MARS status report for 2020-2021: Tuning of rare isotope beams ^{7}Be, ^{9}Li, ^{20}F, ^{35}Ar, ^{11}Be, ^{95}Zr

B.T. Roeder and A. Saastamoinen

This year, we continued the program of providing rare isotope beams (RIBs) for the physics program at the Cyclotron Institute at Texas A&M University with the Momentum Achromat Recoil Separator (MARS) [1]. Despite the COVID-19 pandemic, the MARS beam line was utilized in 8 separate experimental runs for RIB development and various experiments. Beams developed in previous years that were employed in physics experiments this year are as follows. ^{11}Be beam, made with the ^{13}C+^{9}Be reaction at 30 MeV/u, was provided to Dr. Rogachev's research group for a commissioning run of the new TexCAAM detector. A production rate of 32 eV/nC was obtained with about 10% contamination from ^{8}Li. ^{7}Be and ^{9}Li secondary beams had been produced before, but this year we produced them at low energy for experiments with Dr. Rogachev's group and the TexAT detector. Details of these low energy RIBs are described in the following paragraphs.

Three new RIBs were developed this year: ^{20}F, ^{35}Ar, and an attempt to make ^{95}Zr. These new MARS tunes are also described in the following paragraphs.

The low energy ^{7}Be beam was requested by Dr. Rogachev's group to measure ^{7}Be+^{7}Li reactions with TexCAMM. ^{7}Be was produced using the p(^{7}Li,^{7}Be)n reaction at 3.5 MeV/u with beam from the K150 cyclotron. To obtain the lowest possible secondary beam energy for the ^{7}Be, while providing the needed beam intensity for the experiment, we used for the first time thinner HAVAR windows for the MARS gas target. The MARS gas target was configured with a 0.16 mil (4 µm) entrance window, a 0.1 mil (2.5 µm) exit window. The H_2 gas pressure used was 100 torr, and the gas cell was cooled with liquid nitrogen to 77 K. Due to small pinholes in the thin exit window, a leak rate of about 2 torr/hr was observed in the gas target. We compensated for this loss by adding about 20 torr of H_2 gas to the target every 8-12 hours. After tuning, the ^{7}Be beam had 14 MeV total energy and a production rate of $1.5*10^{5}$ p/s with about 90 nA of ^{7}Li beam on target, resulting in an estimated production rate of about 1667 eV/nC. Earlier beam development runs have shown that ^{7}Be secondary beam with energies as low as 8 MeV total energy can be produced if desired for future experiments.

A low energy solution was also requested by Dr. Rogachev's group for ^{9}Li secondary beam, which had been produced previously at intermediate energy with the ^{11}B+^{9}Be 2-proton removal reaction [2]. The 2n-transfer reaction ^{18}O(^{7}Li,^{9}Li)^{16}O was considered the best production reaction candidate because the Q-value is -6.1 MeV (versus -15.6 MeV for the ^{11}B+^{9}Be reaction). However, ^{7}Li+^{18}O reaction required ^{18}O gas as the target. Thus, if the MARS gas target was cooled with the traditional liquid N2 to ~77 K, the ^{18}O gas volume would partially liquify depending on the final temperature of the MARS gas target. In the equilibrium conditions, the partial liquification of ^{18}O occurred at about 180 torr pressure, but with heating from the beam, the pressure increased over time to 250 torr. Due to these unstable conditions, it was decided to run the ^{18}O gas at room temperature instead of cooling it to keep the gas pressure in the target more stable. The result of the lower energy ^{9}Li secondary beam is as follows. ^{7}Li beam at 10.3 MeV/u from the K150 cyclotron impinged on the MARS gas target to produce

^{9}Li secondary beam. The MARS gas target was filled with 775 torr of ^{18}O gas at room temperature. The resulting ^{9}Li secondary beam had 59.6 MeV total energy (6.6 MeV/u) and a production rate of 9 eV/nC. Thus, with 200 nA of ^{7}Li in the MARS coffin FC, we had a typical rate of about $1.8*10^{3}$ p/s for ^{9}Li. Contaminant beams of 6He (2 eV/nC) and ^{3}H (unknown rate) were also present at the same focal plane position. While the production rate for ^{9}Li was about 5 times higher with the $^{11}B+^{9}Be$ reaction, the lower secondary beam energy obtained with $^{7}Li+^{18}O$ made it the preferred choice for the experiment. The experiment with the ^{9}Li from this production method had already been carried out in October 2020.

^{20}F beam was developed this year for an upcoming half-life measurement for Dr. Melconian's group using the tape drive setup. First, the $d(^{21}Ne,^{20}F)^{3}He$ reaction was attempted with 28 MeV/u ^{21}Ne beam from the K500 cyclotron. The MARS gas target was filled with deuterium gas at a pressure of 2 atm and cooled with liquid nitrogen to 77K. A production rate of 1180 eV/nC was obtained with about 8% contamination from $^{20}Ne^{9+}$ and $^{18}O^{8+}$. Next, the $^{21}Ne+^{9}Be$ reaction was tried. The total production rate for ^{20}F was still about 1130 eV/nC, but the total contamination was a bit higher, closer to 12%, mostly from $^{18}O^{8+}$. However, contamination from $^{20}Ne^{9+}$ was not observed in the $^{21}Ne+^{9}Be$ reaction. With this production rate, $^{20}F^{9+}$ at rates greater than 105 p/s should be possible. The ^{20}F half-life measurement is planned for the coming year.

^{35}Ar beam was developed this year for an upcoming transfer reaction measurement with Dr. Christian's group. The $p(^{35}Cl,^{35}Ar)n$ reaction was chosen with 14 MeV/u ^{35}Cl beam from the K150 cyclotron. The MARS gas target was filled with hydrogen gas at a pressure of 0.5 atm and cooled with liquid nitrogen to 77K. A production rate of 700 eV/nC was obtained, with a tail of ^{32}S contamination. To see if more production was possible, the target pressure was increased to 500 torr and 1000 torr and MARS was retuned for each case. The ^{35}Ar production was unchanged in each case; it was still about 700 eV/nC. However, higher target pressures, in particular the 500 torr case, reduced the contamination from the ^{32}S tail at the MARS focal plane. With this production rate, ^{35}Ar at rates greater than 10^{5} p/s should be possible for future experiments.

Finally, production of ^{95}Zr from the $d(^{94}Zr,^{95}Zr)p$ reaction was attempted. In the measurement, a ^{94}Zr beam at 13 MeV/u from the K500 cyclotron impinged on the MARS gas target. The gas target was filled with deuterium gas at a pressure of 250 torr and cooled to 77K with liquid nitrogen. Due to the relatively low beam energy and the heavy mass of the beam and product, it was nearly impossible to separate ^{95}Zr from the charge states of the ^{94}Zr primary beam. Perhaps the best case was $^{95}Zr^{35+}$, where the $^{95}Zr^{35+}$ was separated from $^{94}Zr^{35+}$ by a few millimeters. Even in this case, it was not possible to separate $^{95}Zr^{35+}$ from the tail of $^{94}Zr^{34+}$ in y-position. It may be possible to obtain more mass dispersion if higher voltage on the velocity filter is used. However, a cleaner ^{95}Zr secondary beam is only possible via direct acceleration of ^{95}Zr either from a ^{95}Zr radioactive source (t1/2 = 64 days) or a re-accelerated ^{95}Zr beam from the Light Ion Guide.

A summary of the rare isotope beams produced this year with MARS is given in Table I.

Table I. Summary of MARS RIBs for 2020-2021.

RIB beam	Reaction	Primary Beam	Purity	Intensity on Target
^{7}Be	$p(^{7}Li,^{7}Be)n$	^{7}Li at 3.5 MeV/u	100%	$1.5*10^{5}$ p/s
^{9}Li	$^{18}O(^{7}Li,^{9}Li)^{16}O$	^{7}Li at 10.3 MeV/u	~10%	$1.8*10^{3}$ p/s
^{20}F	$d(^{21}Ne,^{20}F)^{3}He$ $^{9}Be(^{21}Ne,^{20}F)X$	^{21}Ne at 28 MeV/u	~92% ~88%	~10^{5} p/s
^{35}Ar	$p(^{35}Cl,^{35}Ar)n$	^{35}Cl at 14 MeV/u	~99%	~10^{5} p/s
^{95}Zr	$d(^{94}Zr,^{95}Zr)p$	^{94}Zr at 13 MeV/u		inconclusive

[1] R.E. Tribble, R.H. Burch, and C.A. Gagliardi, Nucl. Instrum. Methods Phys. Res. **A285**, 441 (1989).

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