$0.04</td>
<td>0.11$\pm$0.02</td>
<td>0.095$^{+0.02}_{-0.03}$</td>
</tr>
<tr>
<td>$^{65}$As</td>
<td>634</td>
<td>0.397$\pm$0.06</td>
<td>0.14$\pm$0.02</td>
<td>0.19$^{+0.02}_{-0.03}$</td>
</tr>
<tr>
<td>$^{66}$As</td>
<td>545</td>
<td>0.382$\pm$0.05</td>
<td>0.08$\pm0.03$</td>
<td>0.10$^{+0.01}_{-0.02}$</td>
</tr>
</tbody>
</table>

Table 1

Halflife results from the decay spectra analysis. Information on the total number of implanted ions, and derived $R_b$ and $\epsilon_d$ values are given for reference. The superscripted and subscripted values indicate the corresponding plus and minus $\sigma$ uncertainties, respectively, in the last digits.

Fig. 2. Summed decay spectra for the indicated nuclei. (a) $^{64}$Ge data with the solid line indicating the extracted background level. (b)-(f) decay spectra for $^{62}$Ga, $^{61}$Ga, $^{63}$Ge, $^{65}$As, and $^{66}$As, respectively, where the solid line represents the total decay curve and the dashed line indicates the background level.

**value. Figs. 2b-2f are the decay spectra for the indicated isotopes with the total decay curve shown as a solid line and the background level shown as a dashed line.**
The present experimental result indicating that $^{65}$As decays by beta emission as opposed to proton emission is very significant. This conclusion is supported not only by our observation of a beta-decay spectrum and a detection efficiency close to that of $^{62}$Ga, but also by the fact that we observed no evidence for ground-state proton decay within the $E_\gamma$ detector during the experiment. Since Coulomb barrier effects will allow $^{65}$As to live long enough to beta decay, even if it is proton unbound, it is interesting to examine the limits which the current halflife measurement sets on the mass excess of $^{65}$As. The proton separation energy, $S(p)$, must be greater than $-250$ keV since proton emission does not appear to compete with the beta decay [5]. When taken in combination with the mass excess of $^{64}$Ge ($-54.43 \pm 0.25$ MeV [16,19]), this places an upper limit on the $^{65}$As mass excess of $-46.89 \pm 0.25$ MeV. This compares well with a Coulomb displacement model [20] calculation which predicts a mass excess of $-46.75 \pm 0.10$ MeV ($S(p) = -0.4 \pm 0.3$ MeV). In both cases, the uncertainty in $S(p)$ is dominated by the uncertainty in the $^{64}$Ge mass. Using a shell-model calculation based on the F5P interaction with no restrictions [21,22] and assuming the beta decay to be between the $\frac{3}{2}^-$ mirror ground states of $^{65}$As and $^{65}$Ge, an $f_\beta$-value of 4800 s is obtained. This $f_\beta$-value is dominated by the Fermi transition between $T = \frac{1}{2}$ isospin states ($B(F) = 1$, $B(GT) = 0.3$) and provides an estimate for $Q_\beta$ of 9.1 $\pm$ 0.8 MeV which is in good agreement with the values predicted by various mass models [7,19]. Combined with the mass excess of $^{65}$Ge ($-56.41 \pm 0.10$ MeV [19]), this $Q_\beta$ value indicates $^{65}$As mass excess of $-47.3 \pm 0.8$ MeV ($S(p) = 0.2 \pm 0.8$ MeV). Although the uncertainties are large, the implication is that $^{65}$As is either bound with respect to proton emission or unbound by such a small amount that beta decay dominates.

The implications of this result for the rp-process center mainly on its termination point. As stated above, $^{65}$As may be unbound to proton emission by up to $\sim 250$ keV. However, because its halflife is dominated by beta decay, the rp-process will proceed through $^{65}$As primarily by proton capture to the proton bound nucleus $^{66}$Se even though photodisintegration may begin to play an important role if $^{65}$As is proton unbound [8]. (See fig. 1.) Therefore, $^{65}$As will not cause the rp-process to terminate at $^{66}$Ge, but rather provides the path to higher masses without significantly slowing the process. Final determination of the rp-process termination point will depend on a measurement of the halflife of $^{69}$Br as there are indications that the processing of nuclei will be slowed significantly at $^{72}$Kr due to $^{72}$Rb being unbound with respect to proton emission [6,23]. As shown in fig. 1, $^{61}$Ga, $^{63}$Ge, and $^{65}$As all lie along the rp-process path. The halflife of $^{63}$Ge is important in determining the cycle time for this process path, while $^{61}$Ga and $^{65}$As provide a path to higher mass nuclei by fast proton capture to the proton-bound nuclei $^{65}$Ge and $^{66}$Se, respectively. By measuring the beta-decay halflife of $^{65}$As, we have shown that the rp-process will proceed beyond $^{64}$Ge without being significantly slowed. While future experiments are planned to extend the measurement of $T_\beta = \frac{1}{2}$ halflives up to $^{69}$Br as well as improve the accuracy of the present results, other experiments will eventually be needed to measure the masses and structure of these nuclei.

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References