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Photoproduction of Tritium

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March 23, 1995

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1 Executive Summary

Irradiation of ${}^7\text{Li}$ by low-energy photons produces tritium (${}^3\text{H}$) via the photodisintegration process. Waste heat from the ${}^7\text{Li}$ target can be extracted and used for the direct generation of electricity. Other advantages include: negligible residual radioactivity, simple target technology, small low-energy electron accelerators for bremsstrahlung production (the photon source), developed liquid metal technology, modularity, simple extraction of ${}^3\text{H}$ from a recirculating ${}^7\text{Li}$ target, abundant supply of ${}^7\text{Li}$, and straightforward target-accelerator-bremsstrahlung converter interface.

A schematic plant characterized by very low risk is described, and a figure-of-merit is obtained. Electrons accelerated to low energies strike a high Z target, producing bremsstrahlung with high efficiency. The bremsstrahlung strikes a liquid ${}^7\text{Li}$ target. The competition between atomic and nuclear interactions takes place in a photon energy region where the cross section for atomic processes is at a minimum while the nuclear cross section is high. The major atomic process, Compton scattering, creates so little energy loss that the photon can be reused for photodisintegration. Liquid metal technology was developed for the breeder reactor program. ${}^7\text{Li}$ is available and abundant. The interface between accelerator, bremsstrahlung converter, and the ${}^7\text{Li}$ target does not require development. Low-energy, high-efficiency electron accelerators are available commercially. The process does not produce long term radioactivity in the sense of fission or spallation products. Liquid ${}^7\text{Li}$ is recirculated by a pump. Tritium is extracted, and waste heat is recycled to energy in a heat exchanger or the magnetohydrodynamic pro-

cess during recirculation.

The figure-of-merit for ${}^3\text{H}$ production for this schematic plant expressed as grams of ${}^3\text{H}$ produced per MegaWatt year is:

$$N_T \approx 2.08 \text{ g}/(\text{MW y}).$$

2 Introduction

${}^3\text{H}$ (Tritium) is required for maintenance of nuclear weapons in the stockpile. The National Defense need for ${}^3\text{H}$ was historically met by the Savannah River Facility. This facility is no longer safe for operation. ${}^3\text{H}$ decays with a mean lifetime $\tau = 17.8 \text{ y}$, and therefore new methods of ${}^3\text{H}$ production are required to meet US military requirements. Nonproliferation issues are also of concern when discussing tritium production.

2.1 APT

Accelerator production of tritium (APT) has been proposed using high current and high energy proton accelerators [LA-APT-4]. Protons accelerated to $\approx 1 \text{ GeV}$ strike a spallation target surrounded by a neutron multiplier blanket. The spallation neutrons are moderated in the target assembly and are captured in ${}^3\text{He}$ channels located within the target assembly. ${}^3\text{H}$ is produced by the ${}^3\text{He}(n,p){}^3\text{H}$ reaction. Characteristics of this method are:

- Target assemblies with massive amounts of residual radioactivity in the form of spallation productions
- Technical advances in accelerator design are required

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- Large and powerful accelerator(s) with devoted large (≈ 500 MW) power stations.

3 PPT

Alternative methods for large scale ^3H production need to be considered. ^3H can be produced directly in low energy nuclear reactions. Irradiation of ^7Li by low energy photons produces ^3H via the photodisintegration process (PhotoProduction of Tritium, PPT):

Conceptually, a PPT facility design is straight forward: electrons accelerated to $E_e \approx 12$ MeV by a high current CW linac strike a high-Z bremsstrahlung converter such as Ta. The bremsstrahlung, which is forward directed, strikes a target assembly of ^7Li . ^3H is produced via the γ, α reaction above. The ^3H is extracted from a recirculating ^7Li target, and waste heat is reclaimed for electricity. A schematic of the conceptual design discussed above is given in Fig. 1.

A - Accelerator
B - Bremsstrahlung
H - Heat Exchanger

T - Tritium
P - Pump

Figure 1: Conceptual schematic of ^3H production by photodisintegration of ^7Li .

Risk associated with this process is low:

- Technical risk is low since no technical advances are required

Table 1: Symbols and units.

Symbol	Definitions
N_T	number of ^3H atoms produced
i	incident electron current
Φ_e	incident electron flux
E_e	incident electron energy
ϵ_{brems}	bremsstrahlung conversion efficiency
ϵ_γ	bremsstrahlung fraction producing ^3H
σ_T	nuclear cross section
L	^7Li assembly length
μ_{pair}	pair production coefficient
N_0	Avogadro Number
a	ampere
h	hour
y	year
g	grams
MW	MegaWatt

- ES & H risk is low. The main residual radioactivity is 8 h ^{180}Ta which is localized in the converter. The main problem appears to be at the ^7Li -bremsstrahlung interface. The ^7Li assembly must be kept from water.

This appears to us to be an alternative ^3H production method worth considering. Although the (electrical) cost per gram is larger than the APT value, PPT has distinct advantages.

4 Figure-of-Merit

This section of this paper presents numerical details of a simplified calculation for the number of ^3H atoms produced per ampere-year of incident electrons in this schematic arrangement. The production rate is also presented in grams per MegaWatt-year for a useful figure-of-merit. The number of ^3H atoms is given by:

$$N_T = \Phi_e \times N_{^7\text{Li}} \times \sigma_T.$$

4.1 Definitions

The meaning of symbols and units used in this document is given in Table 1.

Figure 2: Cross section for atomic processes in Li. (From [Ple78].)

4.2 Numerical Values

Φ_e : The number of electrons for an ampere-year,

$$\Phi_e = 1.97 \times 10^{26}$$

N_{7Li} : The number of target atoms N_{7Li} is estimated simply by multiplying the atom density of 7Li [$\rho N_0/A = 0.534 N_0/7$] by the target length L . The absorption processes for photons in Li are given in Fig. 2. Pair production is the only atomic mechanism for photon absorption in Li for photons in the energy range between 6 and 12 MeV, since photoelectric absorption is negligible, and the Compton process scatters photons with little energy loss and no absorption. The appropriate length for $1/e$ absorption is $1/\mu_{pair}$. The interpolated value of $\mu_{pair} = 4.08 \times 10^{-2}$ b at 9 MeV [Ple78], and therefore $L = 10.7$ m. Therefore,

$$N_{7Li} = L \times \rho N_0/A = 81.5 \times N_0$$

σ_T : Skopik, *et al.*, [Sko79] have measured the differential cross section σ_T at $\theta_\gamma = 90^\circ$ for $6 < E_\gamma(\text{MeV}) < 50$, and the total cross section over a much narrower range, $6 < E_\gamma(\text{MeV}) < 15$. The experimental results are illustrated in Fig. 3, (a) and (b) respectively.

Figure 3: (a) The 90° cross section for the ${}^7Li(\gamma, t)$ ■ and (γ, α) • reactions. (b) The total cross section for the ${}^7Li(\gamma, t)$ reaction for E_γ between 6 and 15 MeV. (From [Sko79].)

The data show a resonance at $E_\gamma = 7$ MeV, with a width ≈ 7 MeV, and a smaller broad resonance around $E_\gamma = 18$ MeV. These data suggest 12 MeV as a first cut for the incident electron energy. The integral of the total cross section estimated from Fig. 3b between $E_\gamma = 6$ and 12 MeV is

$$\sigma_T = 2550 \text{ MeV } \mu \text{ b}/(6 \text{ MeV}) = 425 \mu \text{ b}$$

The product of the three items gives:

$$N'_T = 11.34 \times N_0 = 34.0 \text{ g/(a y)}.$$

This value must be corrected for the efficiency with which the accelerated electrons produce

bremsstrahlung (ϵ_{brems}) and the fraction of the bremsstrahlung photons that undergoes a nuclear reaction in the ${}^7\text{Li}$ assembly (ϵ_γ). Estimating $\epsilon_{brems} = 0.75$ and $\epsilon_\gamma = 0.5$,

$$N_T = N'_T \times \epsilon_{brems} \times \epsilon_\gamma = 12.8 \text{ g/(a y)}.$$

The main operating cost in accelerator based ${}^3\text{H}$ production is the cost of electrical energy. Therefore the significant figure-of-merit for comparison with APT is ${}^3\text{H}$ production in grams per MegaWatt-year, or g/(MW y), assuming unit accelerator efficiency and unit ${}^3\text{H}$ recovery. Thus,

$$\begin{aligned} N_T &= N_T / (E_e \times i) = 12.8 / (12 \text{ MeV} \times 1 \text{ a}) \\ &= 1.06 \text{ g/(MW y)}. \end{aligned}$$

5 Discussion of parameters

Conservative values were used in the estimate of N_T in section 4. Very simple steps can greatly increase N_T .

1. The choice of electron incident energy is not optimized. Although the cross section σ_T falls $\approx$ a factor of 2 between 10 and 12 MeV (See Fig. 3), an incident electron bombardment energy $E_e = 12$ MeV was assumed and the cross section averaged for E_γ between 6 and 12 MeV.
2. ${}^3\text{H}$ reaction cross section below $E_\gamma = 6$ MeV is not used in the estimate of the integrated cross section, even though σ_T is still maximum at 6 MeV. The low energy cross section has not been measured, and Fig. 3 suggests that there is significant integrated cross section below $E_\gamma = 6$ MeV.
3. The target length used is $1 \times \mu_{pair}^{-1}$. Doubling the target length increases ${}^3\text{H}$ production by 37%, or 1 e-fold. μ_{pair} was evaluated at $E_\gamma = 9$ MeV. It is dropping logarithmically with E_γ and therefore the estimate of L is unrealistically low.
4. Reclamation of waste heat and electricity generation with 30% efficiency increases electrical efficiency by 43%.

The last two items in the list are straight forward, and including them in the calculation increases N_T substantially, from 1.06 to

$$\begin{aligned} N_T(PPT) &= 1.06 \times (1 + 0.37) \times (1 + 0.43) \\ &= 2.08 \text{ g/(MW y)}. \end{aligned}$$

The corresponding number for APT is (Appendix A.):

$$N_T(APT) = 29.5 \text{ g/(MW y)}.$$

PPT is therefore a small but appreciable fraction of APT: $\approx 7\%$.

6 Advantages of photoproduction of tritium (PPT)

Photoproduction of ${}^3\text{H}$ as schematically outlined above has several advantages:

- negligible residual radioactivity
- simple target technology
- small low-energy electron accelerators for bremsstrahlung production
- modularity (spreading Risk)
- liquid metal technology developed for breeder reactors
- simple ${}^3\text{H}$ extraction from a recirculating ${}^7\text{Li}$ target
- abundant supply of ${}^7\text{Li}$
- straight forward interface of accelerator-target-bremsstrahlung
- waste heat recovery for direct generation of electricity

7 Proposal

Scenarios exist where PPT may be attractive. The production efficiency given in section 4 is an appreciable fraction of the APT figure-of-merit given here. We propose a program to investigate the potential of ${}^3\text{H}$ production by photodisintegration of ${}^7\text{Li}$. The first steps include:

1. Experiments to measure total ^3H production as a function of incident electron energy.
2. Detailed transport calculations which include the relevant cross sections and their angular dependence. Optimal choice are required for bombardment energy and bremsstrahlung converter thickness. The choice of incident electron energy may have a strong effect on accelerator design.
3. Inventory of radioactive products in PPT.
4. Engineering studies of the heat recovery and electricity generation.
5. Detailed accelerator design, emphasizing reliability and current capacity.

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A APT in g/(MW y)

Reasonable parameters are assumed for APT in order to arrive at a estimate of the ^3H production in grams/MegaWatt-year. Assume:

- a 1 GeV proton accelerator
- a current of 0.1 a for 1 y
- n/p conversion = 30
- unit efficiency for n to ^3H conversion

The APT accelerator will produce

$$N_T = 1.97 \times 10^{25} \times 30/N_0 = 981 \times N_0 \\ = 2.95 \times 10^3 \text{ g/y,}$$

or,

$$N_T/(E_p \times i) = 2.95 \times 10^3/(1 \text{ GeV} \times 0.1 \text{ a}) \\ = 29.5 \text{ g/(MW y).}$$

B Output per accelerator

A reasonable CW electron current design goal is 0.5 a. The ^3H output per accelerator is $2.08 \times 0.5 = 1.04 \text{ g/y}$, with the assumptions of Section 4. Accelerator farms are required to meet National Defense requirements. There is no inherent disadvantage to this, and there may well be advantages.

C Residual Radioactivity

The conceptual arrangement proposed here produces very little residual radiation. Choice of a Ta bremsstrahlung target means the $^{181}\text{Ta}(\gamma, n)$ reaction ($Q = -7.57 \text{ MeV}$) in the converter will produce 8 h ^{180}Ta nuclei. Natural Ta is essentially monoisotopic, > 99.98% ^{181}Ta . ^{180}Ta decays to a stable product. The γ, n reaction in the ^7Li target is just at the threshold energy ($Q = -2.46 \text{ MeV}$). Therefore, neutron production in the ^7Li assembly will be small, and the reaction product ^6Li is stable. The main impurities are expected to be ^{12}C and ^{16}O . The γ, n reaction on these elements has Q values of -18.72 and -15.66 MeV , respectively, and so produces no residual radioactivity. The main background is expected to be at the ^7Li container walls.

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