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Prompt Radiation Detectors To Monitor Target Conditions

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Abstract. Lessons learned by basic scientists in the study of experimental nuclear physics can often go unnoticed by cyclotron operator's intent on meeting a demanding schedule of tracer production. Prompt neutrons and gammas are the signature that the desired reaction is occurring, providing a robust measure of the expected yield.

Keywords: nuclear physics, neutron detection, gamma detection
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INTRODUCTION

Subtle changes in target conditions can go unnoticed if the operator restricts his attention to such independent variables as beam current, overpressure and temperature. Continuous monitoring of the penetrating gamma and neutron radiations can close the loop, providing a direct signature that the desired nuclear reaction is actually proceeding as expected.

MATERIALS AND METHODS

The cyclotron vault is a hostile environment for performing spectroscopy: crowded, with crippling magnetic and radiation fields. Rather than detailed energy-resolved spectrometry, our goal is:

- to simply count and log the separate gamma and neutron emissions arising from the target,
- recognizing the imperfect n-γ discrimination in the detector,
- as well as the overwhelming gamma flux arising from the neutron absorption in the shielding walls of the cyclotron vault.

The isolation of the target as the radiation source is addressed by the geometrical placement of the detector, and is also dependent on the beam transmission of the accelerator. Today's negative ion cyclotrons have greatly improved extraction optics and attention paid to choosing materials for neutral beam baffles. Any n-γ discrimination must be a (passive) intrinsic property of the detector, since active techniques such as pulse-shape discrimination useful in organic scintillators stumble

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when faced with tera-Becquerel neutron source strengths. Finally, the neutron capture gamma flux from the walls at $E_\gamma \approx 10$ MeV is almost unavoidable, impossible to screen out with conventional shielding, but suggest small detectors to minimize the detection event rate. Finally, any gamma detector must not become activated (e.g. NaI), and the proximal electronics must be "hard" in the neutron field.

Neutrons

Neutron detection is described in a rich literature (1), detailing detectors covering ten decades in sensitivity S and n-γ discrimination. As a gedanken example of a perfect neutron detector for logging the $^{18}O(p,n)^{18}F$ reaction, imagine that the target body has a separate, dedicated water cooling trace, looping out of the cyclotron vault to a buffer tank observed by a NaI spectrometer in a quiet counting environment. Neutrons above 10 MeV can induce ^{16}N activity in the cooling water, decaying with a 7-second half-life and a characteristic 6.14 MeV gamma line, fulfilling every criterion of low background, neutron specificity and adjustable sensitivity. While this may be an ideal neutron detector, few cyclotron operators would jeopardize the essential cooling of their production target. However, a parallel surrogate water loop, divorced from the cooling function and tuned for optimal ^{16}N transport, may gain favor. For prompt neutron logging in real time, we have employed five separate approaches, listed in Table 1, varying in detection mechanism, $\log_{10}$ sensitivity (counts/neutron) and n-γ discrimination, strongly favoring C and E.

TABLE 1. Different approaches to neutron detection

Detector	**Mechanism**	**$\log_{10}S$**	**n-γ discrimination**
^{235}U-fission	Proportional	-6 to -9	Excellent
p-recoil	H(n,p)	-6 to -9	Good at $E_n > 1$ MeV
$^{10}BF_3$	Proportional	-5 to -7	Excellent at $E_n > 1$ MeV
Eljen 410	H(p,n) scintillation	-6 to -9	Excellent at $E_n > 1$ MeV
Eljen 426	6Li(n,α) scintillation	-6 to -9	Excellent at $E_n > 1$ MeV

Gammas

Two gamma detectors have been found to satisfy the above criteria. A heavily shielded $LaBr_3$ scintillator (2.5 cm diam x 2.5 cm), laser-aligned on target with a 1 μsr solid angle at 5 meters through a 200 kg Pb collimator, serves to identify the characteristic gamma lines at sub-micro amp currents at 11 MeV, but is swamped during an actual production run. Under those conditions, a simple scrap of $CaWO_4$ intensifier screen on a 931A photomultiplier tube provides a nA-μA anode current sufficient for gamma monitoring.

RESULTS

Gamma and neutron rates have been routinely logged (sec^{-1}) during operation since the installation of our legacy RDS 112 (1985) and the PETtrace (2009). In truth, the utility of these plots are greeter at 11 MeV than 16 MeV proton energies, capable of characterizing isotopic enrichment, void formation in liquid targets and localized "sweet thick spots" when irradiating plated solid targets. The neutron rate also serves as the driver input signal R for a "leaky integrator" (2)

$$\frac{dN}{dt} = R - \lambda N$$

numerically integrating the first order differential equation to predict the end-of-bombardment activity.

A recent example of the neutron data rate signaling an otherwise imperceptible target gas leak (< 1 psig/min @ 250 psig) is shown at the right in Figure 1 below. The rising neutron counting rate as the N_2 gas pressure falls is a complex function of shifting solid angle and beam strike on the chamber walls, but the fact that it dramatically changes and correctly predicts that the ^{11}C-synthesis will fail makes it an invaluable sentinel in a production situation.

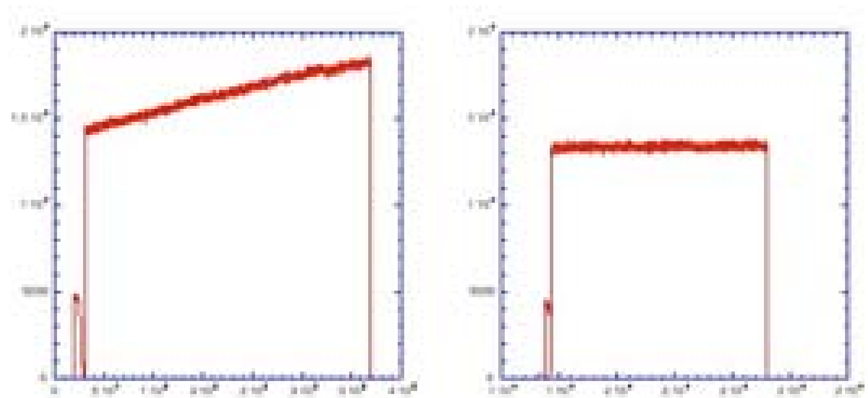

FIGURE 1. Leaky target (right) vs. tight target (left), reflected in the neutron counting rate.

A different situation arose in our irradiation of molybdenum and dysprosium targets for the production of long-lived radionuclides ^{95m}Tc (61 days) and ^{163}Ho (6000 yr). The neutron data rate, sampled at 1 Hz over tens of hours of 16 MeV proton irradiation at 50 μA showed intermittent periods of "hash", high frequency ±5% fluctuations beyond the statistical precision expected at 20 kcps data rates. The abrupt onset of this observable jitter after several hours coincided with RF fluctuations seen in the tetrode screen current, evidently causing small oscillations in the beam current. Later inspection revealed the root source of the problem, ion source chimney erosion, whose replacement resolved a multitude of problems. Clearly, the routine logging of neutrons and gammas provided an early diagnostic indicator that would have gone unnoticed.

CONCLUSION

To a physicist, the idea of **not** monitoring the neutrons characterizing a nuclear reaction is recipe for disaster (see Cold Fusion, 1989). In the words of HG Wells, "in the country of the blind, the one-eye man is king". What is less obvious, however, is that a steadfast attention to the neutron and gamma flux can reveal subtle conditions within the cyclotron and the associated targets that would go otherwise unnoticed. Such hidden variables, if neglected, contribute to a lingering mystique that spirits are afoot. Such spirits can be exorcised with diligence and discipline.

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