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EMBEDDED D-³HE FUSION REACTIONS AND MEDICAL ISOTOPE PRODUCTION IN AN INERTIAL ELECTROSTATIC CONFINEMENT DEVICE

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The high-energy 14.7 MeV protons generated from the D-³He fusion reaction can be used to produce medical radioisotopes. Steady-state D-³He operation is possible using Inertial Electrostatic Confinement (IEC); however, the location of the reactions must be known to use them effectively for isotope production. In the University of Wisconsin IEC device, it has been found that as much as 2/3 of the total D-³He reaction rate can be due to embedded fusion reactions, reactions occurring within the cathode due to ion implantation. Therefore, the cathode surface sees a large, high-energy proton flux. Using a solid molybdenum cathode, and taking advantage of the embedded reactions, about 1 nCi of the medical isotope ^{94m}Tc was created via ⁹⁴Mo(p,n)^{94m}Tc in a proof of principle experiment. This represents the first time the IEC concept has been used to produce a radioisotope using D-³He fusion.

I. INTRODUCTION

The University of Wisconsin Inertial Electrostatic Confinement (IEC) device has continued to make progress in the burning of the advanced, D-³He fusion reaction. The D-³He reaction produces ⁴He and a 14.7 MeV proton. The IEC concept relies on spherical, concentric, nearly transparent electrodes to radially accelerate ions to substantial fusion cross sections.^{1,2} The project has achieved a record steady state D-³He reaction rate of 3.5×10^8 p/s at a cathode voltage of 140 kV and current of 46 mA.³ The 14.7 MeV protons created from the reaction have various commercial uses, such as for the production of short-lived medical radioisotopes.⁴ Currently, the proton production rate is high enough for proof of principle isotope production.

The location of the D-³He reactions, and thus the source of the protons must be known to pursue work in this area. An assumption based on previous work of Thorson⁵ with D-D plasmas at the 1-10 mtorr level suggested that

the reactions occur uniformly throughout the chamber as a volume source. Thorson found that 90% of the reactions occur outside of the cathode region. Recently, strong evidence from the D-³He reaction has shown that another source of the fusion reactions can be obtained through embedded reactions occurring within the cathode as a result of ion implantation.

Most isotopes used in medicine today come either from nuclear reactors using the strong neutron flux, or from accelerators using high-energy charged particle reactions. Cyclotrons are typically used for proton activation by accelerating protons from 10 to 20 MeV. However, cyclotrons are large and costly devices, costing between \$2-3 million. The cost and size somewhat limits their use. Typically a cyclotron will be located in a dense population area to supply the needed isotopes to hospitals in the area. There is also a practical lower limit to the half-lives of the isotopes being created. The half-life must be long enough to allow time for processing and transportation to the patient.

The IEC device, on the other hand, is small and relatively inexpensive. It could be built for around \$100,000 and could allow for portable isotope production. For example, if the IEC device were placed on the back of a truck, isotopes could be used in more remote areas, and it would open the door to the use of much shorter-lived isotopes that could be produced on-site.

The isotopes used in Positron Emission Tomography (PET) fall into the category of short-lived species. Table 1 shows four potentially useful positron emitters. All of these isotopes can be created with protons at the energies from the D-³He reaction. The isotope ¹⁸F is very commonly used in brain studies using a ¹⁸F-dopamine tracer. The 110 minute half-life allows for a few hours to process and transport the isotope to the location of interest. The other isotopes listed in the table would be used more, but their half-lives severely limit their availability.

PET Isotope	Production	Half-life (min)
^{18}F	$^{18}\text{O}(p,n)^{18}\text{F}$	110
^{15}O	$^{15}\text{N}(p,n)^{15}\text{O}$	2
^{13}N	$^{16}\text{O}(p,\alpha)^{13}\text{N}$	10
	$^{13}\text{C}(p,n)^{13}\text{N}$	
^{11}C	$^{14}\text{N}(p,\alpha)^{11}\text{C}$	20

Table 1: Common PET Isotopes⁶

The shorter-lived species are more desirable for imaging because they give a smaller residual radiation dose. The isotopes ^{15}O and ^{13}N especially would be desirable for imaging of small children or pregnant women. Their short half-lives would provide a smaller dose after the diagnostic procedure is completed.

Initial work on the production of isotopes using the IEC device is focusing on producing the short-lived positron emitters. IEC-produced isotopes may find a niche market in this area. The initial experiments of this research have focused on the production of $^{94\text{m}}\text{Tc}$, a positron emitter with a 52-minute half-life. This isotope has been used in limited medical physics research.⁷

II. EXPERIMENTAL OPERATION

The UW IEC experiment is shown schematically in Figure 1. A cylindrical, aluminum vacuum vessel with pumping system allows for base pressures in the mid 10^{-7} torr range. The 10 cm, spherical cathode grid is made from a tungsten-rhenium wire, and a high-voltage insulator allows typical operation between -50 to -180 kV. The 50 cm anode is made from stainless steel wire and is kept at ground potential. The gridded construction makes the electrodes mostly transparent to ions.

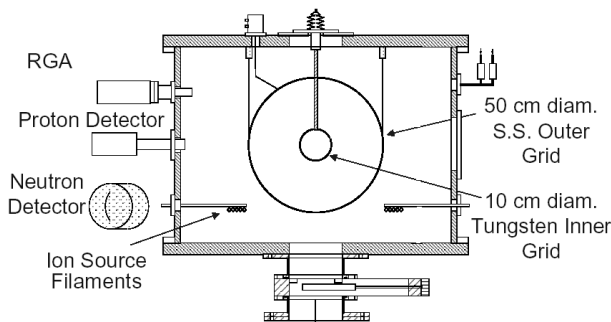


Figure 1: UW IEC Setup

Typically the device is operated at a background gas pressure of 2 mtorr. Three light-bulb filaments are used to ionize the background gas outside of the anode. The ions get accelerated towards the inner grid and may recirculate a few times. At voltages from 50 to 180 kV, the ions can reach considerable fusion cross sections. There are three main reaction regimes that may occur in this setup:⁵ the converged core regime, the volume regime, and the embedded regime.

Converged core involves ion-ion and ion-background gas fusion events. Because the ions have most of their energy at the center of the device, this reaction regime is localized at the core. The volume regime is due to charge-exchange fast neutrals that fuse with the background gas. At pressures of a few mtorr, it is more likely that an ion will charge exchange than fuse. These fast neutrals can fuse at any point within the chamber, leading to a diffuse source of reactivity. Embedded reactions occur within the cathode grid wires from ion implantation and further ion bombardment.

A residual gas analyzer (RGA) determines which gases are present in the chamber. A ^3He neutron detector is the main diagnostic for determining the D-D fusion rate. A silicon proton detector pointed towards the center of the device counts both D-D protons and D- ^3He protons and is the only diagnostic for determining the D- ^3He fusion rate. The D- ^3He protons only deposit about 5 MeV into the detector, and the D-D protons deposit about 1.9 MeV into the detector.

III. RESULTS AND DISCUSSION

III.A. Embedding Experiments

The work by Thorson⁵ with D-D plasmas only suggested that the embedded contribution to the fusion rate is a small fraction of the total, 10% at the most. This means a small amount of deuterium is retained within the cathode. However, Thorson did not work with ^3He , and there are differences between running a D-D plasma and a D- ^3He plasma.

The first evidence of a large D- ^3He embedded regime was seen during D-D runs following D- ^3He runs. Figure 2 shows a typical multichannel analyzer proton energy spectrum for two runs. The large D- ^3He proton peak at 5 MeV is the raw data from a D- ^3He plasma run at 100 kV, 30 mA, and 2.1 mtorr. In a subsequent D-D plasma run at the same conditions, a smaller but still significant D- ^3He proton peak showed up. Even though the RGA showed

that there was no ^3He in the background gas, there were still $\text{D-}^3\text{He}$ reactions occurring. The initial conclusion was that ^3He was embedded into the cathode during the previous run, and bombardment of the cathode by D^+ ions in the D-D run allowed for embedded reactions to occur.

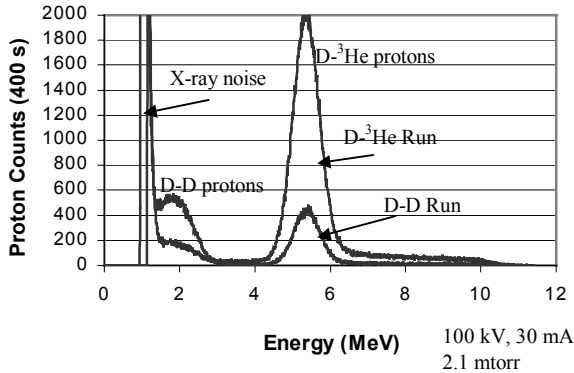


Figure 2: Initial ^3He Embedding Evidence ($\text{D-}^3\text{He}$ Protons Generated from D-D Plasmas)

Since there appeared to be differences in D^+ vs. $^3\text{He}^+$ retention in the cathode, two experiments were planned to determine the effect on the fusion rates. Two new, virgin grids were fabricated to test the effect. Because the grids were new, there was no deuterium or helium within them before installation into the chamber. One grid was used to determine the effect of $^3\text{He}^+$ embedding, and one was to determine the effect of D^+ embedding.

For the $\text{D-}^3\text{He}$ experiment, the new grid was installed and conditioned using only deuterium. Conditioning is done at lower voltages to heat up the grid and drive out any impurities. Then, for the $\text{D-}^3\text{He}$ experiment, the voltage was ramped up from 40-80 kV five times in a row. $\text{D-}^3\text{He}$ proton data was taken every 10 kV, and time was recorded at each data point. The assumption was that if ^3He was being retained in the cathode, the rates would increase with run time.

Figure 3 is a plot of the reaction rate as a function of run time for 60, 70, and 80 kV. A clear saturation trend can be seen in the data; that is to say that the rates increase with time and then appear to level off. The leveling off is most likely due to reaching a maximum embedded density.

For each voltage, an exponential saturation equation was fit to the data of the following form:

$$R_{\text{total}} = R_{\text{plasma}} + R_{\text{embed}}(1 - e^{-\lambda t}) \quad (1)$$

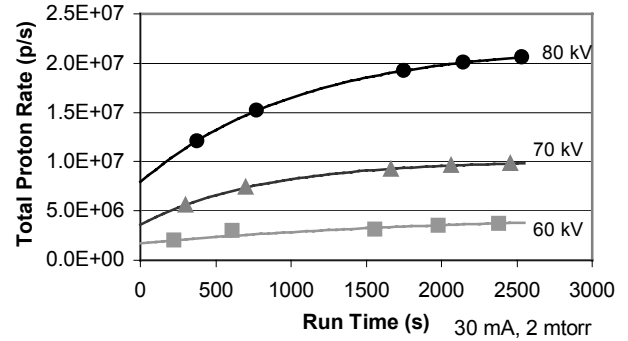


Figure 3: $\text{D-}^3\text{He}$ Rate Increase Due to ^3He Embedding

In this equation, R_{total} is the reaction rate at time t , R_{plasma} is the reaction rate in the plasma, and R_{embed} is the portion in the embedded regime. The ions implant and build up with time, so an appropriate exponential factor is included. Using this equation, it was possible to compare the initial rate to the saturated rate to find that about 2/3 of the maximum rate is due to the embedded regime. This fraction was much larger than expected.

Likewise, a similar plot was made for the D-D neutron rates with the new grid as shown in Figure 4. This figure shows that in general, the D-D rates are constant with run time. The slight changes are within the scatter in the data. This graph suggests that deuterium does not build up to high levels within the grid.

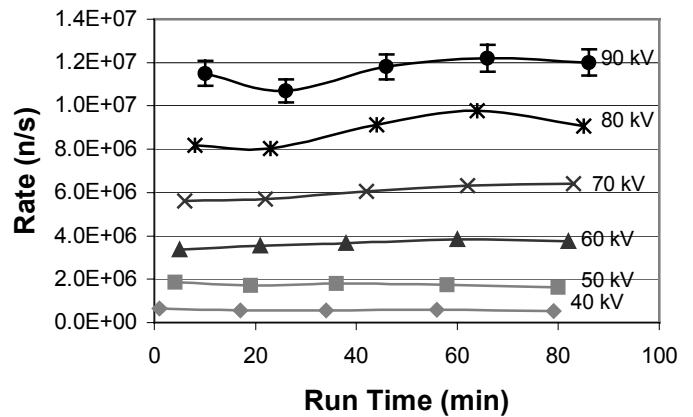


Figure 4: D-D Rates Constant with Time

The difference in the results from Figures 3 and 4 most likely stems from the fact that hydrogen and helium isotopes behave very differently in metals. Hydrogen moves freely through most metals,⁸ but helium is impermeable and forms bubbles upon implantation.⁹ The grid heats up to over 1000°C during runs, so the diffusivity for deuterium is probably very high; the deuterium

implants and then diffuses out very quickly. On the other hand it is felt that the helium is able to stay trapped longer and may form bubbles below the surface.

III.B. Isotope Production

Since a large fraction of the D-³He reactions occur just below the surface of the cathode, the proton flux is the highest in that location. Therefore, near the cathode may be the best location for producing isotopes. To test this theory, a solid, spherical cathode was fabricated to replace the tungsten grid. This solid cathode in effect changed the IEC into a beam-target setup, forcing only embedded reactions to occur at the surface. During a D-³He run, ³He builds up just below the surface. Further bombardment by deuterium causes fusion reactions. The protons are generated isotropically at the surface, so roughly half travel deeper into the target and can activate elements within (See Figure 5).

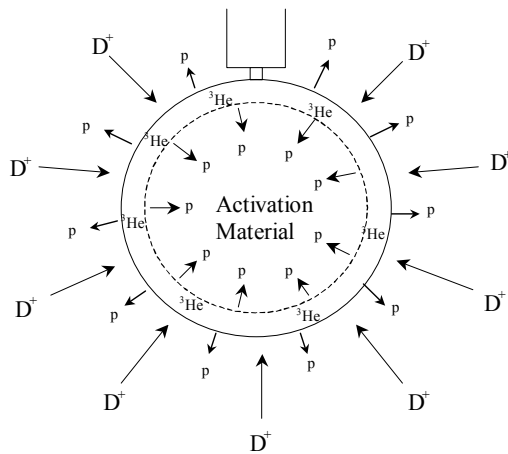


Figure 5: Solid Target Activation

Molybdenum was chosen as the material for an initial activation experiment. It has a high melting temperature to withstand the power input inside the IEC device. It also has similar hydrogen diffusivity properties as compared to tungsten.

Natural molybdenum contains 10% ⁹⁴Mo, and this isotope has a large (p,n) cross section for the production of ^{94m}Tc (see Figure 6). This particular technetium isotope has been used in limited nuclear medicine research and is a positron emitter with a 52 minute half-life. The large cross section and short half-life allow for the production of larger activities for an initial proof of principle experiment.

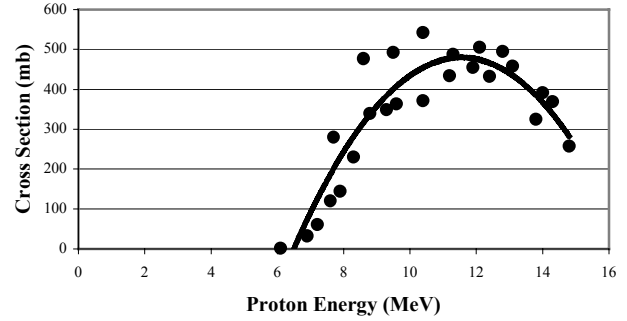


Figure 6: ⁹⁴Mo(p,n)^{94m}Tc Cross Section¹⁰

The solid molybdenum target is shown in Figure 7. It was installed in the chamber in place of the inner grid. During the run, the target heated up to very high temperatures (~1200°C).



Figure 7: Solid Molybdenum Cathode

In the D-³He experiment, both gases were run into the chamber, and the voltage was ramped from 40 to 110 kV. The current and pressure were kept constant at 30 mA and 2 mtorr. At 110 kV, the voltage was held steady for 15 minutes. On average, about 5x10⁶ p/s were generated within the surface for about 20 minutes. Then the machine was shut down, the chamber was opened, and the molybdenum target was counted on a NaI detector.

The activation spectrum is shown in Figure 8. The count was taken 40 minutes after the run for 1 hour, and the background was subtracted out. There is a very clear peak at channel 50, which corresponds to the 511 keV peak expected from a positron emitter. After the ^{94m}Tc isotope releases the positron, it is left in an excited state and emits an 871 keV gamma to return to the ground state. The smaller peak above channel 80 is this gamma. Using collection efficiency, it was estimated that about 1 nCi of

^{94m}Tc was produced. This is the first time the IEC device has been used to produce an isotope.

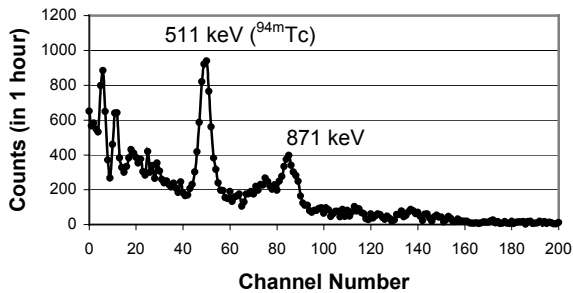


Figure 8: ^{94m}Tc Evidence

IV. CONCLUSION

The large embedded fusion regime present in the IEC device is unique to the $\text{D}-^3\text{He}$ reaction. Perhaps as high as $2/3$ of the maximum proton production rates are due to embedded reactions at the cathode. The $\text{D}-\text{D}$ reaction does not seem to have a significant embedded portion. Further work is needed to understand the differences in the behavior of D^+ and $^3\text{He}^+$ ions when implanted into the cathode. The embedded regime changes the understanding of the device and must be taken into account in any modeling work done in the future.

This large fraction of $\text{D}-^3\text{He}$ reactions occurring at the cathode has allowed for successful isotope production at that area. Using a solid molybdenum cathode, about 1 nCi of ^{94m}Tc was created, representing a proof of principle demonstration of the concept. Future work will focus on designing a system that allows isotopes to be generated and removed in a more commercially viable manner.

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