Alpha particle velocity space and orbit sensitivity of gamma-ray spectroscopy diagnostics based on the $^{10}B(\alpha,p\gamma)^{13}C$ reaction

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One of the most important mid-term goals for the development of nuclear fusion as an energy source is the exploration of the physics of the so-called "burning plasmas", i.e. a regime where the sustainment of the plasma discharge is primarily due to the self-heating provided by the alpha particles born from the fusion reaction between deuterium and tritium. This is one of the main missions of the ITER tokamak, the largest publicly funded device under construction in France, and of complementary private or public-private initiatives, such as the SPARC and BEST tokamaks that are being built in the USA and China, respectively.

In order to understand the physics of a burning plasma, measuring the alpha particle phase space has long been recognized as a key task which is, however, experimentally challenging and will require the combination of measurements obtained with different diagnostics. Gamma-ray spectroscopy is one of the few demonstrated methods that can access the alpha particle phase space by the observation of the line emission from spontaneous nuclear reactions between the alpha particles and impurities in the plasma (Kiptily & al., 2002) (Nocente & al., 2020). Following the adoption of tungsten as the first wall material of ITER - and its use in other burning plasma experiments currently under construction - this work presents, for the first time, the velocity space and orbit sensitivity of alpha particle measurements based on gamma-ray emission reactions between the alpha particles and boron impurities. Boron, in lieu of beryllium formerly used as the target for gamma-ray spectroscopy diagnostics, is expected to be present in the plasma due to its use for wall conditioning or because it is injected on purpose.

In the past years, gamma-ray spectroscopy has been established primarily at the Joint European Torus (JET) as a means to measure the properties of the energetic ions. This relied on the spontaneous nuclear reactions with ^{12}C or ^{9}Be impurities, depending on the material used for the first wall of JET throughout its operational lifetime. In the most recent deuterium-tritium DTE2 and DTE3 campaigns with a beryllium first wall, alpha particle measurements based on gamma-ray emission spectroscopy have been demonstrated in some discharges, both using a high purity germanium detector (Kiptily & al., 2024) and with the $LaBr_3(Ce)$ scintillator (Nocente & al., 2022). The measurements relied on the 4439 keV line (nominal energy) due to the $^{9}Be(\alpha,n\gamma)^{12}C$ reaction between the alpha particles and ^{9}Be impurities naturally found in the core of JET plasmas, at a typical concentration of 1%. On the theoretical side, methods to determine the velocity space sensitivity of gamma-ray spectroscopy measurements based on $^{9}Be(\alpha,n\gamma)^{12}C$ reaction have been developed and formulated in terms of "weight functions". The latter are matrices that provide the probability of measuring a certain region in the alpha particle velocity space when counts are observed in a given energy channel of the gamma-ray spectrum. Figure 1 shows an example of weight functions for the 4484 keV channel in the blue-shifted tail of the 4439 keV (nominal) line from the $^{9}Be(\alpha,n\gamma)^{12}C$ reaction observed at JET, when measurements are made along a line of sight that makes an angle of 30 degrees or 90 degrees with respect to the magnetic field.

Following the re-baseline of the ITER project, no burning plasma device currently plans to use beryllium as the first wall material and alternative nuclear reactions must be sought to observe alpha particles using gamma-ray spectroscopy. An interesting candidate is provided by the $^{10}B(\alpha,p\gamma)^{13}C$ reaction that occurs when ^{10}B impurities are available in the plasma, for example due to the use of boron to condition the first wall of the

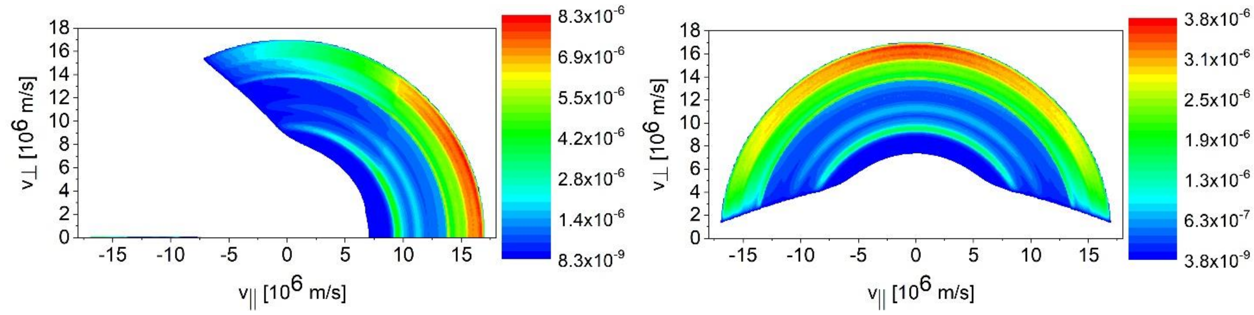

Figure 1. (left) Weight functions associated with the blue-shifted 4484 keV energy bin of the 4439 keV (nominal) line from the $^{9}Be(\alpha,n\gamma)^{12}C$ reaction, when the line of sight makes an observation angle of 30 degrees (left) and 90 degrees (right) with respect to the magnetic field.

device. The ^{10}B(α,pγ)^{13}C reaction has a smaller cross section compared to ^{9}Be(α,nγ)^{12}C but, on the other hand, it leads to three (rather than one) emission lines, at nominal energies of 3089 keV, 3684 keV and 3854 keV, providing enhanced alpha particle velocity space capabilities.

Benefitting from a recent, detailed evaluation of the cross section to generate the 3089 keV, 3684 keV and 3854 keV peaks from ^{10}B(α,pγ)^{13}C (Kiptily, 2024), we have calculated, for the first time, the velocity space sensitivities of boron based gamma-ray measurements. These are presented in this work and used to discuss the velocity space regions than can (and cannot) be measured by gamma-ray spectroscopy, also depending on the line of sight of the instruments and assuming an ideal response function of the detector.

We then consider the special case of the ITER Radial Gamma-Ray Spectroscopy diagnostics, which is a set of three gamma-ray spectrometers under design for installation along three independent radial lines of sight viewing the core of ITER plasmas. Depending on the detector used, $LaBr_3$(Ce) or HpGe, we can evaluate the corresponding synthetic spectrum (see Figure 2) that, due to the finite energy resolution and specific response features of the instrument, appears as a rather complex superposition of lines, particularly if $LaBr_3$(Ce) is used. By encompassing the detector response matrix in the weight function formalism, we are able to identify the impact that the choice of the detector has on the velocity space resolution of the measurements and to provide guidance on the detector choice from a physics point of view. By exploiting a recently developed method to calculate the sensitivity of gamma-ray spectroscopy measurements to the fast ion orbits (Valentini & al., 2025), rather than energies and pitch, we can furthermore evaluate which alpha particle orbits can (and cannot) be measured by RGRS at ITER and understand how the (ideal) orbit space resolution of the measurements is affected by the properties of the detectors.

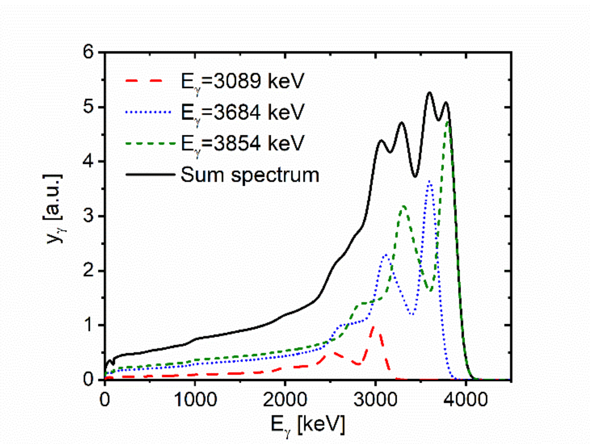

Figure 2. Simulation of the gamma-ray emission spectrum from the $^{10}B(\alpha,p\gamma)^{13}C$ reaction measured along one of the RGRS lines of sight assuming $LaBr_3(Ce)$ as the detector and without neutron induced background.

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