A hybrid surface arc discharge ion source to produce ultra pure Ca^{+2} beams for $^{40}Ca(\alpha,\gamma)^{44}Ti$ reaction studies at ISAC/TRIUMF[a)]

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ISAC is an accelerator facility primarily dedicated to astrophysical studies. Off-line and online ion sources provide up to 65 keV of stable and radioactive beams to the ISAC accelerators. Initial acceleration is done via a constant velocity radio frequency quadrupole that requires 2 keV/u. Then the beam is further accelerated to 1.5 MeV/u at ISAC-I and 6.5 MeV/u at ISAC-II. To study radiative capture reactions relevant for astrophysics, the recoil mass spectrometer DRAGON was built in the experimental area. $^{40}Ca(\alpha,\gamma)^{44}Ti$ is identified as one of the key reactions in supernovae to produce ^{44}Ti and is given highest priority. For this experiment, an ultrapure Ca^{+2} beam was requested from the off-line ion source. Initial tests showed that, when using conventional ion sources, ^{40}Ar and ^{40}K are the impurities that are most difficult to eliminate. In order to overcome this problem, a new concept was needed and the hybrid surface arc discharge ion source was born. The hybrid surface ion source consists of a small surface ionizer and an arc discharge placed in a solenoid field. A very low ratio of $^{40}Ar/^{40}Ca=8\times10^{-5}$ was achieved with this new source and the experiment was completed successfully. The source is described in detail and its performance is discussed in this article. © *2008 American Institute of Physics.*
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INTRODUCTION

The study of supernovae became an important field in understanding the universe, which uncovered many secrets. It was found that in supernovae about half of the heavy ions were synthesized. Space-based γ-ray studies provide a large amount of knowledge about nucleosynthesis in supernovae. The detection of the 1.157 MeV γ-ray line in supernova remnant Cas A[1] proved the abundance of the short-lived nuclide ^{44}Ti (half-life of 58.9 years) and increased the necessity to study its production thoroughly. ^{44}Ti is mainly produced in the alpha-rich freeze-out of a core collapse supernovae. Therefore, the $^{40}Ca(\alpha,\gamma)^{44}Ti$ experiment[2] was proposed at the recoil mass spectrometer DRAGON[3] at ISAC[4] and obtained highest priority. Subsequently a ^{40}Ca beam was requested with the highest purity from the off-line ion source.

Since the ISAC radio frequency quadrupole (RFQ)[5] accepts only 2 keV/u beam and the beam line is limited to 60 kV, a $^{40}Ca^{+2}$ beam or higher charge must be provided by the source. A high purity $^{40}Ca^{1+}$ beam can be provided using a surface ion source, but the ISAC requirement demands multicharge ions. To produce multicharge ions a plasma source is usually needed. The problem is that ^{40}Ar is plenty in the residual vacuum and ionizes easily. The source of ^{40}Ar is abundant in most vacuum systems especially when the vacuum system is made of welded aluminum boxes. Argon gas was used as the background gas during the welding process. The other obstacles are $^{20}Ne^{+1}$ and $^{40}K^{+2}$. Existing plasma-type ion sources are not adequate enough to produce high purity Ca^{+2} beams.

SOURCE CONCEPT AND PERFORMANCE

Ca^{+1} ions with first ionization potential of 6.113 eV can be produced using a simple surface-type ion source. Due to a high efficiency of the surface ion source for $^{40}K^{+1}$ with first ionization potential being 4.341 eV, it may also be a potential contaminant even though ^{40}K abundance is very low in natural isotopic ratio. On the other hand, ISAC requires multicharge ions over mass 30. However, multicharge ions can be usually produced only by plasma ion sources since the surface ionization is not sufficient enough to produce Ca^{+2} with the second ionization potential at 11.871 eV. A test from the microwave ion source[6] showed that ^{40}Ar impurities are unacceptably high at $M/Q=20$ and a desire to develop a new type of ion source had arisen.

On the other hand, first and second ionization potentials of Ar are 15.75 and 27.629 eV, respectively. If one can create an ion source with a controlled electron temperature, it is possible to minimize $^{40}Ar^{+2}$ contamination in the $^{40}Ca^{+2}$ beam. The $^{40}K^{+2}$ beam can also be suppressed because of its second ionization potential, which is equal to 31.625 eV. Therefore, a solenoid field and an arc discharge were added to the surface ion source in order to boost up the electron temperature in the plasma in a controlled manner. Figure 1

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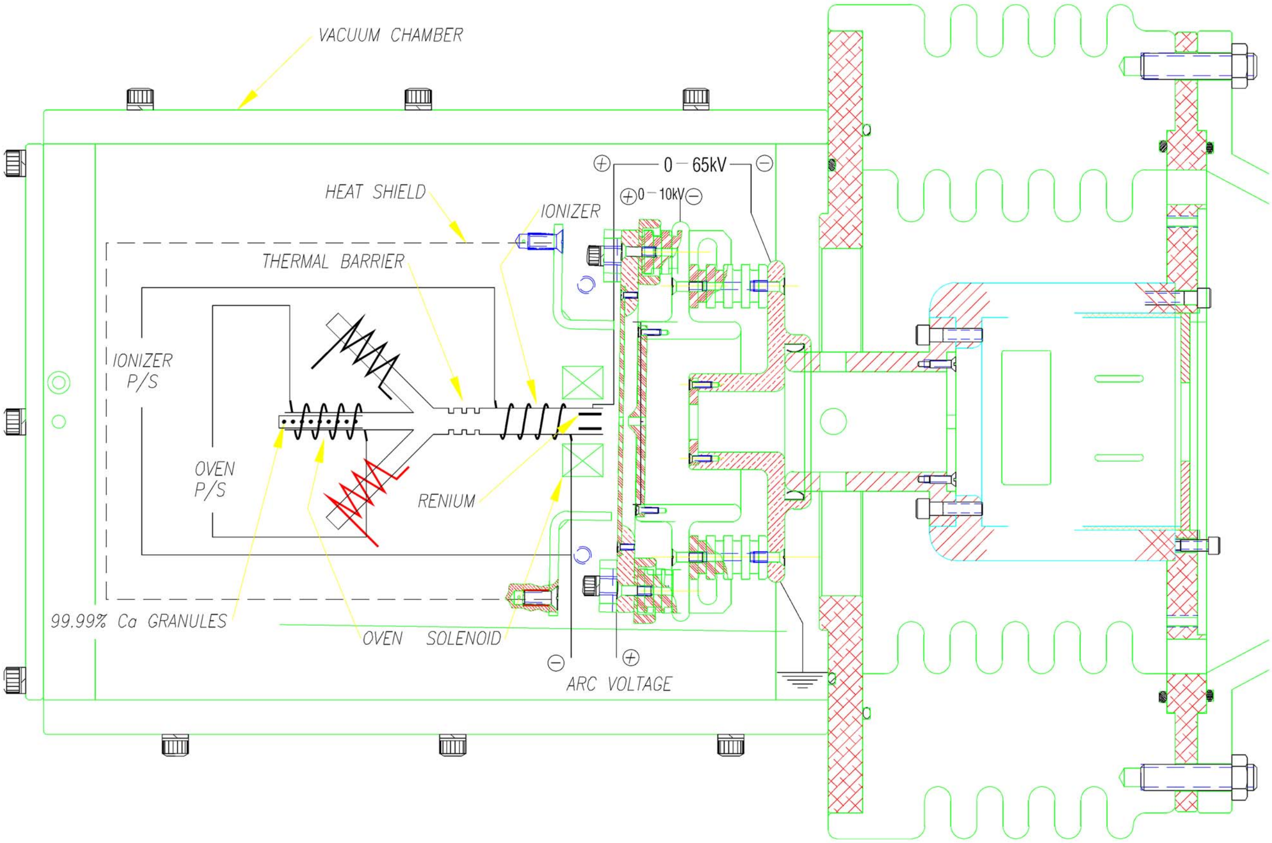

FIG. 1. (Color online) The schematic of the hybrid arc discharge ion source with three ovens to cover three different temperature regions. Three-electrode extraction system is design to produce low emittance from 6 to 60 kV beam energy.

shows the schematic of the ion source. The arc voltage and the axial magnetic field were optimized to maximize the Ca^{+2} beam. Research grade He gas was injected and optimized for best performance.

Figure 2 shows a M/Q spectrum at 40 kV extraction voltage. The doubly charged Ca ion beam is as high as singly charged ions. When the arc voltage was switched off, the single charged ions increased three times. It clearly shows that the efficiency of boosting +1 to +2 is very high and the estimated efficiency value is around 50%.

For emittance measurements, an improved version of electric sweep scanner (ESS) originally proposed by Allison[7] was used. It contains a pair of 76 mm long electric deflection plates located in between a pair of 0.025 mm slits. The slits were aligned with highest accuracy possible using a laser interference diagram. Figure 3 shows the emit-

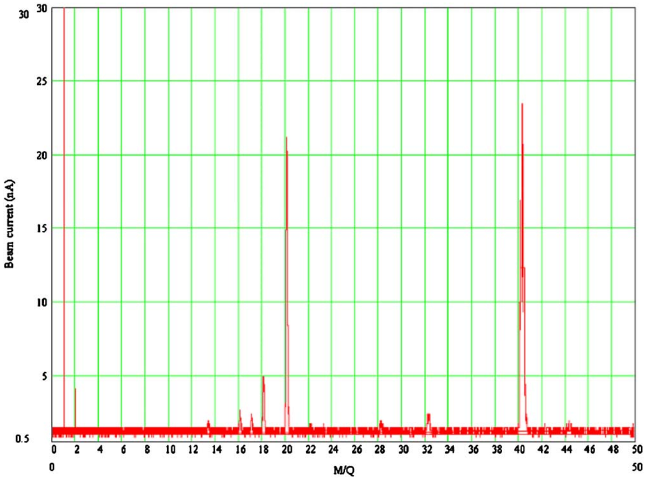

FIG. 2. (Color online) A M/Q spectrum at 40 kV extraction.

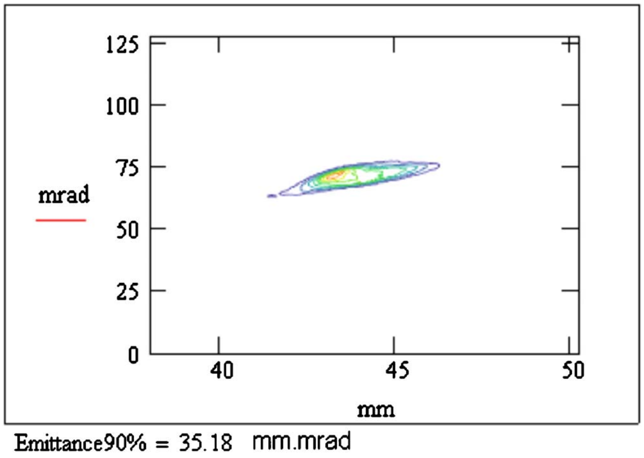

FIG. 3. (Color online) Emittance profile from the hybrid ion source for $^{40}Ca^{+2}$ beam.

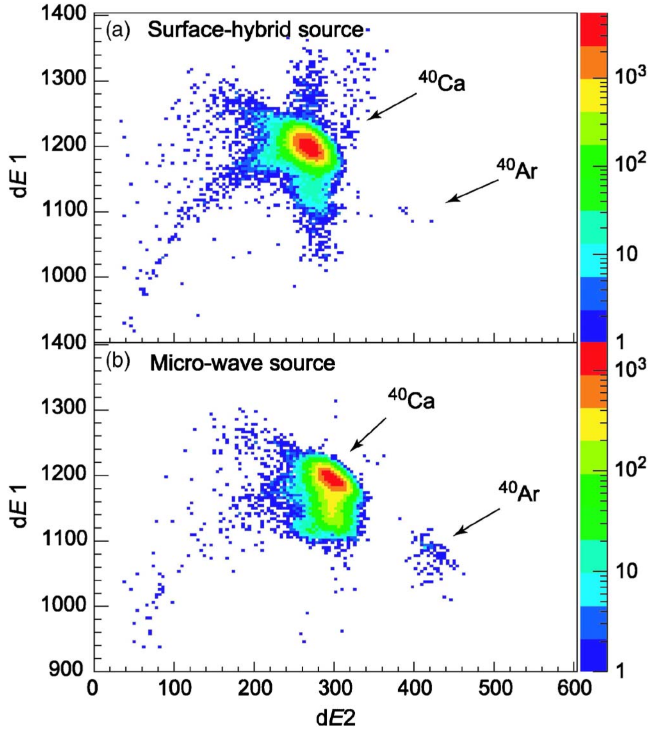

FIG. 4. (Color online) Beam contamination from the OLIS hybrid surface arc discharge ion source. A ^{40}Ar/^{40}Ca ratio of 8×10^{-5} for the hybrid surface ion source (above) and 5×10^{-3} for the microwave ion source (bellow) was measured using an attenuated beam in the DRAGON ionization chamber. The pileup and peak distortions are visible due to the high count rate.

tance profile from the hybrid surface ion source for the ^{40}Ca^{+2} beam which is much less than the ISAC accelerator acceptance.

Beam contamination from the ion source can only be measured at high energy in an ionization chamber at the end of the recoil mass separator, since the mass difference is less than 10^{-5} amu. A ^{40}Ar/^{40}Ca ratio of 8×10^{-5} for the hybrid surface ion source was measured using an attenuated beam in the DRAGON ionization chamber (see Fig. 4), whereas the microwave ion source gave much higher values ($>5\times10^{-3}$). No indication of ^{40}K contamination was found.

The current for the ^{40}Ca^{+2} beam was about 10–50 nA, enough to successfully perform the ^{40}Ca$(\alpha,\gamma)^{44}$Ti experiment[8] which needed several weeks of beam time. Figure 5 shows a sample spectrum where the ^{44}Ti recoils from the ^{40}Ca$(\alpha,\gamma)^{44}$Ti reaction are clearly identified. The yield for ^{44}Ti is very low at the astrophysical relevant energies $E_{\mathrm{lab}}=0.6-1.13$ MeV/u ($Y=10^{-10}$ down to 10^{-14}).

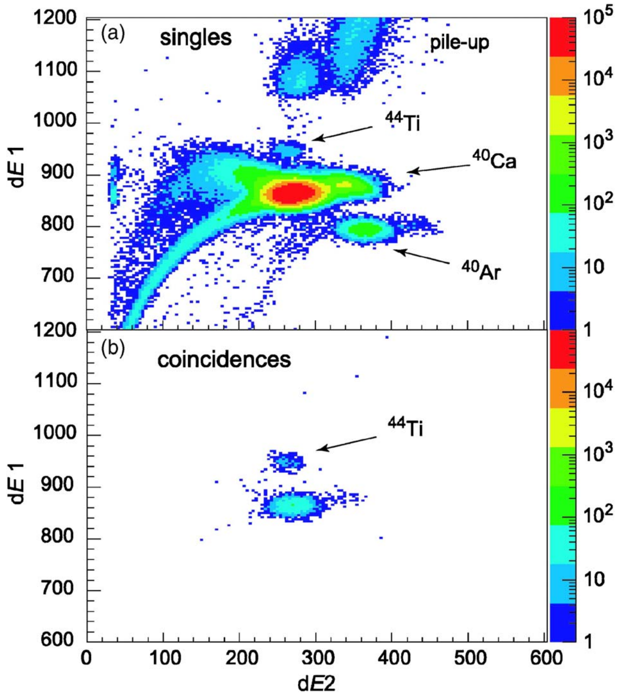

FIG. 5. (Color online) The ^{44}Ti recoils at the resonances at 9.2 MeV were measured at the rate of ~3500 s^{-1} in the ion chamber at DRAGON. The main peak is a leaky ^{40}Ca beam through the recoil separator.

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