MARS status report for 2015-2016:
Development of rare isotope beams of ^{25}Si, ^{6}He, ^{9}Li, ^{23}Si, and ^{22}Si

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This year we developed five new rare isotope beams for the physics program at the Cyclotron Institute at Texas A&M University with the Momentum Achromat Recoil Separator (MARS) [1]. The ^{25}Si beam was employed to commission the AstroBox2 detector. The ^{6}He and ^{9}Li beams were developed for future experiments to be conducted near the neutron dripline. The ^{23}Si and ^{22}Si beams were developed to study exotic decay schemes such as multiple proton decay near the proton dripline. The ^{23}Si and ^{22}Si beams are also of note because they are five and six particles away, respectively, from the nearest stable silicon isotope. This makes these two beams among the most exotic rare isotope beams ever produced with the MARS spectrometer.

^{25}Si beam production for the AstroBox2 commissioning run

The ^{25}Si rare isotope beam was originally produced in October 2010 during the search for a method of producing ^{27}P [2]. In October 2010, a ^{28}Si primary beam at 40 MeV/u was fragmented on several different targets including ^{9}Be, ^{27}Al, and Havar. While ^{25}Si was produced with all the targets, the best production was found when an aluminum target was used. Since the beta-delayed proton decay of ^{25}Si is relatively well known [3], and its proton decay branching ratios are relatively high, ^{25}Si decay was determined to be a good case for the commissioning of the AstroBox2 detector [4] in April 2015. To produce ^{25}Si, ^{28}Si at an energy of 40 MeV/u from the K500 cyclotron was used to bombard a 254 μm thick aluminum target. The resulting reaction products were separated and transported through MARS. The magnetic rigidity of MARS was set assuming that the best reaction mechanism to produce ^{25}Si was the fragmentation reaction. As a result of this reaction, ^{25}Si was produced at a rate of 5.3 eV/nC with the MARS momentum slits at ± 0.5 cm, which corresponds to a momentum spread of the secondary beam of $\Delta P/P \approx 0.6\%$. The magnetic rigidity was 1.5153 T·m. This production rate gave about 100-200 ^{25}Si particles/sec at the MARS focal plane. This amount of ^{25}Si was ideal for the calibration of the AstroBox2 and will used again in the future runs.

^{6}He rare isotope beam production

In May 2015, we produced and separated ^{6}He with MARS for an experiment for the group of G. Rogachev. Details of the measurement are given in a separate report. The ^{6}He beam was developed previously in 2009 [5], but it was never used. For this measurement, the ^{6}He was made in inverse kinematics with the d(^{7}Li,^{6}He)^{3}He transfer reaction in inverse kinematics with ^{7}Li primary beam at 7.0 MeV/u from the K150 cyclotron. Deuterium gas at a pressure of 2 atm and at a temperature of 77K was used in the MARS gas cell target. With the MARS momentum slits at ± 1.5 cm, which corresponds to a momentum spread of the secondary beam of $\Delta P/P \approx 1.8\%$, a production rate of 397 eV/nC was obtained.

The total energy of the ^{6}He beam was 35.4 MeV. Tritium (^{3}H) contamination was also present in the secondary beam and came at about the same rate as the ^{6}He. The maximum production of the ^{6}He was found within a very narrow range of magnetic rigidity, which is a result consistent with the direct transfer reaction mechanism. The final tune of the ^{6}He secondary beam as measured by the MARS target detector is shown in Fig. 1.

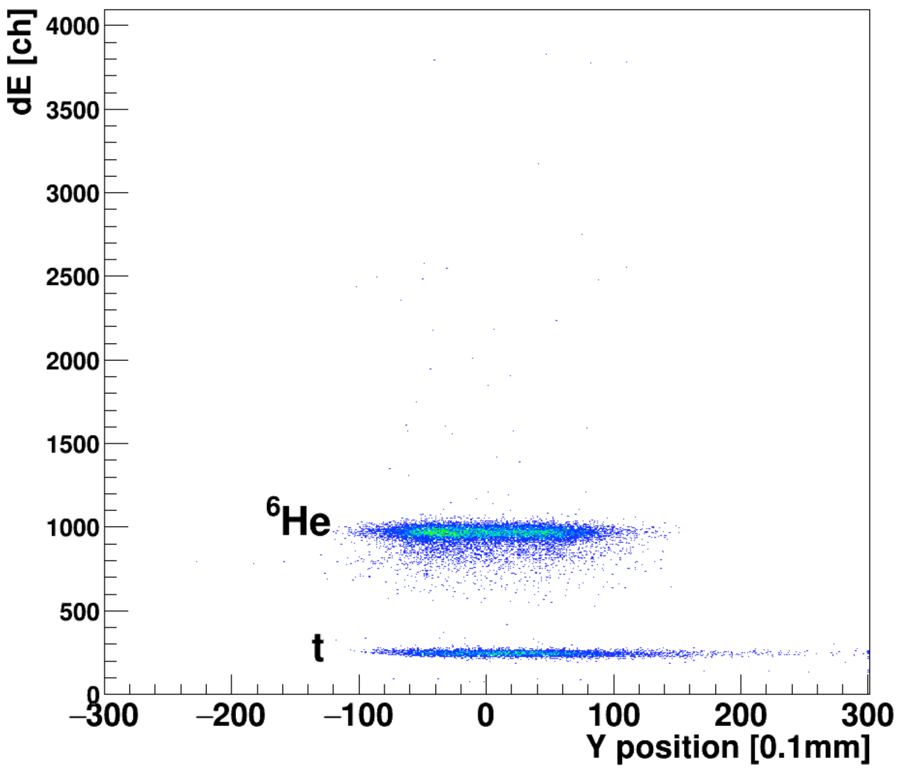

FIG. 1. Result of the ^{6}He MARS tuning for the May 2015 experiment. Note the tritium (^{3}H) contamination at the same focal plane position as the ^{6}He.

^{9}Li rare isotope beam production

In November 2015, we produced and separated ^{9}Li for the first time with MARS for another upcoming experiment for the group of G. Rogachev. The ^{9}Li was made in inverse kinematics with the ^{11}B+^{9}Be two-proton removal reaction in inverse kinematics with ^{11}B primary beam at 23 MeV/u from the K500 cyclotron. A solid ^{9}Be target 456 μm thick was employed as the production target. 23 MeV/u was chosen as the initial energy because it provided the maximum energy available while still allowing the ^{9}Li recoil particles to be transported through MARS highly rigid. With the MARS momentum slits at ± 1.5 cm, which corresponds to a momentum spread of the secondary beam of $\Delta P/P \approx 1.8\%$, a production rate of 55 eV/nC was obtained for ^{9}Li. The total energy of the ^{9}Li beam was 174 MeV. ^{6}He at a rate of 46 eV/nC and tritium (^{3}H) at a rate of 190 eV/nC were also present as contamination in the secondary beam.

While the tritium rate is about 3.5 times higher than the ^{9}Li, this amount of contamination is acceptable for the upcoming experiment. The maximum production of the ^{9}Li was found with the magnetic rigidity setting predicted by LISE++ [6] for the "fragmentation" reaction mechanism, although the reaction mechanism at this beam energy is more likely a deep inelastic transfer reaction. The final tune of the ^{9}Li secondary beam as measured by the MARS target detector is shown in Fig. 2.

Production of ^{23}Si and ^{22}Si rare isotope beams

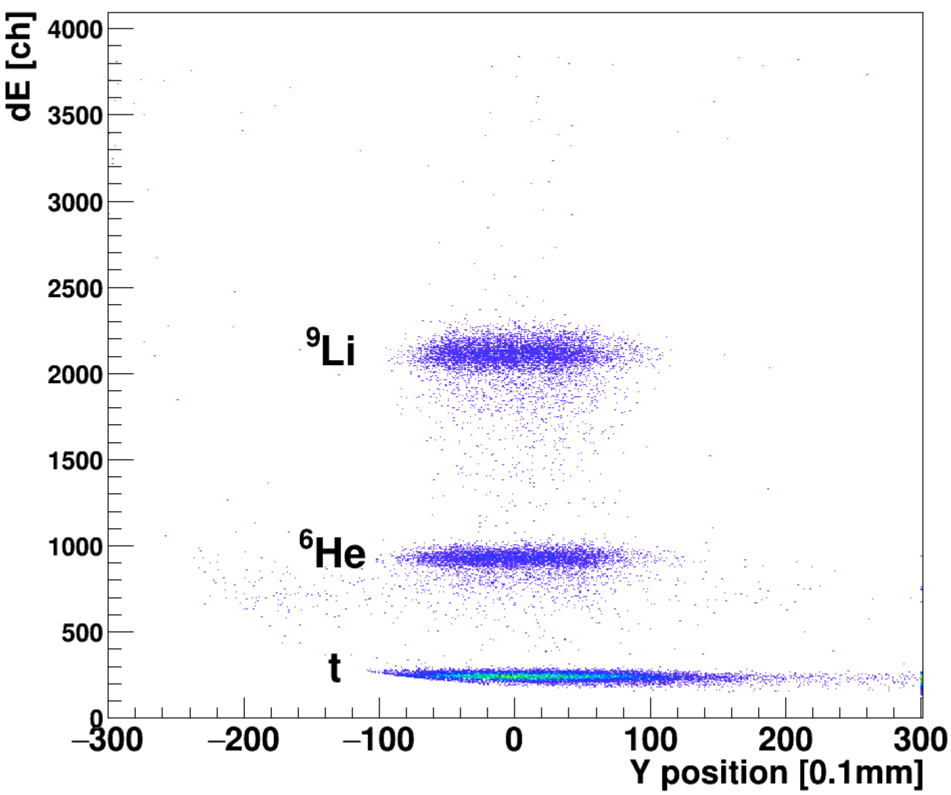

FIG. 2. Result of the ^{9}Li production test with MARS. The main contaminants of the secondary beam are from ^{6}He and ^{3}H which come at the same position in the MARS focal plane.

In March 2016, ^{23}Si and ^{22}Si were produced for the first time with MARS for an upcoming experiment in collaboration with a group from Warsaw University in Poland. ^{23}Si and ^{22}Si were made in inverse kinematics with the fragmentation reaction in inverse kinematics with ^{28}Si primary beam at 45 MeV/u from the K500 cyclotron. A solid natural nickel target 150 μm thick was employed as the production target. Nickel was chosen as the production target because it provided the lowest threshold energy for the reactions needed to produce the ^{23}Si and ^{22}Si. Also, in some previous MARS production tests with nickel and Havar targets, there have been some indications of five and six particle removal from the primary beam. With the MARS momentum slits at ± 1.5 cm, which corresponds to a momentum spread of the secondary beam of $\Delta P/P \approx 1.8\%$, a maximum production rate of 13 eV/μC was obtained for

^{23}Si at a magnetic rigidity of 1.398 T·m, close to the prediction of the LISE++ program [6]. With the primary beam intensity available, this gives about 1 particle of ^{23}Si per 5 seconds, which is enough for the planned experiment. By tuning MARS toward lower magnetic rigidities, some ^{22}Si events were also observed. When MARS was set for a magnetic rigidity of 1.344 T·m, both ^{23}Si and ^{22}Si were obtained simultaneously at the MARS focal plane at different positions on the silicon detector. The ^{23}Si at this rigidity had a production rate of 6.5 eV/μC, or about 1 particle per 15 seconds, and the ^{22}Si had a production rate of 0.5 eV/μC, or about 1 particle per 5 minutes. The particle identification plot where both ^{23}Si and ^{22}Si were present is shown in Fig. 3. Despite these small production rates, the collaborators from Warsaw University are planning experiments with both of these rare isotope beams in the coming year.

Following the success of producing rare isotopes five and six particles from stability in the cases of ^{23}Si and ^{22}Si, it is also planned in the near future to attempt to produce other rare isotopes near the proton dripline using fragmentation on a nickel target.

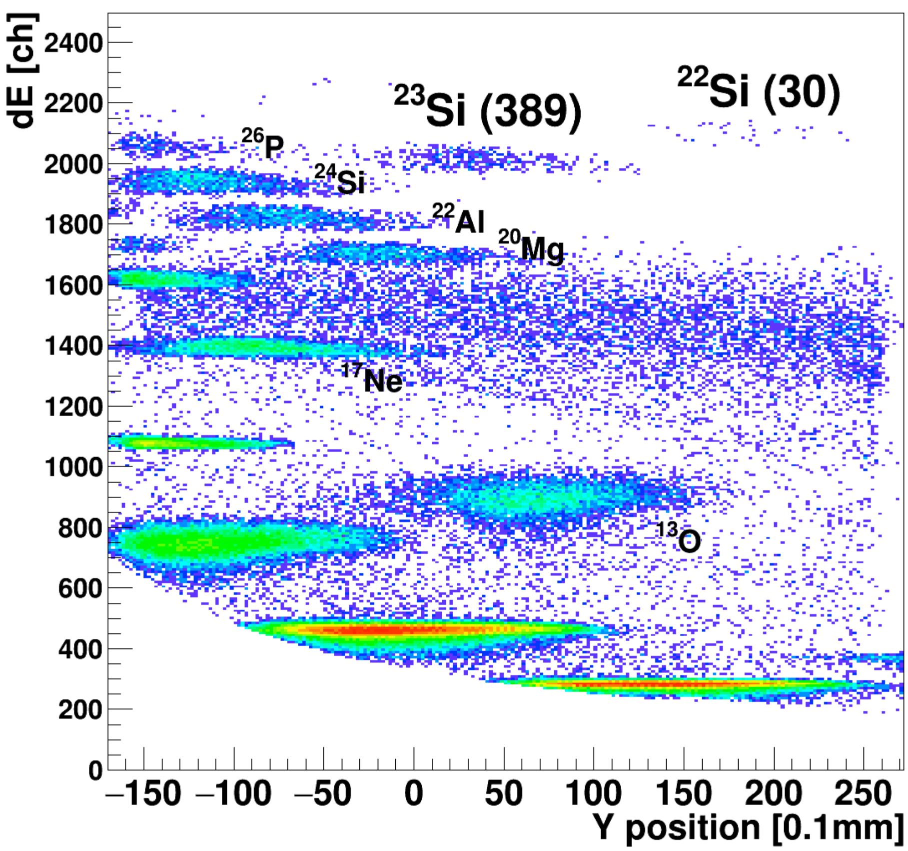

FIG. 3. Result of the two hour measurement at the MARS magnetic rigidity setting where both ^{23}Si and ^{22}Si were present. The number in parentheses shows the number of ^{23}Si and ^{22}Si events that were obtained during the measurement. Other rare isotopes produced are also labeled.

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