LA-UR-13-27001

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Author(s): Hayes, Anna C
Jungman, Gerard

Intended for: Report

Issued: 2013-09-09

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THE RELATIONSHIP BETWEEN KNOCK-ON CHARGED-PARTICLE REACTIONS AND REACTION-IN-FLIGHT NEUTRONS

ANNA C. HAYES AND GERARD JUNGMAN

ABSTRACT. Here we present the physics of knock-on charged particle reactions and reaction-in-flight neutrons and show how the two processes are closely related. The both probe mix in burning DT capsule, but is complementary ways. Thus, a simultaneous measure of these reactions in a NIF capsule would provide unique information on the state of the plasma formed.

Theoretical Division, Los Alamos National Laboratory, Los Alamos, NM 87545

In a burning NIF capsule, 14 MeV DT neutrons elastically scatter off of plasma ions. Although the capsule is approximately transparent to high-energy neutrons, about 10% of the produced neutrons suffer at least one such elastic collision. Recoiling knock-on ions are produced with a spectrum of energies, up to more than 10 MeV for D or T ions. In this way, a local flux of high-energy deuterons and tritons is produced throughout the capsule, at a rate proportional to the local density of ions and the local neutron flux.

These high-energy knock-on charged particles are slowed by the stopping power of the ambient plasma. Simple estimates show that the capsule hotspot is essentially transparent to charged particles with energies greater than a few MeV, while the cold fuel is effectively opaque. The stopping length for MeV charged particles in the cold DT fuel of a typical NIF capsule is quite short, of order $1\text{ }\mu\text{m}$, compared to the size of the capsule, which is more than an order of magnitude larger. Nevertheless, the high-energy particles have a chance to react with plasma ions before they are stopped. If the high-energy D or T ions suffer DT reactions with ambient plasma ions, the resulting DT neutrons are produced with a spectrum of energies well above 14 MeV, by simple kinematics; these reaction-in-flight (RIF) neutrons are the signal for the existence of an out-of-equilibrium knock-on flux in a NIF capsule. If the high-energy D or T ions react with some other ion component in the plasma, then the resulting nuclear reactions can be used to diagnose the overlap of this component with the effective region where the charged particle flux is high. Because the stopping length in the cold fuel is short, this overlap can be a useful measure of the mixing of ablator ions into the cold fuel [1]. In this note, we will refer to such reactions as radiochemical (Radchem) reactions, since the products of such reactions would generally be measurable by radiochemical assay techniques.

The purpose of this note is to examine the similarities in the physics determining the rates of these two types of knock-on reactions and the effect of ablator mixing on these rates. We will discuss radiochemical reactions which may be of interest and comment on the possibility to measure these reactions at NIF.

Date: September 6, 2013.

We begin with the general expressions for the two reactions rates per unit volume. The radiochemical reaction rate per unit volume is an integral of the reaction cross-section over the charged-particle flux,

$$\frac{d\Gamma_{\text{RC}}}{dV} = n_{\text{RC}} \int_0^{E_{\text{KO}}^{\text{max}}} \frac{d\psi_{\text{KO}}}{dE_{\text{KO}}} \sigma_{\text{RC}} dE_{\text{KO}}.$$

The RIF reactions produce neutrons in an energy spectrum, so the volume rate is differential in RIF neutron energy,

$$\frac{d\Gamma_{\text{RIF}}}{dE_{\text{RIF}} dV} = n_{\text{DT}} \int_0^{E_{\text{KO}}^{\text{max}}} \frac{d\psi_{\text{KO}}}{dE_{\text{KO}}} \sigma_{\text{DT}} \frac{dF}{dE_{\text{RIF}}} dE_{\text{KO}}$$

Here $d\psi_{\text{KO}}/dE_{\text{KO}}$ is the energy-dependent fluence of the knock-on ions, n_{RC} is the density of the radiochemical target ions, and n_{DT} is the density of the target ions for a DT reaction, D in the case of a T knock-on, and T in the case of a D knock-on. σ_{RC} and σ_{DT} are the radiochemical and DT cross sections, which are dependent on the incident knock-on energy. The factor dF/dE_{RIF} arises from the kinematics of the $d + t \rightarrow \alpha + n$ reaction, as measured in the lab frame. The measured RIF neutron signal is an integral of the differential rate over an energy window, typically above 15 MeV to avoid contamination from the 14 MeV thermonuclear peak.

Both high-energy deuterons and tritons contribute to RIF neutron production, whereas the radiochemical reactions will be specific to either initial deuterons or tritons, but not both for the same reaction.

For any plasma region in which the stopping length is short compared to the scale of variations in the temperature and density, the differential knock-on fluence can be related [2] to the stopping power dE/dx and the initial knock-on source $q(E_0) = Q_0 q_0(E_0)$,

$$(1) \quad \frac{d\psi_{\text{KO}}}{dE_{\text{KO}}}(E_f) = \frac{Q_0}{|dE/dx(E_f)|} \int_{E_f}^{E_0^{\text{max}}} dE_0 q_0(E_0).$$

Here the source of knock-ons is defined in terms of its magnitude Q_0 and a normalized initial energy spectrum $q_0(E_0)$. The shape of this spectrum is known by simple kinematics. The magnitude is determined from the 14 MeV neutron fluence ψ_{14} , the density of DT ions n_{DT} , and the knock-on cross section σ_{KO} , $Q_0 = n_{\text{DT}} \psi_{14} \sigma_{\text{KO}}$. From eq. (1), it follows that a determination of the knock-on fluence $d\psi_{\text{KO}}/dE_{\text{KO}}$ in the plasma, through a measurement of the radiochemical and/or RIF reactions, *directly* determines the stopping power.

Both the electrons and ions in the plasma contribute to the stopping power, but over the range of knock-on energies relevant for RIF and Radchem production, the electron stopping dominates. For knock-on velocities small compared to the thermal electron velocity, the stopping power can be approximated as

$$(2) \quad \frac{dE}{dx} \approx -c \frac{n_e}{\theta_e^{3/2}} \sqrt{E} \log(\Lambda).$$

Here θ_e and n_e are the electron temperature and number density; E is the kinetic energy of the ion; $\log(\Lambda)$ is the Coulomb logarithm that describes the interplay between the long- and short-range Coulomb interactions; c is a constant very nearly independent of plasma conditions. Forms of the stopping power correct for all projectile velocities are given by the perturbative calculations of Brown, Preston,

FIGURE 1. RIF neutron production rates, expressed per knock-on, per target. Multiply by the knock-on Q_0 and the target density n_{DT} to obtain the RIF neutron production rate per unit volume.

and Singleton (BPS) [3], or by the model for weakly-coupled plasmas of Maynard-Deutsch [4]. In the numerical results presented here, we will use these full forms for the stopping power. However, the approximation of eq. (2) gives reasonable estimates and provides any needed intuition for the dependence of stopping power on electron density and temperature. It is important to note that the improved theoretical forms of BPS or Maynard-Deutsch are still restricted to the weakly-coupled plasma regime. No fully reliable calculation of stopping power for strongly-coupled plasmas has yet been made. This gap in the theoretical literature is interesting and important for NIF physics, since the cold fuel region of the capsule is not weakly-coupled.

Figure 1 shows a typical RIF neutron spectrum for knock-ons in the cold fuel of a NIF capsule. The separate D on T and T on D contributions are shown, along with the total rate, differential in energy.

We next consider the effects of mixing of high-Z ablator material of a NIF capsule into the DT plasma. Such mixing affects both RIF neutron rates and radiochemical reaction rates. The effect on RIF neutron rates follows from the dependence of the stopping power on electron density, which is increased by the mixing of high-Z material into the DT fuel. Mixing high-Z material into the DT fuel will reduce RIF neutron rates, other things being equal. Table 1 displays the expressions for

number density of ions in the gas	$n_{gas} = n_{dt} + n_m$
number density of mix ions	$n_m = f n_{gas}$
number density of DT ions	$n_{dt} = (1 - f) n_{gas}$
electron number density	$n_e = n_{dt} + Z_{\text{eff}} n_m$ $n_e = (1 - f + Z_{\text{eff}} f) n_{gas}$

TABLE 1. Definition of the mix fraction f in terms of the ion and/or electron densities in the gas. Z_{eff} is the number of free electrons introduced into the gas per mix atom.

various physical quantities in terms of the mix fraction f , which is defined as the ion number densities, see the second line of the table.

Radiochemical reaction rates are effected by changes in the stopping power, in precisely the same way as RIF neutron rates, by the induced change in the high-energy particle flux. When the radiochemical targets are carried into the DT by the mixing process, because they exist as dopants in the ablator, a large increase in reaction rate can occur, because the target ions are brought into close proximity to the DT, where the knock-on flux is highest. This mixing enhancement is typically large enough that it dominates over the decrease in signal due to the increased electron density.

Using the expressions in the table to write the physical quantities in terms of the mix fraction f , we find the following expressions for the production rates.

$$(3) \quad \frac{d\Gamma_{\text{RIF}}}{dV} \propto n_{\text{DT}} \left(\frac{n_{\text{DT}}}{n_e} \right) \theta_e^{3/2} = \frac{n_{gas}(1-f)^2}{1-f+fZ_{\text{eff}}} \theta_e^{3/2},$$

$$(4) \quad \frac{d\Gamma_{\text{RC}}}{dV} \propto n_{\text{RC}} \left(\frac{n_{\text{DT}}}{n_e} \right) \theta_e^{3/2} = \frac{n_{gas}f(1-f)}{1-f+fZ_{\text{eff}}} \theta_e^{3/2}.$$

These expressions show how to scale the RIF and radiochemical rates with changes in the mix, given the ion density and electron temperature in the cases of interest.

This comparison between RIF neutron production and charged-particle radiochemical reaction rates is motivated by recent interest in a set of diagnostic reactions for high-energy (knock-on) deuterons in plasma. The set of reactions is listed in Table 2. For all the listed reactions, the main competing reaction is (p,n) with the same initial and final states. The ^{52}Mn final state is a combination of ground states and the first isomer.

It may be possible to observe and measure these reactions in NIF experiments. Cryogenic experiments would be required, to attain the necessary fuel density and temperature. Since these are all incident deuteron reactions, the physics of charged-particle transport affects them in precisely the same way. Therefore, the independent ratios obtainable from this set provide direct information on the reactions themselves, independent of stopping power or mixing. It would, however, be necessary to insure that a significant amount of mixing occurs in the experiments, to raise the radiochemical signatures to detectable levels.

$^{48}\text{Ti}(\text{d},2\text{n})^{48}\text{V}$
$^{52}\text{Cr}(\text{d},2\text{n})^{52}\text{Mn}^{\text{g,iso}}$
$^{79}\text{Br}(\text{d},2\text{n})^{79}\text{Kr}$
$^{127}\text{I}(\text{d},2\text{n})^{127}\text{Xe}$
$^{151}\text{Eu}(\text{d},2\text{n})^{151}\text{Gd}$

TABLE 2. High-energy (knock-on) deuteron reactions of interest. There are competing reactions that need to be taken into account in calculating the production of the final nucleus in any plasma. The main competing reaction is (p,n) with the same initial and final state.

The noble gas final states are particularly interesting since a gas-collection system is already in place at NIF and has demonstrated successful extraction of noble gas products. Other final states would require the development of a debris collection capability, which the focus of some ongoing work.

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THEORETICAL DIVISION, LOS ALAMOS NATIONAL LABORATORY, LOS ALAMOS, NM 87545