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Proton bremsstrahlung and its radiation effects in fusion reactors

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ABSTRACT

Protons and neutrons are emitted in many fusion processes of light nuclei. In a fusion reactor, a proton and a neutron thus generated may again fuse with each other. Or they can in turn fuse with or be captured by an un-reacted nuclear fuel, for example deuterium. The average center-of-mass energy for such reaction is around 10 keV in a typical fusion reactor. At this low energy, the reacting nucleons are in an s-wave state in terms of their relative angular momentum. The single-gamma radiation process is thus strongly suppressed due to conservation laws. Instead the gamma ray released is likely to be accompanied by soft X-ray photons from a nuclear bremsstrahlung process. The generated soft X-ray has a continuous spectrum and peaks around a few hundred eV to a few keV. The average photon energy and spectrum properties of such a process are calculated with a semi-classical approach, with the explicit example of proton–neutron capture. This phenomenon may have been observed in some prior tokamak discharge experiments, and its interpretation is complicated by the presence of electron bremsstrahlung. However, it also opens up the possibility of new plasma diagnostics which are more sensitive to the ionic or nuclear degree of freedom.

1. Introduction

Three nuclear fusion processes, namely, deuteron–deuteron (D–D), deuteron–tritium (D–T) and D–^{3}He, are among the most studied candidates for fusion power generation [1]. All of the three involve generation of nucleons, namely proton or neutron or both. For future thermonuclear reactors based on the D–T reaction, the generation of neutrons is the natural consequence of the major power producing reaction. However, protons are also generated by the parasitic D–D reaction according to

$$d + d \rightarrow {}^3\mathrm{H} + p, \tag{1}$$

where d is a deuteron. This reaction has a small but non-negligible rate compared to the D–T reaction. In fact its rate is from one to two orders of magnitude within that of D–T between 10 keV and 100 keV.

The proton, once generated, could again participate in the thermonuclear process via other reactions. The simplest is the proton capture on neutron,

$$p + n \rightarrow {}^2\mathrm{H} + \gamma. \tag{2}$$

Alternatively, it can fuse with the un-reacted deuterium fuel via

$$p + d \rightarrow {}^3\mathrm{He} + \gamma. \tag{3}$$

Processes (2) and (3) are well known to generate a gamma photon (2.23 MeV and 5.49 MeV, respectively), with possible complications to the reactor vessel design. We now consider an associated or parasitic radiation accompanying (2) and (3) due to a nuclear bremsstrahlung process, which will generate soft X-rays on the order of 1 keV besides the MeV gamma. For example, the reaction (3) is more precisely

$$p + d \rightarrow {}^3\mathrm{He} + \gamma + X, \tag{4}$$

where the total energy carried away by the gamma and the soft-X ray is 5.49 MeV, minus the small recoil kinetic energy of the ^{3}He, which is often negligible. Similarly reaction (2) is more appropriately

$$p + n \rightarrow {}^2\mathrm{H} + \gamma + X. \tag{5}$$

The bremsstrahlung X-ray spectrum is continuous, and the photon released in this process is very soft, on the order of a few keV or less. Because soft X-ray of this energy is difficult to detect, and gamma ray in Eq. (4) is still very close to 5.49 MeV, this reaction is difficult to differentiate from the standard one in Eq. (3). In essence, the soft X-ray generation is due to the following physical process.

First take the simplest case of p–n capture as an illustration. A proton and a neutron attract each other via the nuclear (strong) force. The strong nuclear attraction causes both nuclei to accelerate to each other. Because the proton is charged, electromagnetic EM radiation is generated according to the theory of classical electrodynamics. The radiation is therefore similar to a bremsstrahlung in

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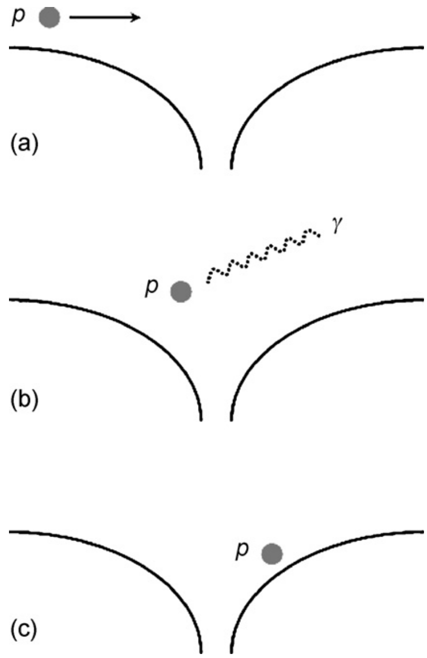

Fig. 1. . The nuclear bremsstrahlung process that releases soft X-ray in the proton–neutron capture and proton–deuteron fusion. The solid curves represent the attractive nuclear potential of a neutron (deuteron) felt by a proton. The length dimension shown is ∼10 fermi. (a) The proton, having an initial positive kinetic energy of several keV, is moving towards the neutron (deuteron) due to nuclear attraction. (b) The proton accelerates in the process, and therefore starts radiating EM waves or photons. (c) The proton, having lost all of its initial kinetic energy and maybe more, now has a total energy of negative value, i.e., it is now in a bound state around the neutron (deuteron). Afterwards, it may emit a gamma of 2.23 (5.49) MeV and then combine with the neutron (deuteron) to finally form a ^{2}H (^{3}He).

the nuclear domain. The release of the energy of the nuclei, is not through the deceleration alone, it also proceeds during *acceleration* by the strong force because the nucleons undergo both acceleration and deceleration in such a process. Here we loosely term it nuclear Bremsstrahlung, or maybe nuclear Startstrahlung to accentuate its origin in acceleration due to the nuclear force. Such a mechanism radiates X-ray photons around 1 keV, as we will demonstrate later.

Similar processes happen in other fields of physics. Beschleunigungsstrahlung or the emission of "acceleration radiation", results when target electrons are accelerated by the Coulomb field of the incident nucleus [2]. In astrophysics, the acceleration of charged particles due to gravity near a black hole also results in strong radiation.

The case for proton–deuteron nuclear bremsstrahlung is in principle similar to that of the *p*–*n* type. An added complication is due to the Coulomb repulsion. However, once the Coulomb barrier is overcome by quantum mechanical tunneling, the strong nuclear attraction still causes both nuclei to accelerate to each other, albeit at different rates due to the mass difference. Both particles are charged and hence they all radiate EM quanta. Because both particles are positively charged but move in opposite directions, the radiation from them tends to cancel at the far field due to opposite accelerations. The cancellation is however not complete because the acceleration is not identical for proton and deuteron due to their mass difference.

The aforementioned process is summarized in Fig. 1. The potential field is that felt by the proton in the coordinate of a neutron (deuteron). In reality, the frame of reference attached to the neutron (deuteron) is not stationary because the neutron (deuteron) also accelerates and decelerates in the same time in an inertial frame of reference. The acceleration of neutron is radiation free, so one only needs to consider radiation from the proton in the *p*–*n* reaction. For the *p*–*d* fusion, however, the deuteron radiates too. Such a radiation is not labeled out in Fig. 1 for the purpose of clarity.

Soft X-ray bremsstrahlung is often encountered in charged nucleon interaction [3]. The accurate measurement of it is often complicated with the lack of proper window material for the detector and the lack of proper crystals that match its wavelength. A soft X-ray is also well known for its strong attenuation in solids. One consequence is therefore the possible intense heating to the shallow inner surface of a fusion reactor.

The soft X-ray process outlined in Eq. (4) and its *n*–*p* equivalent should also accompany some other fusion reactions of light nuclei. Because the bremsstrahlung power is proportional to the acceleration squared, it should be more pronounced to lighter nuclei. The D–T fusion, for example, should have a similar but nevertheless smaller effect. In the D–D reaction, the bremsstrahlung tends to cancel out, at least in the electric dipole level, due to the identical mass of the two deuterons. The proton–deuteron fusion turns out to have the most pronounced bremsstrahlung effects among charged-nuclear fusions. It also has the largest Coulomb tunneling rate due to the lightness of its reduced mass, which enhances the effect of a nuclear bremsstrahlung at low center-of-mass (COM) energy.

Therefore, it is rather clear that our studies of nuclear bremsstrahlung effects in fusion reactors should focus on the two model reactions of *p*–*n* and *p*–*d*. Of the two, the *p*–*n* tends to have higher nuclear cross-sections (note that here we are not interested in the Coulomb collisional cross-sections) at, say 10 keV, because there is no Coulomb barrier to overcome for a neutron. However, the *p*–*n* nuclear cross-section tends to decrease with energy while that of *p*–*d* increases, at least for the energy range interested to us. When only the two-body nuclear cross-section is considered, the *p*–*n* is likely more important at 10 keV or below. At higher energy, the contribution from *p*–*d* could be significant too. In a fusion reactor, the relative importance of the two is complicated by factors such as the collisional mean free path, and the fuel used.

With the simple yet profound physics in mind, one might wonder why nuclear bremsstrahlung has rarely been observed or probed at a few keV. Two possible reasons are as follows. First, the particle or high energy physics communities have mainly focused on increasingly higher energy scale in the past 70 years. At very high kinectic energy, the nuclear bremsstrahlung loss is small percentage-wise when compared with the total kinetic energy of the reacting nuclei. Second, at lower kinetic energy, say 1 keV or below, the loss due to bremsstrahlung is comparable to the total kinetic energy, the effects on nuclei motion are significant. However, the soft X-ray is still difficult to measure, let alone to say a careful characterization of the spectrum. A 1 keV soft X-ray photon has an average penetration of roughly 1 μm for medium-Z materials. Such a radiation is therefore difficult to differentiate from a thermal effect, and might be easily discounted as a long wavelength background in, for example, gamma ray spectroscopy.

However, we do notice recently reported anomalies in neutron–proton scattering cross-section at epithermal energy (up to ∼1 keV) [4,5]. The early suggested explanation in terms of "quantum entanglement" does not stand up well against the new experiments [5]. The authors of this paper do believe that this anomaly is intrinsically a nuclear phenomenon associated with the additional loss of energy due to nuclear bremsstrahlung. In essence, the loss of kinetic energy for the neutron slows it down more than expected, making the effective *n*–*p* capture cross-section higher. As the result, fewer neutrons are scattered to the detector, manifested as a deficiency in the neutron counts compared to the expected. The release of soft X-ray is also a logical reason for the break-down of the "impulse approximation" assumed in the standard analysis of neutron cross-section [5].

A detailed account of this anomaly in neutron–proton scattering is beyond the scope of this paper, and will constitute a separate