Production of new radioactive beams ^{42}Ti, ^{35}K, ^{9}C, ^{8}B, and ^{20}O with MARS

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This year we produced and separated several new radioactive beams for the physics program at the Cyclotron Institute at Texas A&M University with the Momentum Achromat Recoil Separator (MARS) [1]. While the production tests for ^{35}K, ^{9}C, and ^{8}B were more or less straightforward, the production tests of the new ^{42}Ti and ^{20}O beams were challenging. Details about the production and separation of each of these beams are provided in this report. All of the beams in this report will be used in experiments in the coming year.

I. Production of ^{42}Ti secondary beam

In November 2013, we studied the production and separation of ^{42}Ti with MARS for the group of Prof. J.C. Hardy. ^{42}Ti is needed as part of his research group's continuing study of the lifetime and branching ratios for superallowed β-decays.

The nuclei for the superallowed β-decay studies are usually produced with the fusion-evaporation reaction (p,2n) in inverse kinematics with primary beam energies around 30 MeV/u. However, this reaction is not available in the case of ^{42}Ti because it is too far from the valley of stability in this region of the nuclear chart (A > 40). If a ^{45}Sc primary beam is used with the hydrogen gas target, the reaction p(^{45}Sc,^{42}Ti)4n requires much higher primary beam energy (> 50 MeV/u) and would produce ^{42}Ti at energies too high to be stopped efficiently inside the tape-transport system used for studying the superallowed β-decays. Further, ^{45}Sc primary beam is known have a relatively weak intensity, in particular when a high charge state is needed to produce this beam at this energy with the K500 cyclotron. Another possible method to produce ^{42}Ti beam would be to employ a high energy beam such as ^{50}Cr at 50 MeV/u with a thick ^{9}Be target and produce ^{42}Ti with the projectile fragmentation reaction mechanism. However, this method, in addition to the high energies and weak beam intensities mentioned in the previous case, is also not a good choice because additional contamination from nuclei close to the ^{42}Ti would be produced with similar or higher intensities than the ^{42}Ti.

Thus, with the above considerations in mind, we decided to attempt to produce ^{42}Ti with ^{40}Ca primary beam and gas targets of ^{3}He and ^{4}He. ^{40}Ca beam is available with high intensity at beam energies from 5-40 MeV/u. Simulations of the ^{40}Ca+^{3}He and ^{40}Ca+^{4}He reactions were conducted with the LISE++ program [2] prior to the production test. These simulations suggested that ^{42}Ti would be produced with the most intensity at low beam energies (~10-15 MeV/u) with the fusion-evaporation reaction mechanism, but also that it would still be possible to produce ^{42}Ti with reasonable intensity at higher primary beam energies with the direct-transfer reaction mechanism. Given that a primary beam of at least 30 MeV/u is needed to implant the ^{42}Ti secondary beam into the tape-transport system, a primary beam energy of 32 MeV/u was chosen for the production test.

The results of the production tests for ^{4}He(^{40}Ca,^{42}Ti)2n and ^{3}He(^{40}Ca,^{42}Ti)n at 32 MeV/u are shown in Fig 1. ^{42}Ti was produced and separated with MARS in both reactions. For the ^{40}Ca+^{4}He case, with 2 atm of ^{4}He gas at a temperature of 77 K in the MARS gas cell target, ^{42}Ti was produced at a rate of 7 events/nC. In that case, about 50% of the total secondary beam was made up of impurities, with the most intense contribution coming from ^{40}Sc produced at ~30% of the rate of the ^{42}Ti. For the ^{40}Ca+^{3}He case, with 1 atm of ^{3}He gas at a temperature of 77 K in the MARS gas target, ^{42}Ti was produced at a rate of 6.3 events/nC. This implies that the production rate with the ^{3}He gas target could be higher than the ^{4}He case if 2 atm of ^{3}He gas were to be used. However, in the ^{3}He target case, impurities in the secondary beam made up 63% of the total secondary beam intensity. Also, ^{40}Sc was produced in this case at a slightly higher rate (~7% higher) than the ^{42}Ti. Therefore, the ^{4}He(^{40}Ca,^{42}Ti)2n production reaction was favored by Prof. Hardy's research group as it produced ^{42}Ti at an acceptable rate of ~1400 particles/sec (assuming ~200 nA of ^{40}Ca primary beam) and with less impurities in the secondary beam.

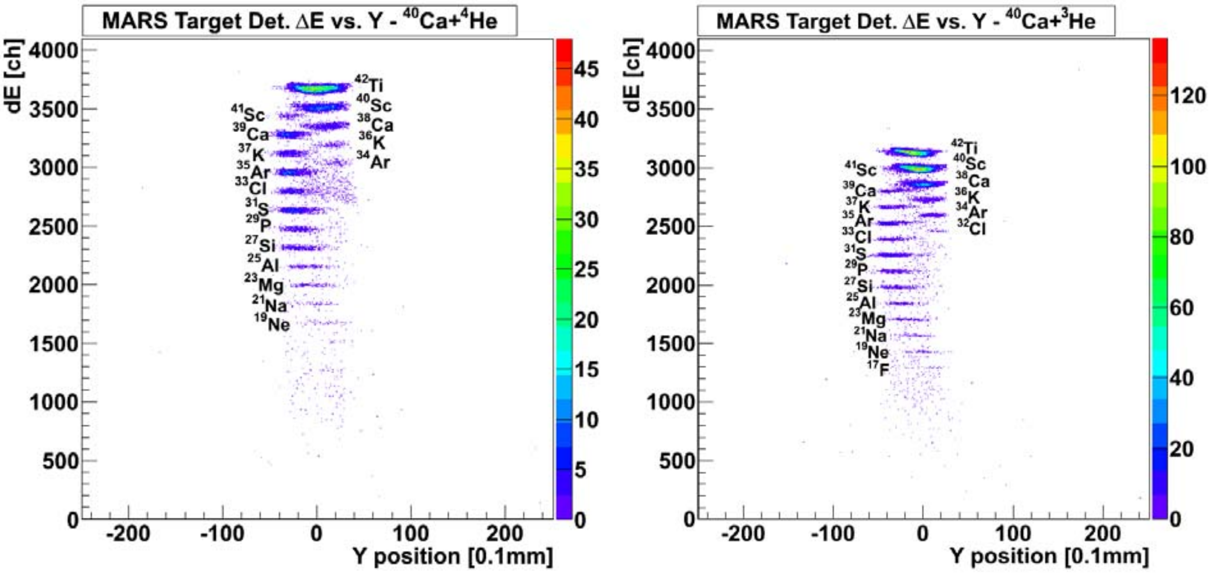

FIG. 1. (left panel) Results of the ^{42}Ti production test with the ^{40}Ca+^{4}He reaction. Impurities in the secondary beam are also labeled. (right panel) Results of the ^{42}Ti production test with the ^{40}Ca+^{3}He reaction. In the latter case, the impurities were found to be more intense.

Prof. Hardy's research group made a preliminary measurement of the ^{42}Ti lifetime during this production test. The details of that measurement are given in a separate report [3].

II. Production of ^{35}K secondary beam

In March 2014, we produced and separated ^{35}K with MARS. ^{35}K is needed by the group of Prof. R.E. Tribble for the latest experiment in the series of measurements of β-delayed proton decay of proton-rich nuclei [4]. The ^{35}K was produced with the fusion-evaporation reaction (p,2n) in inverse kinematics with ^{36}Ar primary beam at 35 MeV/u. Hydrogen gas at a pressure of 2 atm and at a temperature of 77K was used in the MAS gas cell target.

In the planned experiment, the ^{35}K secondary beam will be slowed down and implanted into a thin silicon strip detector that is only ~45 μm thick. Thus, the ^{35}K secondary beam must have a small momentum spread such that all the nuclei produced are implanted into the detector. For the ^{35}K production test, we set the MARS momentum slits (the "coffin slits") to ± 0.5 cm, which corresponds to a momentum spread of the secondary beam of $\Delta P/P \approx \pm 0.3\%$. With this momentum slit setting, we produced ^{35}K at a rate of 3.5 events/nC. This should give a production rate of between 350 and 1000 particles/sec of the ^{35}K, depending on how much primary beam will be available for the future experiment.

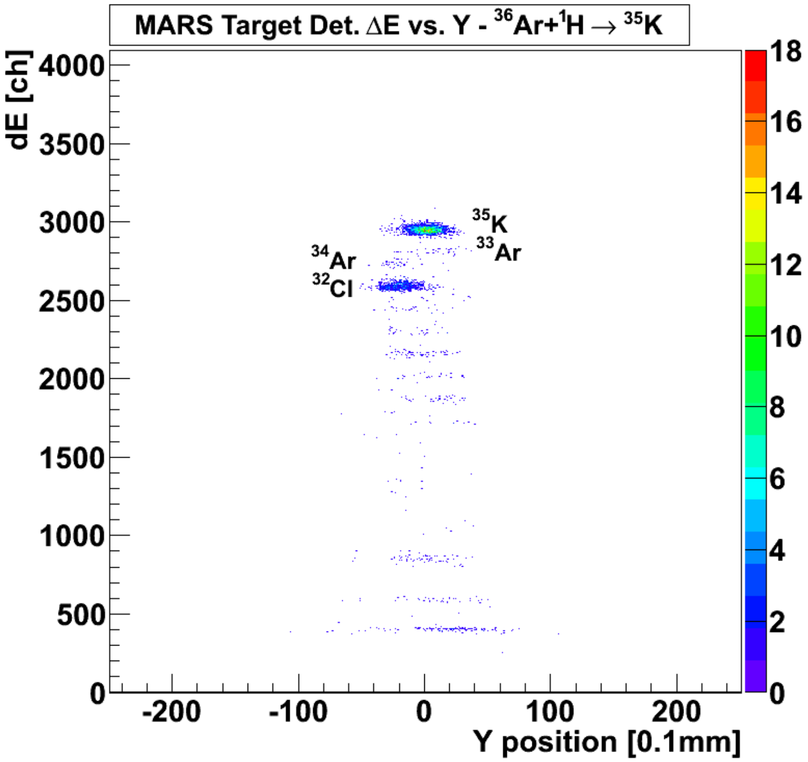

FIG. 2. Results of the ^{35}K production test.

The MARS target detector spectrum showing the final tune of the ^{35}K secondary beam is shown in Fig 2. While the ^{35}K is the most intense species shown in the secondary beam, about 45% of the secondary beam is from impurities. The most intense impurity is from the "tail" of the ^{32}Cl distribution. It was found that reducing the MARS gas cell pressure down to 1.5 atm of H_2 gas reduced the ^{35}K production rate down to 2.7 events/nC, but it also reduced the impurity ratio in the secondary beam to 34%. If the reduction of impurities will be important for the measurement, lower gas cell pressure seems to be one possible way of reducing the secondary beam impurities. It should be noted that most of the secondary beam impurities will not stop in the thin silicon strip detector or have low β-delayed proton or α-particle decay branching ratios relative to the ^{35}K. Thus, these impurities are not expected to cause problems in the future measurement.

The ^{35}K β-delayed proton decay measurement is planned for June 2014.

III. Production of ^{9}C and ^{8}B secondary beams

Also in March 2014, we produced and separated ^{9}C and ^{8}B with MARS. ^{9}C and ^{8}B are needed by the group of Prof. G. Rogachev for their upcoming experiments with resonant elastic proton scattering using the Thick Target Inverse Kinematics (TTIK) method. These experiments will be similar to those that have been conducted in the past by V. Goldberg at TAMU [5]. The ^{9}C secondary beam will be employed to study the unbound ^{10}N nucleus and the ^{8}B secondary beam will be used to study resonances in the ^{9}C nucleus. Both experiments are expected to be conducted later this year.

For the ^{9}C production test, a ^{10}B primary beam at 30 MeV/u bombarded the MARS gas cell target. The gas cell target was filled with 2 atm of hydrogen gas at a temperature of 77K. The ^{9}C was produced with the fusion-evaporation reaction (p,2n) in inverse kinematics. The Q-value for the p(^{10}B,^{9}C)2n reaction is -25.7 MeV. Thus, 30 MeV/u was chosen for the primary beam energy as a compromise between the production rate for ^{9}C, which is better at higher primary beam energies, and the desire to have the ^{9}C at the lowest possible energy. The optimum setting for the ^{9}C production was found at the MARS D1 dipole setting of 443 A, which corresponds to a ^{9}C beam energy of 23.2 MeV/u. For the planned experiment, this energy will be reduced to ~10 MeV/u with degraders.

The optimized production rate for the ^{9}C secondary beam was 4.1 events/nC, which will give ~10^{3} particles/sec with 250 nA of ^{10}B beam on target. The ^{9}C secondary beam was relatively pure, although there is some contamination in the beam from α-particles and ^{3}He. Some of this contamination will be removed in the future experiment by closing the slits of MARS.

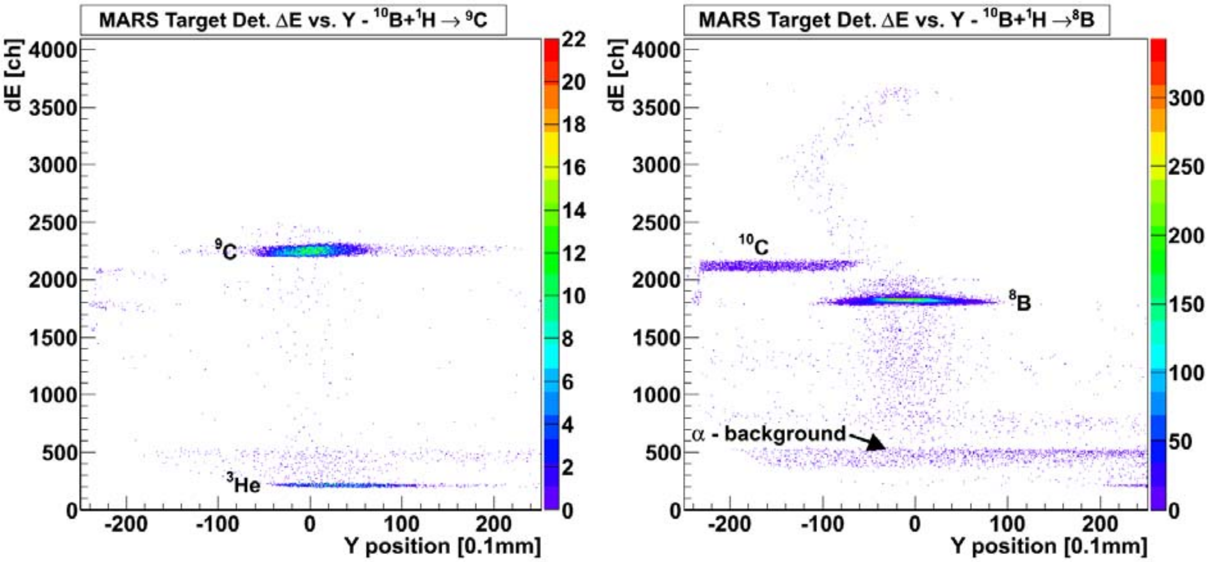

FIG. 3. (left panel) Results of the ^{9}C production test. The main contaminant of the secondary beam is from ^{3}He. (right panel) Results of the ^{8}B production test. The contributions from the ^{10}C and other backgrounds will be reduced by the MARS slits for the planned experiments.

For the ^{8}B production test, a ^{10}B primary beam at 24 MeV/u bombarded the MARS gas cell target. The gas cell target was filled with 2 atm of hydrogen gas at a temperature of 77K. The ^{8}B was produced with the (p,t) reaction in inverse kinematics. The Q-value for the p(^{10}B,^{8}B)t reaction is -18.5 MeV. Thus, 24 MeV/u was chosen for the primary beam energy to have a good production rate for ^{8}B, while still producing it at a reasonable energy. The optimum setting for the ^{8}B production in case was found at the MARS D1 dipole setting of 451 A, which corresponds to a ^{8}B beam energy of 21.1 MeV/u. For the planned experiment, this energy will also be reduced to ~10 MeV/u with degraders.

The optimized production rate for the ^{8}B secondary beam was 130 events/nC, which will give ~$3*10^{4}$ particles/sec with 250 nA of ^{10}B beam on target. The ^{8}B secondary beam was relatively pure, although there is some contamination in the beam from α-particles. Some of this contamination will be removed in the future experiment by closing the slits of MARS and focusing the beam better with the quadrupole magnets of MARS.

The MARS target detector spectra for the ^{9}C and ^{8}B secondary beams are shown in Fig. 3.

IV. Production of ^{20}O secondary beam

The final production tests for this year were to produce and separate ^{20}O secondary beam with MARS at two energies. ^{20}O secondary beam was requested by group of Prof. Rogachev and by a group from Washington University in St. Louis (WUSTL) for separate experiments planned for later this year.

In the first production test, an ^{18}O primary beam at 15 MeV/u bombarded the MARS gas cell target. The gas cell was filled with ^{4}He gas at a pressure of 2 atm and a temperature of 77K. The reaction of ^{18}O+^{4}He had been employed previously to produce ^{20}O with MARS in 2007 [6]. In the previous measurement, it was noted that in addition to ^{20}O, this reaction produced other secondary beams in charge states with the same charge-to-mass (q/m) ratio, and in some cases, the same mass as the ^{20}O^{+8}. To properly identify these contaminants in the secondary beam, a 143 μm thick position sensitive silicon detector was employed as the ΔE detector in the MARS focal plane and a 500 μm thick silicon detector was used behind it. Thus the particle identification could be verified with both the ΔE vs. Y-position and ΔE vs. E techniques.

The result of the ^{20}O production test with the ^{18}O+^{4}He reaction is shown in Fig. 4, left panel. The secondary beam contained 6 species, ^{20}Ne^{+8}, ^{20}F^{+8}, ^{20}O^{+8}, ^{15}N^{+6}, ^{15}C^{+6} and ^{10}Be^{+4}. These other species cannot be separated from the ^{20}O^{+8} by MARS because they all have q/m = 0.4. Of particular note is the ^{20}F^{+8}, which is produced at 2 times the rate of the ^{20}O^{+8}. The best production rate of ^{20}O^{+8} obtained was 9.8 eV/nC at the MARS D1 dipole setting of 450 A. This corresponds to a secondary beam energy of 8.7 MeV/u for the ^{20}O^{+8}. With about 115 nA of ^{18}O beam on target, ^{20}O^{+8} rates of ~10^{3} particles/sec are possible.

In the second production test, a ^{22}Ne primary beam at 31 MeV/u bombarded the MARS gas cell target. This time, the gas cell was filled with ^{2}H gas at a pressure of 2 atm and a temperature of 77K. The reaction of ^{22}Ne+^{2}H was employed because LISE++ simulations [2] predicted that it would have would less contamination in the secondary beam from ^{20}F^{+8}. Further, the simulation also predicted that ^{22}Ne+^{2}H would have a better cross section for ^{20}O at the higher beam energy requested by the WUSTL group. To identify the reaction products, the same 143 μm thick position sensitive silicon detector was employed as the ΔE detector in the MARS focal plane and a 500 μm thick silicon detector was used behind it.

The result of the ^{20}O production test with the ^{22}Ne+^{2}H reaction is shown in Fig. 4, right panel. The secondary beam again contained 6 species, ^{20}Ne^{+8}, ^{20}F^{+8}, ^{20}O^{+8}, ^{15}N^{+6}, ^{15}C^{+6} and ^{10}Be^{+4}. These other species cannot be separated from the ^{20}O^{+8} by MARS again because they all have q/m = 0.4. The best production rate of ^{20}O^{+8} obtained was 10.1 eV/nC at the MARS D1 dipole setting of 818 A. This corresponds to a secondary beam energy of 25.0 MeV/u for the ^{20}O^{+8}. With about 100 nA of ^{22}Ne beam on target, ^{20}O^{+8} rates of 10^3 particles/sec again are possible, which is similar to the lower energy case. However, with the ^{22}Ne+^{2}H reaction, ^{20}O^{+8} is the most intense species in the secondary beam and is more than 2 times as intense as the ^{20}F^{+8}. This result is consistent with what was predicted by the LISE++ simulation.

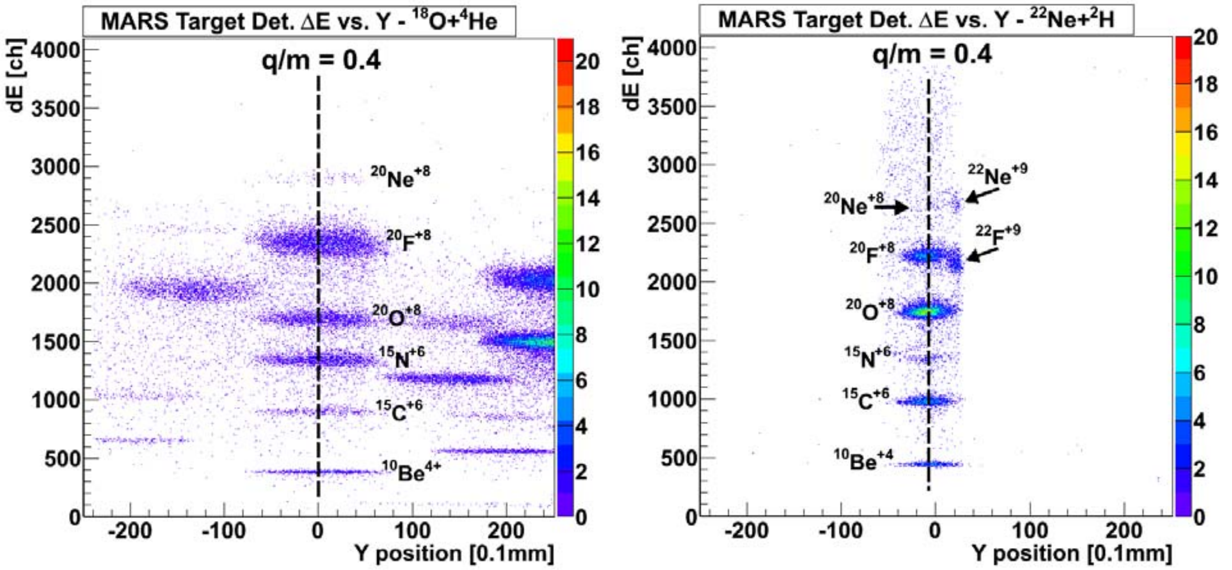

FIG. 4. (left panel) Results of the ^{20}O production test with the ^{18}O+^{4}He reaction at 15 MeV/u. Components of the secondary beam with q/m=0.4 can not be separated from the ^{20}O. The final slits of MARS were left open in this experimental run. (right panel) Results of the ^{20}O production test with the ^{22}Ne+^{2}H reaction at 31 MeV/u. The results are similar to the lower energy case, except that the ^{20}O in this case is the most intense component of the nuclei with q/m = 0.4. The final slits of MARS were also closed around the ^{20}O in this experimental run.

The contamination in the ^{20}O secondary beams will require event-by-event tracking of the secondary beam. The planned experiments will take this consideration into account.

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