

**Fluorine-18 Production via the $^{18}\text{O}(p,n)^{18}\text{F}$
Reaction Using the AccSys PL-7 RF Proton Linac**

Results of Initial Target Tests

G.D. Robinson, Jr. and R.W. Hamm

AccSys Technology, Inc.
1177A Quarry Lane
Pleasanton, CA 94566
Tel: (510) 462-6949
Fax: (510) 462-6993
e-mail: GRobinson@linacs.com

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Fluorine-18 Production via the $^{18}\text{O}(p,n)^{18}\text{F}$ Reaction Using the AccSys PL-7 RF Proton Linac: Results of Initial Target Tests¹

Gerald D. Robinson, Jr. and Robert W. Hamm

ABSTRACT

The prototype PL-7 rf proton linac from AccSys Technology, Inc. was used to perform initial performance tests for fluorine-18 production via the $^{18}\text{O}(p,n)^{18}\text{F}$ nuclear reaction. One short irradiation on ^{16}O -water was used to verify target integrity and then three consecutive one hour irradiations of 2% ^{18}O -water with 3-4 μA of beam current were performed. Yields of fluorine-18 were more than 80% of theoretical. Results of these initial studies using the 7.0 MeV beam from the Model PL-7 rf proton linac to produce fluorine-18 via the $^{18}\text{O}(p,n)^{18}\text{F}$ nuclear reaction confirm the viability of this approach to production of positron emitting isotopes. The first production PULSAR™ unit, which incorporates the PL-7 linac for this application, is scheduled for delivery late in 1997.

INTRODUCTION

AccSys Technology first began developing an rf ion linac based system for production of positron isotopes in 1985.² The announcement of PULSAR™ in 1994 is the most recent step in this decade long evolution. PULSAR™ consists of a PL-7 rf proton linac for acceleration of H^+ to 7.0 MeV with integrated targets and shielding for production of positron isotopes and positron labeled radiotracers.

The status of development and remaining challenges of PULSAR™ were most recently discussed in 1995.³ At that time, the major questions involved the nature of the pulsed beam of the PL-7 linac and the implications on target effectiveness and reliability when such a beam is used for isotope production. The studies described here were designed to begin to answer these questions and to provide empirical evidence of the practicality of the PULSAR™ approach.

EXPERIMENTAL METHODS

The accelerator used for these initial target tests was the prototype PL-7. This rf proton accelerator has been described in detail elsewhere.⁴ Briefly, however, the PL-7 is a proton only accelerator with an energy of 7.0 MeV which is achieved by closely coupling a 3.0 MeV RFQ section with a short 4.0 MeV DTL section to boost the final proton energy to 7.0 MeV. The prototype accelerator was operated with a beam duty factor of 0.12% at a pulse repetition rate of 10 Hz. These studies were done at the AccSys Technology facility in Pleasanton, CA, but the PL-7 itself has since been installed at the Indiana University Cyclotron Facility where it will be used to inject polarized negatively charged hydrogen ions into a synchrotron.

The proton injector used for the PL-7 during these tests was a duoplasmatron based ion injector for deuterons running at up to 5 mA peak current and 10 Hz to match the linac repetition rate. Maximum output current from this injector for protons mode much less than the 150 μ A average for PULSAR™ because the injector was designed to operate with deuterons rather than protons, and the duty factor was limited by the maximum pulse rate of the PL-7 design for this application.

A stainless steel beam line of 76.4 cm (30 in.) length and 2.23 cm (7/8 in.) ID was attached to the high energy end of the PL-7 and the target was attached to the beam line. The beam line dimensions were selected based on beam dynamics calculations which predicted that, based on the emittance of the PL-7 proton beam, the 2.55 cm (1.00 in.) diameter target beam strike area would be uniformly irradiated. The target assembly included a 2.00 cm (0.79 in.) diameter collimator located 5 cm in front of the target. Beam current on both the collimator and the target were measured during the irradiations.

The prototype target used by the PL-7 for producing fluorine-18 via the $^{18}\text{O}(p,n)^{18}\text{F}$ reaction was developed in cooperation with Dr. David Schlyer's chemistry group at Brookhaven National Laboratory under a Department of Energy Cooperative Research and Development Agreement (CRADA)⁵. The target body was machined from titanium with an internal volume of 810 μ l. The front foil was 0.001 in. thick (1 mil) Havar supported with an aluminum "grid" which was 50% transparent to the beam. Energy loss in this foil was approximately 1.0 MeV for 7.0 MeV protons incident, giving a 6.0 MeV proton beam on the ^{18}O -water. All other target components were machined from aluminum. The target assembly, including the foil support grid, is shown in figures 1 and 2. Immediately prior to an irradiation, the target was manually filled through PE tubing with 2% oxygen-18 water and run at 75 psig air overpressure.

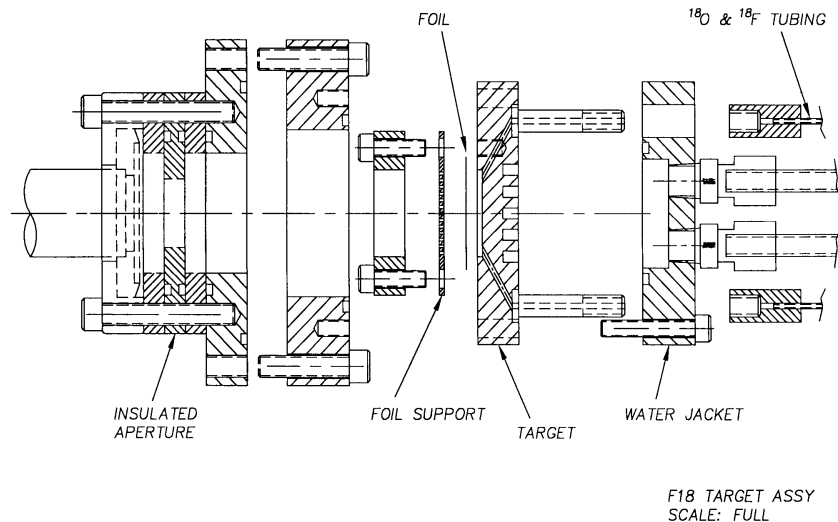


Figure 1. Assembly drawing of target used for initial tests of fluorine-18 production via the $^{18}\text{O}(p,n)^{18}\text{F}$ with the PL-7 RF proton linac.

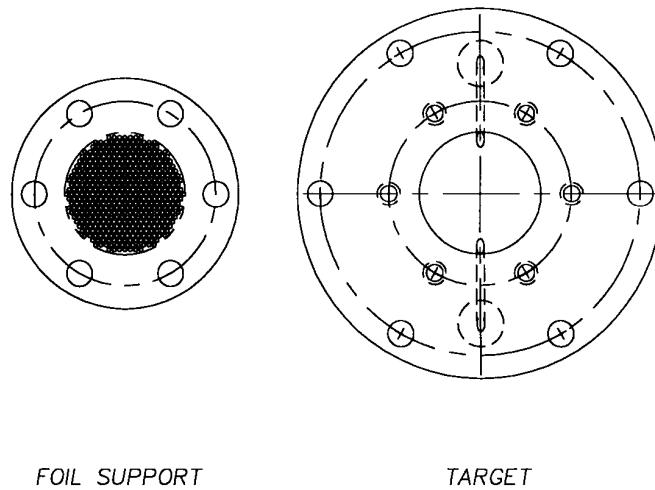


Figure 2. Front view of target front foil support “grid” and target body for prototype PULSAR™ fluorine-18 target.

Initial estimates of isotope production yields were made by measuring the dose rate at a distance of 20.4 cm (8.00 in.) from the irradiated 2% oxygen-18 water. A crude estimate of isotopic purity was made from the decay rate of the samples by taking several such measurements at different times. For one experiment, the samples were transported to the Metabolic Imaging Laboratory at Lawrence Berkeley Laboratory⁶ for more precise measurements of isotope yield and isotopic purity.

The initial target irradiation was for 15 min at three μA of proton beam current with the target filled with ^{16}O -water to assure target integrity. Three individual one hour irradiations at 3-4 μA were performed during the next two days. During these longer irradiations the target overpressure slowly increased to 140 psig at the end of one hour. All irradiated water was recovered within two min of end of bombardment (EOB). After the final one hour irradiation, the emptied target was rinsed with water to determine the completeness of recovery of the fluorine-18 produced.

RESULTS

Inspection of the target at the end of these tests showed no evidence of any effect on the target assembly, front foil or foil support “grid”.

Over 95% of beam passed through the collimator onto the target and comparable amounts of activity were produced in each of the one hour irradiations. Based on theoretical calculations using a gamma-ray dose constant, Γ , of 4.4 R/mCi at one cm distance for fluorine-18,⁷ the amounts of activity produced in the first and third one hour irradiations were: 350 and 420 μCi , respectively. This is shown in Table 1. The activity measured in a calibrated dose calibrator at 83 min post EOB for the fluorine-18 produced during the second one hour irradiation was 223 μCi . This is equivalent to 393 μCi at EOB.

In the one test run in which the target was rinsed with water after emptying, over 98% of the fluorine-18 was recovered directly with the initial emptying of the target.

Table 1: Fluorine-18 produced during the three one hour irradiations on 2% ¹⁸O-water at 3-4 mA

Run Date	Survey Meter (mR/hr @ 8 in.)	Calculated (μCi)	Dose Calibrator (μCi)
11/19/96	4.7	440	370*
11/20/96	5.0	470	393
11/21/96	5.5	530	440*

* Corrected values derived from the measured ratio (393/470 = 0.794) between the survey meter based calculation and the dose calibrator result for sample 2 (11/20/96).

Gamma-ray spectra of samples recovered from the target after the initial test (¹⁶O-water for 15 min) and the first two one hour irradiation (2% ¹⁸O-water) are shown in figures 3 and 4.

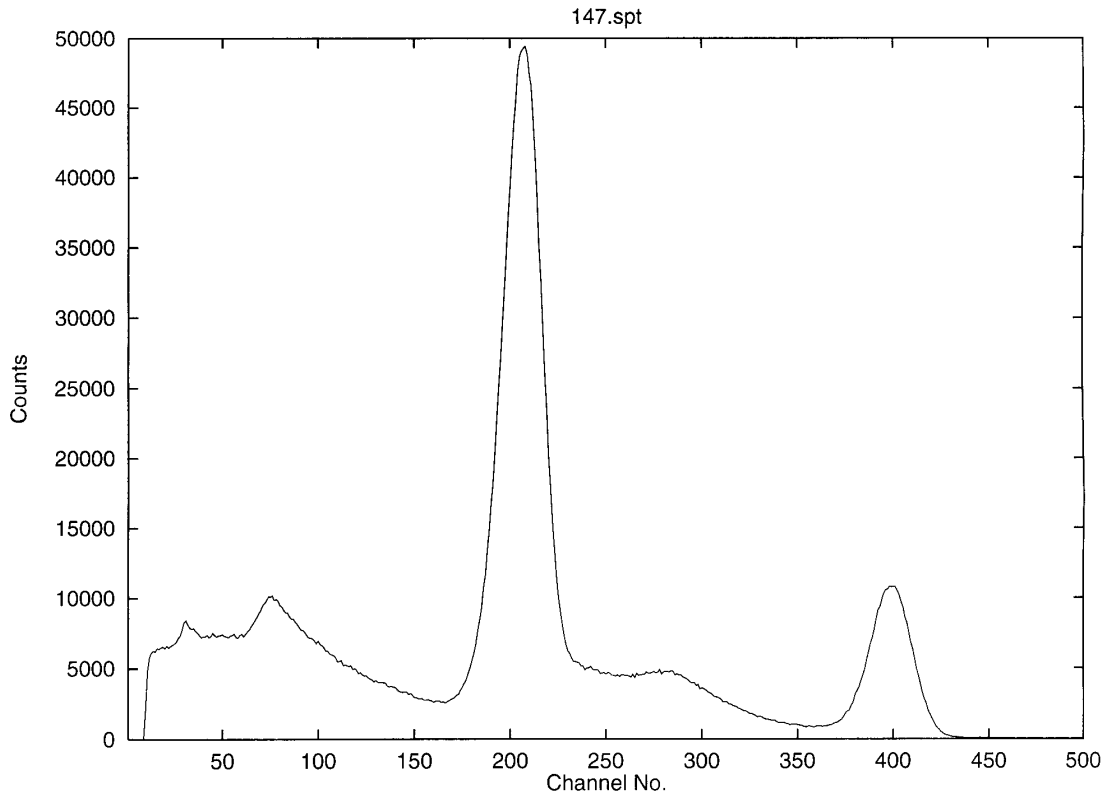


Figure 3. Gamma-ray spectrum (principal peak is at 511 keV) of radioactivity produced by proton irradiation of 2% ¹⁸O-water during initial PULSAR™ target tests.

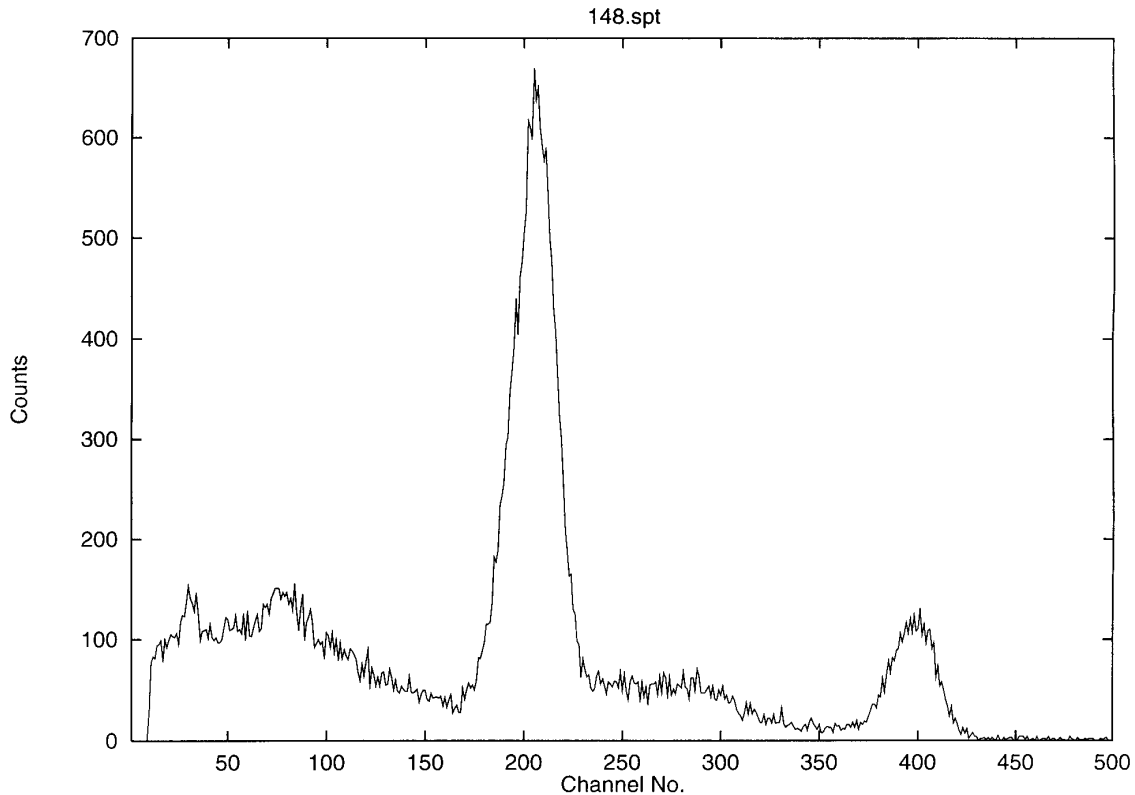


Figure 4. Gamma-ray spectrum of obtained 24 hr after proton irradiation of 2% ^{18}O -water during initial PULSARTM target tests.

DISCUSSION

Effect of Pulsed Proton Beam

The 10 Hz repetition rate which was used for these experiments is 10% of the 100 Hz repetition rate which is used for PULSARTM. This was required to accommodate the unique parameters of the PL-7 configuration manufactured for use as a synchrotron injector rather than for isotope production.

Schlyer, et. al.⁸ have used model thermodynamic calculations to estimate that the rate of temperature rise of the ^{18}O -water in a target such as that used here should be on the order of $48,000^\circ\text{C}/\text{sec}$ during the intense proton beam pulse. However, the short duration of the individual pulses ($\cong 120\ \mu\text{sec}$) should result in an actual temperature rise of less than 6°C during a single pulse. For a well cooled target, the heat input is easily dissipated during the relatively long interval between pulses ($\cong 80$ times the pulse duration).

Fluorine-18 Production Yields

The excitation function for the $^{18}\text{O}(p,n)^{18}\text{F}$ nuclear reaction has been well characterized.⁹ Assuming a saturation yield of 60 mCi/ μA at the 6.0 MeV energy incident on the 2% ^{18}O -water, the yields of fluorine-18 are reasonably consistent (\cong 83% of theoretical) with results which would be obtained in cyclotron targets under similar beam current conditions. Verification at higher currents which will be used for routine production remain to be completed.

For the target tests with the prototype PL-7, the beam was not uniformly distributed over the intended target beam strike area (2.55 cm dia.), but was concentrated in a elliptical spot with long and short axes of 6.4 and 3.2 mm, respectively. Current density was $4.0 \mu\text{A}/0.161 \text{ cm}^2 = 24.8 \mu\text{A}/\text{cm}^2$. By providing adjustable magnetic quadrupole beam optics it is straightforward to spread the proton beam uniformly over the target beam strike area (2.55 cm dia. = 5.11 cm^2) and the total current can be increased to 125 μA at comparable current density.

One of the principal qualities of the PL-7 beam is its uniformity. With uniform irradiation of the entire beam strike area at 125 μA , the saturation yield of the prototype PULSAR™ fluorine-18 target under the conditions studied here is 7,500 mCi. For a one hour irradiation at 125 μA the yield will be on the order of 2,400 mCi.

Radionuclidic Purity

Gamma-ray spectroscopy of the irradiated 2% ^{18}O -water showed the characteristic 511 keV radiation from positron annihilation. Because of the limited availability of counting equipment at the AccSys facility, the earliest spectra obtained were approximately two hrs after EOB. All radioactivity in the samples had decayed by 48 hours after EOB. The spectra obtained are shown in Figures 3 and 4.

The rate of decay of irradiated samples were consistent with the 110 min half-life of fluorine-18. This is shown in figure 5. The presence of possible short-lived radionuclidic impurities could not be evaluated by repeated well counting because of the delay after EOB due to transportation of the samples to the laboratory at UC Berkeley. Repeated measurements of dose rate of the samples over the first 15 min. after EOB were inconclusive. Production of nitrogen-13 from the $^{16}\text{O}(p,\alpha)^{13}\text{N}$ reaction is not expected to contribute significantly at this low proton energy.¹⁰

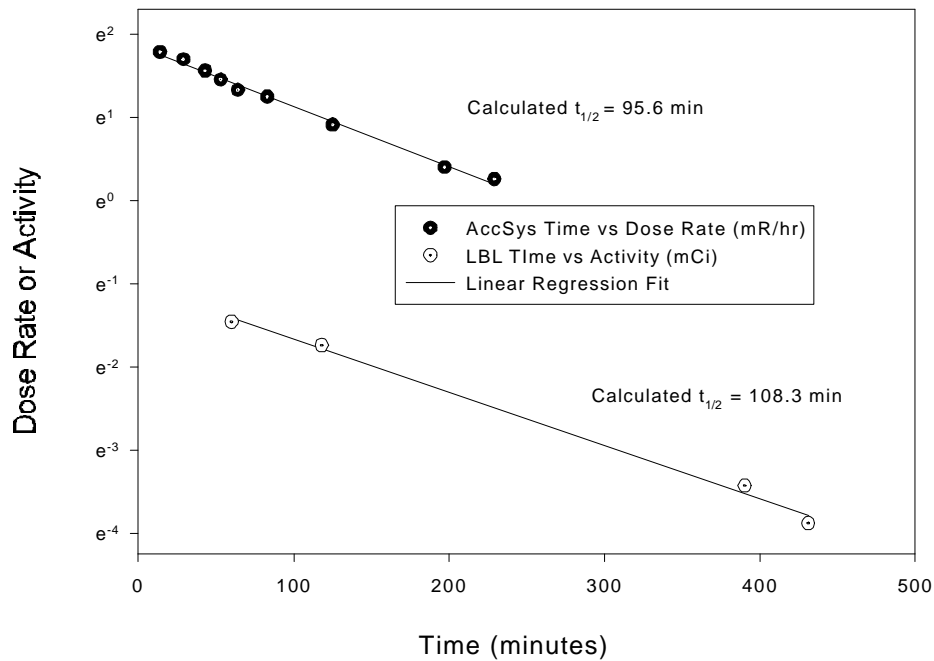


Figure 5. Decay of radioactivity produced by proton irradiation of 2% ^{18}O -water during initial PULSARTM target tests.

Short-term Improvements

While the results of these initial experiments are very encouraging and are consistent in all respects with the predicted performance of PULSARTM, several simple improvements which should improve performance and robustness of the fluorine-18 target are suggested.

The gradual increase in target overpressure which was observed is probably due to inadequate target cooling. One hundred μA average current of protons at 7.0 MeV incident on the target, which might be used for routine isotope production, represents a total of 700 W of power. It is probably reasonable to extrapolate to such higher total beam currents at constant current density provided that the increased heat load is handled properly. This can be addressed by providing better overall target cooling by using a dedicated target cooling system with increased total water flow through the target itself

Schlyer, et. al.⁴ have suggested several alternatives for the design of the foil support “grid” used here. The “grid” provides support which allows the use of an unusually thin target front foil while enhancing reliability and robustness of the target. The design used here is a simple hexagonal array. Optimization of the foil support design parameters, including: hole size, use of non-uniform hole distribution, support thickness, increased transparency to 65-70%, will allow productive use of more than 50% of the incident beam. This will translate directly into higher fluorine-18 production rates at the same total beam current on target.

The density of Havar is approximately 8.3 g/cm^3 and the range of 7.0 MeV protons in Havar is 0.1143 g/cm^3 . The range of the protons in titanium ($\rho = 4.4\text{-}4.5 \text{ gm/cm}^3$) is 0.1091 g/cm^3 . For 7.0 MeV protons incident on the target foil, energy absorbed in a 1 mil (0.001 in.) thick foil will be reduced from 1.0 MeV for Havar to 0.5 MeV for titanium. Thus, proton energy through the titanium foil will be 6.5 MeV; and the saturation yield for fluorine-18 will increase (27%) from 60 to 76 mCi/ μA .

CONCLUSION

The results of these initial studies using the 7.0 MeV beam from the Model PL-7 rf proton linac to produce fluorine-18 via the $^{18}\text{O}(\text{p},\text{n})^{18}\text{F}$ nuclear reaction confirm the viability of this approach to production of PET isotopes.

Extrapolation of these results at limited beam currents suggest that the PULSAR™ specification of 1,500 mCi of fluorine-18 will be achieved with a one hour irradiation at 100 μA using a target configuration similar to that of the prototype unit. Demonstration of such performance with the first production PULSAR™ 7E will be in the near future.

Studies are now underway to use a 4.0 MeV proton beam from the PL-4 which has been installed at BNL to verify the robustness of our initial fluorine-18 target design at higher beam currents than were available during the initial tests reported here. The lower energy protons pose a greater challenge to the target because dE/dx will be greater at the lower energy and, thus, more power will be deposited in the front foil under the test conditions at 4.0 MeV than routinely in PULSAR™ at 7.0 MeV.

A redesigned “next generation” target for fluorine-18 production via the $^{18}\text{O}(\text{p},\text{n})^{18}\text{F}$ reaction, which incorporates improvements such as those suggested above will be included when the first production PULSAR™ unit, which is built around the PL-7 linac for this application, is delivered in late 1997.

REFERENCES

¹ The authors wish to acknowledge the assistance of W.J. Pearce and S. A. Santos, of the AccSys Technology staff, who contributed significantly to this work.

² R.W. Hamm, et. al., “A Compact Proton Linac for Positron Tomography”, Proc. 1986 Linear Accel. Conf., SLAC-Report-303, 141 (1986).

³ G.D. Robinson, Jr. and R.W. Hamm, “Status of the AccSys PULSAR™ System”, Proc. 6th Workshop on Targetry and Target Chemistry, Vancouver, B.C., Canada, Aug. 1995, 33-36.

⁴ R.W. Hamm, “RF Linacs for Radioisotope Production”, Proc 5th Intl. Workshop on Targetry and Target Chemistry, BNL, Upton, NY, Sept. 1993, 12-19.

⁵ DOE CRADA Number BNL-C-95-05.

⁶ The authors gratefully acknowledge H.F. Van Brocklin, Ph.D. for his assistance in these measurements.

⁷ S. Baum and R. Bramlet, "Basic Nuclear Medicine", Appleton-Century-Crofts, New York, N.Y., APPENDIX: Data on Radionuclides Commonly Used in Nuclear Medicine Imaging (Normal Subjects).

⁸ D.F. Schlyer, et. al., Personal communication.

⁹ T.J. Ruth and A.P. Wolf, "Absolute cross section for the production of ¹⁸F via the ¹⁸O(p,n)¹⁸F reaction", Radiochim. Acta, 18:21 (1981).

¹⁰ H.A. Hill, et. al., "High-resolution measurements of the ¹⁶O(p,α)¹³N excitation function, Phys. Rev., 123:1301 (1961).