A Nuclear Diagnostic for Fast Alpha Particles

L. R. Grisham and D. E. Post

Princeton University Plasma Physics Laboratory

Princeton, New Jersey 08544

and

J. M. Dawson

University of California at Los Angeles

Los Angeles, California

ABSTRACT

We investigate the possibility of seeding a fusion plasma with nuclei which can undergo nuclear reactions with energetic alpha particles to produce product nuclei which are radioactive. If a fraction of these product nuclei can be collected and measured, one can obtain information about the presence of fast alpha particles. It appears that a feasible diagnostic could be based upon the $^{10}\text{B}(\alpha, n)^{13}\text{N}$ reaction.

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I. Introduction

Machines in the next generation of magnetic confinement fusion devices, such as TFTR and JET, are expected to produce significant quantities of energetic alpha particles by deuterium-tritium fusion reactions. How well the alpha particles are confined will be one of the most significant questions to be answered. Obtaining information about the fast confined alpha particles is, however, not straightforward, as discussed in reference 1. A technique to measure the velocity distribution of these alpha particles has been proposed [ref. 1], and it appears that this technique would be feasible with a neutral lithium doping beam of several tens of milliamperes-equivalent current, and capable of energies up to ~ 5.3 MeV [refs. 1,2]. If this diagnostic is to be implemented, however, it will require a great deal of development and expense. Accordingly, we have investigated the possibility of using a radiochemical technique to obtain some data about the fast confined alpha particles. This would yield only very coarse information about the alphas, but it would be much less costly than the Li^0 doping beam of references 1 and 2, and it would need far less development. The radiochemical technique involves seeding the plasma with a stable element which could undergo nuclear reactions with the alpha particles to produce radioactive product nuclei. A fraction of these product nuclei would be captured by a probe at the edge of the plasma, which would subsequently be withdrawn to a low-background area to count the decays.

II. Reaction Selection

Ideally, one would prefer to introduce several different isotopes with different threshold energies for alpha-induced reactions. Examining the relative amounts of radioactive daughter nuclei produced would then reveal more details about the confined alpha particle velocity distribution than could be obtained with a single reacting isotope. Unfortunately, as mentioned below, the use of several isotopes with different thresholds does not appear to be very feasible. Therefore, one is left with the simpler prospect of using only one isotope.

We applied several criteria to select possible isotopes for use with this technique. First, the product nucleus must have a usable half-life (more than a second and less than a few hours). Very short half-lives (less than a second) make counting difficult, and very long half-lives reduce the signal to background ratio, while either limiting the number of tokamak discharges that can be measured, or requiring many counting systems to analyze different probes concurrently. Secondly, the target nucleus must either be stable or have a very long half-life. The alpha-induced reaction must have a center-of-mass threshold energy which is sufficiently less than 3.5 MeV for a reasonable reaction cross section. Finally, the target nuclei should be in the lower portion of the periodic table. This is because the increasing coulomb barrier heights cause alpha particle-induced reaction cross sections to decline rapidly as the atomic numbers of the target nuclei increase. In addition, a heavy contaminant would radiate much more energy from the plasma through atomic processes than would a light contaminant.

Among reasonably light elements (we considered product nuclei with $Z \leq 16$), there were only four reactions which partially met these criteria.

Table 1 gives these reactions and their reaction Q-values. Of these, the $^{26}\text{Mg}(\alpha, p)^{29}\text{Al}$ reaction appears unusable for the detection of thermonuclear alpha particles since its threshold energy in the lab frame is 3.23 MeV, barely less than the thermonuclear alpha birth energy. The (α, p) cross section should be very small (and apparently has not been measured at these energies) since the emerging low energy protons would have to compete with the (α, n) and (α, γ) channels, both of which are open. The reaction $^{25}\text{Mg}(\alpha, p)^{28}\text{Al}$ appears more promising since its threshold energy is well below 3.5 MeV. However, this cross section also has not been measured, and is probably small due to competition for decay of the compound nucleus through the open (α, γ) and (α, n) channels. The (α, γ) Q value is + 11.13 MeV, while the (α, n) Q value is + 2.65 MeV, so these channels together should dominate the reaction width.

The $^{14}\text{N}(\alpha, \gamma)^{18}\text{F}$ reaction has a threshold energy of 0.0 MeV, and the product nucleus decays by positron emission with $t_{1/2} = 1.87$ hour. We have been unable to find any measurements for the absolute magnitude of this cross section. A gamma ray yield curve [ref. 3], which consists of scattered isolated narrow resonances, suggests that the energy averaged cross section may be relatively small.

We are left, then, with the reaction $^{10}\text{B}(\alpha, n)^{13}\text{N}$, which appears to be quite usable for this technique. With a positive Q-value, the threshold for this reaction is 0.0 MeV, but its cross

section does not begin to become significant until approximately 1.5 MeV. Boron is sufficiently light so that it will not significantly affect the radiation balance of the plasma if seeded at concentrations of a fraction of a percent. The product nucleus, ^{13}N , decays almost exclusively by positron emission with a convenient half-life of 10 minutes. Thus, one can detect the decays by using GeLi or sodium iodide detectors for the 0.511 MeV annihilation radiation.

III. Implementation

It appears that boron could be introduced straightforwardly as diborane gas (B_2H_6) which, being composed solely of boron and hydrogen, would not contribute any heavier impurities. The time dependence of the central density and the density profile of the fully ionized boron ions can be measured spectroscopically by observing the radiative decay of excited hydrogen - like boron ions produced by the charge exchange of the hydrogen atoms in a neutral doping beam with fully ionized boron ions. This technique has been used successfully on PDX [ref. 4] and other tokamaks to measure the concentration of impurities. Emerging ^{13}N ions could be collected at the edge of the plasma with a probe before they hit the limiter. It is estimated [ref. 5] that a probe subtending 1% of the poloidal angle could intercept approximately 1% of the ^{13}N produced. Carbon appears to be a desirable material for the probe since it should retain the embedded nitrogen, and is a proven limiter material. The probe could be carried by a "rabbit" to a low background area for counting after a shot. Carbon has an additional advantage in that both of its naturally occurring isotopes, ^{12}C and ^{13}C , have very low thermal neutron cross sections (0.00032

and 0.0009 barns, respectively). Even if they did undergo neutron capture with fast neutrons, they would not significantly affect the counting background. The ^{12}C would go to ^{13}C , which is also stable, and the ^{13}C would go to ^{14}C , which has such a long half-life (5568 years) that its decay rate would be low. In any event, ^{14}C decays by β^- emission, so no annihilation radiation would be produced. If the ^{14}C captured another neutron, it would go to ^{15}C , which also β^- decays, and on a timescale much shorter ($t_{1/2} = 2.3$ seconds) than the ^{13}N . In practice, one should try several probe materials to determine which one yields the lowest background radiation in the vicinity of the 0.511 MeV annihilation peak. With a carbon collector, for instance, the $^{12}\text{C} (p, \gamma) ^{13}\text{N}$ reaction could give rise to a significant annihilation radiation background (as pointed out by J. Strachan [ref. 6]) if there is a large flux of unconfined protons at several MeV. Another material which might be useful as a collector is tungsten, which would not give rise to β^+ emitters.

It will be necessary to calibrate the probe to determine the fraction of ^{13}N produced in a discharge. This calibration is probably the greatest source of uncertainty in the measurement. The calibration could be done by seeding the plasma with a percent or more of ordinary nitrogen by pellet injection. The concentration and profile of nitrogen ions as a function of time could be measured in the same way as described for the boron - by using a hydrogen doping beam and observing the radiative decay of the resulting hydrogen - like nitrogen ions [ref. 4]. There should be sufficient nitrogen embedded in the carbon probe to allow its amount to be determined by surface analysis techniques. This would allow a

calibration of the ^{13}N fraction which would actually be caught by the probe.

IV. Signal Level

Figure 1 shows the σv curve for the $^{10}\text{B}(\alpha, n)^{13}\text{N}$ reaction. The cross section was taken from reference 7 above 2.5 MeV, and from reference 8 below that. It is clear that this technique will primarily be sensitive to the higher energy alpha particles in the distribution.

In order to estimate the signal level, we have assumed that a $Q = 1.1$ plasma (approximately energy break even) in TFTR is seeded with ^{10}B at a density of $1 \times 10^{11} \text{ cm}^{-3}$. The average density of fast alpha particles for this case is $9.6 \times 10^{10} \text{ cm}^{-3}$ [ref. 9]. We assumed that their velocity distribution is the "classical" one given in reference 1, which assumes that the alpha particles slow down through two body coulomb collisions. This is the distribution which might be expected if no anomalous processes occur in the slowing down process. This would result in a total reaction rate of $6.4 \times 10^{10} \text{ sec}^{-1}$. If the hot part of the pulse persisted for 0.25 sec, this would give 1.6×10^{10} reactions per discharge. If 1% of the ^{13}N were collected on the probe, this would give a sample of 1.6×10^8 nuclei which, during the first ten minutes, would decay at an average rate of $1.3 \times 10^5 \text{ decays sec}^{-1}$. If the 0.51 MeV annihilation radiation is detected with $\sim 10\%$ efficiency, the count rate could be $\sim 1.3 \times 10^4 \text{ sec}^{-1}$. If the counting can take place between tokamak pulses in an area well shielded from the activated materials around the tokamak, the background in the vicinity of 0.51 MeV should be much lower

than this (by several orders of magnitude). Thus, even if the fraction of ^{13}N which could be captured by the probe was considerably less than 1%, there should be an adequate signal level. In addition, one could probably sacrifice a factor of 5 in the count rate and use diborane gas with natural boron (the isotopic abundance of ^{10}B is 18.8%) instead of requiring that it be isotopically enriched in ^{10}B .

For comparison, we also considered the signal that would result from the other sample alpha particle velocity distribution function discussed in reference 1. This was a "nonclassical" distribution which was simply the "classical" distribution weighted by a $(v/v_0)^4$ term, where v_0 is the alpha particle birth velocity of $1.3 \times 10^9 \text{ cm sec}^{-1}$. This distribution is similar to the classical one at high energies, but becomes depleted as the energy declines. This distribution would, however, result in only a 30% decrease in the production of ^{13}N due to the fact that this technique is much more sensitive to high energy alpha particles than to low energy ones. In the case of the "classical" velocity distribution, 52% of the ^{13}N production arises from reactions with alpha particles between 3.0 and 3.5 MeV, and 84% comes from energies above 2.5 MeV. Thus, this diagnostic would be useful for detecting the presence of high energy alpha particles. It also would be sensitive to even higher energy non-thermonuclear alphas from beam-target reactions. This diagnostic would not, on the other hand, be useful for discriminating between velocity distributions which differed only in their lower energy portions. It is doubtful, for instance, that this diagnostic could be absolutely

calibrated well enough to detect the difference between the two sample distributions we considered, which differed in their ^{13}N yields by only 30%.

V. Conclusion

It appears the $^{10}\text{B}(\alpha, n)^{13}\text{N}$ reaction could be used to obtain a rough measure of the time-averaged number of high energy (> 2.5 MeV) alpha particles in TFTR and similar D-T burning tokamaks. This technique offers less information about the alpha distribution than would the charge exchange techniques of references 1 and 2. However, it is also much simpler and cheaper to implement, and would require very little development.

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Table I

	<u>Reactions</u>	<u>Q-values (MeV)</u>
(1)	$^{10}\text{B}(\alpha, n)^{13}\text{N}$	+ 1.06
(2)	$^{14}\text{N}(\alpha, \gamma)^{18}\text{F}$	+ 4.4
(3)	$^{25}\text{Mg}(\alpha, p)^{28}\text{Al}$	- 1.19
(4)	$^{26}\text{Mg}(\alpha, p)^{29}\text{Al}$	- 2.86

Figure Captions

- (1) σv curve for the reaction $^{10}\text{B}(\alpha, n)^{13}\text{N}$. σ is taken from reference 7 above 2.5 MeV, and from reference 8 below that.

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Fig. 1