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Spectral Broadening of Characteristic γ-Ray Emission Peaks from $^{12}C(^{3}He,p\gamma)^{14}N$ Reactions in Fusion Plasmas

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ABSTRACT

The spectral broadening of characteristics γ-ray emission peaks from the reaction $^{12}C(^{3}He,p\gamma)^{14}N$ was measured in $D(^{3}He)$ plasmas of the JET tokamak with ion cyclotron resonance heating tuned to the fundamental harmonic of ^{3}He. Peak shapes and intensities were analyzed on the basis of detailed Monte Carlo simulations in order to determine the ^{3}He effective temperature and density. The results demonstrate the potential of high-resolution γ-ray spectroscopy measurements as a probe of energetic ions in fusion plasmas.

INTRODUCTION

Investigations of energetic ions in fusion experiments are motivated by the need to understand and, eventually, control the physical processes involving α particles in a burning Deuterium-Tritium (DT) plasma [1]. This is a long-term goal where experimental progress is limited by the availability of high current fusion devices providing good confinement of energetic ions [2]. The Joint European Torus (JET) tokamak is the only operating fusion device suitable for confinement of ions with energies well above 1MeV [3]. MeV ions can be generated in JET by fusion reactions (e.g. 3.5MeV α-particles from DT fusion) or by Ion Cyclotron Resonance Heating (ICRH). The latter accelerates ions in a plane perpendicular to the plasma magnetic field up to energies limited by Coulomb collisions [4]. Measurements of the fast ion energy distribution or its moments are needed in order to perform quantitative experiments with fast ions in fusion plasmas, e.g. to study their effect on the MHD stability of the plasma discharge [5].

Observations of confined fast ions are difficult and generally require the emission of suitable radiation escaping from the plasma. Neutron emission spectroscopy [6] is an effective probe of fast deuterons or tritons undergoing fusion reactions; it is also an indirect probe of α-particles when the so-called "alpha knock-on" mechanism leads to sufficient levels of neutron emission [7,8,9]. Neutral particle emission spectroscopy, due to fast ions that leave the plasma after neutralization reactions, and other atomic radiation processes are used for ions of not too high energy due to the underlying cross sections [10,11]. For more energetic ions γ-ray emission spectroscopy is the main source of in information. A number of nuclear reactions resulting in measurable levels of γ-ray emission have been observed in JET [12]. The most common reactions occur between fast ions and plasma impurities; e.g. reactions involving fast H, D, ^{3}He and ^{4}He ions accelerated by ICRH have been observed in JET. Often information on the fast ion energy distribution is obtained from the intensities of characteristic γ-ray peaks; e.g. most reactions feature energy thresholds, so that energy distributions can sometimes be inferred from observations of the relative intensities of multiple γ-ray peaks. Clearly the information that can be obtained from the analysis of a few peak intensities is valuable but, at the same time, limited and often subject to poorly quantified systematic uncertainties. Over twenty years ago [13, 14] it was realized that more detailed and accurate information could in principle be obtained from the Doppler-broadened shape of the γ-ray peaks. This kind of measurements was proposed for application at future DT fusion experiments but never attempted on present-day plasmas. This letter reports the first high-resolution γ-Ray Spectroscopy (GRS) observations in a fusion plasma. The GRS measurements were performed on JET and interpreted in terms of Doppler broadening of the γ-ray peaks from energetic ^{3}He ions accelerated by ICRH.

The measurements were performed with a High Purity Germanium detector featuring 100% relative photopeak efficiency and 2.4keV energy resolution at the calibration energy $E\gamma = 1.33$MeV [15]. Although commonly available at nuclear radiation laboratories, spectrometers of this kind were never used at fusion devices. Operation in a present-day fusion environment was made possible by choosing N-type germanium, which is more resilient to neutron damage, and by equipping the detector with an electro-mechanical cooling system instead of liquid nitrogen cooling to facilitate operation in restricted areas. List mode digital acquisition recorded pulse height and time of each detection event; these data were converted to energy spectra after calibration with radiation sources providing <1keV accuracy. The detector was placed in a shielded location 23m above the tokamak viewing the plasma along a vertically collimated line of sight orthogonal to the toroidal magnetic field [16]. In these experiments the toroidal field value was 3.45T and the plasma current ranged from 1.8 to 3.0MA, which ensured good confinement of the fast ions. ICRH was operated at a frequency of 33MHz which is the fundamental resonance frequency of ^{3}He at the plasma axis major radius location of 2.84m. Steady state ICRH power levels up to 6MW were coupled to deuterium plasmas with electron densities of $2\text{-}3\times10^{19}$ m^{-3} and electron and ion temperatures of $T_e \approx 3\text{-}8$keV and $T_i \approx 3\text{-}5$keV, respectively. The plasmas contained a moderate level of carbon and other impurities; ^{3}He minority concentration levels of 1-5% were achieved after injecting small amounts of ^{3}He gas. These conditions are suitable for the generation of a population of energetic ^{3}He ions in the plasma in predominantly trapped orbits with velocities nearly perpendicular to the magnetic field. The presence of energetic ^{3}He ions was demonstrated by the γ-ray observations reported here.

A total of seven plasma discharges with several seconds of γ-ray emission were produced. Data collected from all discharges were added up to achieve good statistics in the γ-ray energy spectra. Evidence on energetic ^{3}He ions comes mainly from the two γ-ray spectral peaks at $E_{\gamma1} = 2313$keV and $E_{\gamma2} = 1635$keV shown in Fig.1. Both peaks ride on top of a nearly flat background.

Statistical analysis of the $E_{\gamma1}$ and $E_{\gamma2}$ peaks after back ground subtraction yields intensities of $I_1 = 6516\pm80$ and $I_2 = 2755\pm53$ and peak widths - defined here as $W_1 = 2.355\cdot\sigma$ where σ is the standard deviation - of $W_1 = 39.4\pm0.3$keV and $W_2 = 26.5\pm0.4$keV, respectively. For comparison the instrumental energy resolution is about 3.5keV at these energies, which means that instrumental broadening of the peak shape is negligible. From the calculated HPGe photopeak efficiency and γ-ray attenuation along the viewing line the relative γ-ray yield is determined to be $r = Y_{\gamma1}/Y_{\gamma2} = 2.8\pm0.2$; the uncertainty is dominated by systematic error of photon transport simulations relating the plasma emissivity to the observed event rates. The analysis of the peaks and their shapes requires detailed knowledge of the underlying nuclear reaction differential cross sections and branching ratios for γ-ray emission. The ^{12}C(^{3}He, p)^{14}N* reaction is exothermic, with a Q value of 4.78MeV, which exceeds the energy of the first two ^{14}N excitation levels. Level L1 at 2313keV decays to the ground state with emission of $E_{\gamma 1}$ γ-rays with $b_1 = 100\%$ probability (branching ratio). Level L2 at 3948keV has a $b_2 = 96\%$ probability of decaying to level L1 thus emitting a cascade of $E_{\gamma 2}$ and $E_{\gamma 1}$ γ-rays of equal intensities. At ^{3}He energies in the MeV range, ^{14}N excitation levels above L2 contribute to the peaks at $E_{\gamma 1}$ and $E_{\gamma 2}$ through cascade transitions as summarised in Table 1. The effective cross section for emission of $E_{\gamma 1}$ and $E_{\gamma 2}$ γ-rays is given by $\sigma_{\gamma 1} = \Sigma b_{i1} \cdot \sigma_{Li}$ and $\sigma_{\gamma 2} = \Sigma b_{i2} \cdot \sigma_{Li}$ where σ_{Li} (i=1-8) is the cross section for populating the i-th 14N excitation level. These cross sections were determined from the differential cross section values available in the literature after some interpolation and consistency analysis. All cross sections rise rapidly above1MeV and reach their largest values above 2MeV. Main contributions to the $E_{\gamma 1}$ peak come from L1 and L2; however contributions from the upper levels cannot be neglected. The situation is simpler for the $E_{\gamma 2}$ peak which is entirely due to L2 except for a resonance in the L8 cross section around $E_{^3\mathrm{He}}$ = 3MeV. The relative γ-ray yield $r = \sigma_{\gamma 1}/\sigma_{\gamma 2}$ for monoenergetic ^{3}He is readily determined from the cross section values and is shown in Fig.2. A detailed discussion of its wide oscillations in terms of the underlying nuclear structure properties is beyond the scope of the present work. The measured value $r = 2.8 \pm 0.2$ suggests that most of the γ-emitting ^{3}He ions in the plasma must have an energy below 3MeV. One can go one step further and determine the yield ratio for the case of ^{3}He ions described by a Stix distribution with an asymptotic tail temperature T_{3He} (Fig.2). The simulations show that the r value is only slightly sensitive to T_{3He} in the range $100\mathrm{keV} < T_{3He} < 500\mathrm{keV}$. Any T_{3He} value within this range is compatible within the uncertainties of the measured r value.

The absolute level of the γ-ray count rate in the detector can be used to estimate the ^{3}He density $n_{3\mathrm{He}}$ in the plasma. The average rate at the $E_{\gamma 2} = 1635$keV full energy peak was 98±2 count/s, with a minimum and maximum value of 54 counts/s and 157 counts/s respectively during the seven discharges under analysis. This corresponds to an estimated γ-ray emissivity of $1.7 \cdot 10^{12}$ s^{-1} in the plasma core with systematic uncertainties of a factor 2 mainly due to the viewing line geometry. The emissivity changes significantly with the ^{3}He temperature with an increase of about 3 orders of magnitude as T_{3He} is raised from 200keV to 500 keV. Assuming $T_{3\mathrm{He}} \approx 400$keV and a ^{12}C density of $8.5 \cdot 10^{-17}$ m^{-3} determined by CXRS data, the value $n_{3\mathrm{He}} = 6.8 \cdot 10^{-17}$ m^{-3} is found. This is consistent with ^{3}He concentration values between 1 and 5 % measured in real time during the discharges. Similar results are obtained by analyzing the $E_{\gamma 1} = 2313$ keV full energy peak.

We can now analyse the Doppler broadening of the γ-ray peaks. The γ-ray energy in the lab-system is Doppler shifted with respect to the reference value $E_{\gamma 0}$ by the amount $\Delta E_\gamma / E_{\gamma 0} = (V_\mathrm{N}/c) \cos \theta_{\gamma\mathrm{N}}$, where V_N is the $^{14}\mathrm{N}^*$ velocity and $\theta_{\gamma\mathrm{N}}$ is the angle between the emitted γ ray and the excited ^{14}N nucleus. In turn, the velocity of each excited ^{14}N nucleus emitting a γ-ray is determined by simple kinematics from the initial ^{3}He velocity and the angle θ between the directions of the ^{3}He and the outgoing proton. Thus the final γ-ray energy spectrum reflects the energy and direction distribution of the initial ^{3}He population in the plasma, with weights provided by the differential cross section $d\sigma_i / d\Omega\,(\theta)$ (i = 1-8) for populating the L1-L8 ^{14}N levels.

The γ-ray spectrum is determined here using the Monte Carlo code GENESIS, a modified version of a code developed for neutron emission spectrometry applications [17]. An assumption made in the simulations is the absence of correlation in the γ-ray direction relative to the proton direction; i.e. each γ-ray emission direction with respect to the ^{14}N velocity is equally probable. This allows us to simulate the two reaction steps independently. Although the code can simulate the γ-ray spectrum from an extended ^{3}He distribution in the plasma volume, in this letter we consider the simpler case of emission from a point in the plasma. Furthermore we assume a Gaussian pitch angle distribution of the ^{3}He ions centred at $\theta_p = 90°$,, and with FWHM = 10°; i.e. the ^{3}He ions gyrate with nearly perpendicular velocities around the horizontal magnetic field. Since the γ-ray spectrometry viewing line is also perpendicular to the magnetic field we expect the resulting γ-ray spectrum to be double-humped. This is a well-known feature of fusion neutron spectra for similar viewing geometries [6].Examples of simulated γ-ray spectra for monoenergetic ^{3}He ions are shown in Fig.1 for the $E_{\gamma 1}$ and $E_{\gamma 2}$ peaks and $E_{3He} = 2$, 3 and 4MeV. All spectra are symmetric around the unshifted energies $E_{\gamma 1}$ and $E_{\gamma 2}$ and do have a double hump shape though modulated by the angular dependence of the differential cross sections $d\sigma_i / d\Omega\ (\theta)$. To be noted is the spectral width. This is shown in Fig. 2 where the broadening $W = 2.355 \cdot \sigma$ of the simulated γ-ray emission peaks is plotted for monoenergetic ions of energy up to 5 MeV. The peculiar behaviour of the ^{12}C(^{3}He, pγ)^{14}N reaction cross sections results in a peak width that is practically independent of ^{3}He energy over the 2.0-3.5MeV energy range. In the case of Maxwellian ^{3}He ion population of different temperature T_{3He} (Fig. 2), it is found that the broadening increases with the temperature. However, for T_{3He} values from 300 to 500keV the variation is small (7%). Thus the experimental spectral width value is compatible with a broad range of T_{3He} values.

A similar conclusion is reached by detailed shape analysis of the γ-ray peaks. The simulated spectra fitted to the data in Fig.1 assume ^{3}He ions described by a Stix distribution [4] with an asymptotic tail temperature $T_{3He} = 400$keV. The resulting reduced χ^2 values are $\chi^2 = 1.8$ for the $E_{\gamma 1}$ peak and $\chi^2 = 1.7$ for the $E_{\gamma 2}$ peak. The lower limit T_{3He} value resulting in a χ^2 increase by one is $T_{3He} = 200$keV. No useful upper limit to T_{3He} can be inferred: the simulated spectra shown in Fig.3 feature a remarkable shape invariance above 300keV. We conclude that a temperature value $T_{3He} > 300$keV was reached in the experiments reported here, $T_{3He} \approx 400$keV being a likely value based on the agreement between the expected gamma ray yield and the measured one for ^{3}He densities of a few percents and due to the minimum reduced χ^2 value obtained at this temperature.

Simulations of the RF heated ^{3}He energy distribution were performed with the CYRANO/TOMCAT wave codes [18, 19]. The results indicate that temperatures above T = 300keV were reached in all discharges, in agreement with the experimental evidence reported in this letter.

When observed more carefully, the measured spectra in Fig.1 seem to have an asymmetry in the top part of the spectrum: a few data points on the high energy side are systematically above the fitted curve whereas a few data points on the low energy side are systematically below the fitted curve. Our present model cannot account for the asymmetry which is at the limit of statistical significance. Should better data confirm the evidence of asymmetry, a possible explanation can be sought by taking into account the viewing geometry and how it affects the full observation of gyration orbits around the magnetic field. Indeed we can reproduce the observed asymmetry if we assume that a ~10% fraction of the gyrating ions falls out of the volume viewed by the spectrometer when moving downwards (i.e. away from the spectrometer). Evidence for effects of this kind can be sought e.g. by looking for correlation with the ion orbit size: i.e. larger ion orbits should result in a stronger asymmetry in the GRS spectrum.

Another feature which seems to be marginally outside the statistical uncertainty and not accounted for by our model is an excess of events in the low energy side of the $E_{\gamma 1}$ peak. Peaks from the $^3He(^9Be, p\gamma)^{11}B$ reaction were also observed in the collected γ-ray spectrum, but with lower intensities with respect to those from $^3He(^{12}C, p\gamma)^{14}N$. Transitions from $^{11}B^*$ excited states are expected to yield gamma rays of energies 2298keV and 2265keV, i.e. in the region where the excess of events for the E≥1 peak is observed. A detailed Monte Carlo simulation has not been done for this particular reaction, but we speculate that emission from $^{11}B^*$ may be the reason of the observed excess of counts in the low energy side for the $E_{\gamma 1}$ peak. Because of this unaccounted component only the right hand side ($E > E_{\gamma 1} = 2313$keV) of the $E_{\gamma 1}$ peak was used to determine W_1 and χ^2 values.

In conclusion, first measurements of the spectral broadening of γ-ray emission peaks from fusion plasmas were reported. Analysis of a set of discharges measured in $D(^3He)$ plasmas of the JET tokamak showed that high resolution γ-ray spectroscopy can be used to determine the ^3He effective tail temperature. Limitations due to peculiarities of the reaction $^{12}C(^3He,p\gamma)^{14}N$ cross section were reported. Detailed simulations using the differential cross section $d\sigma_i/d\Omega(\theta)$ (i = 1-8) for populating the L1-L8 ^{14}N excitation levels were needed in order to reproduce the observed γ-ray spectral shapes. The results demonstrate the potential of high-resolution GRS measurements as a probe of energetic ions in fusion plasmas. They also show that the quantitative diagnostic potential of γ-ray spectroscopy must be judged for each type of reaction in the plasma taking into account the complexity of the underlying nuclear cross sections.

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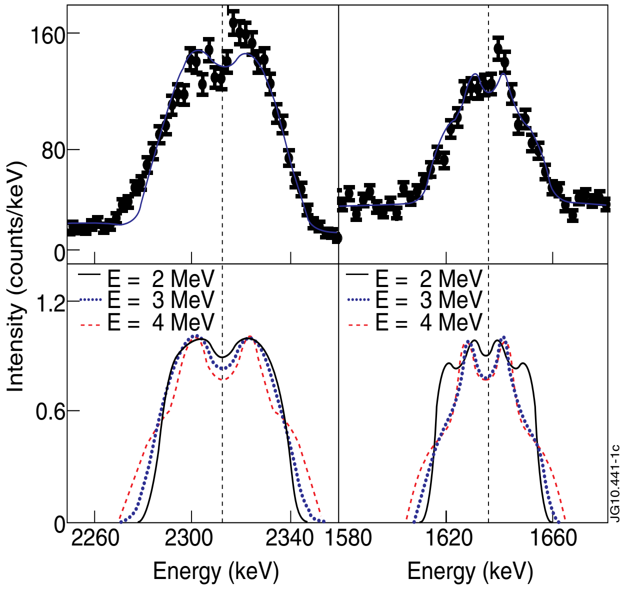
Level	**Energy**	**b_1 (%)**	**b_2 (%)**
L1	2313	100	0
L2	3948	96	96
L3	4915	0	0
L4	5106	20	1
L5	5691	64	0
L6	5834	16	1
L7	6204	77	0
L8	6446	21	19

Table I: Energies of the first eight ^{14}N excited states with branching ratios for emission of γ-rays of energy $E_{\gamma 1}$ = 2313keV and $E_{\gamma 2}$ = 1635keV.



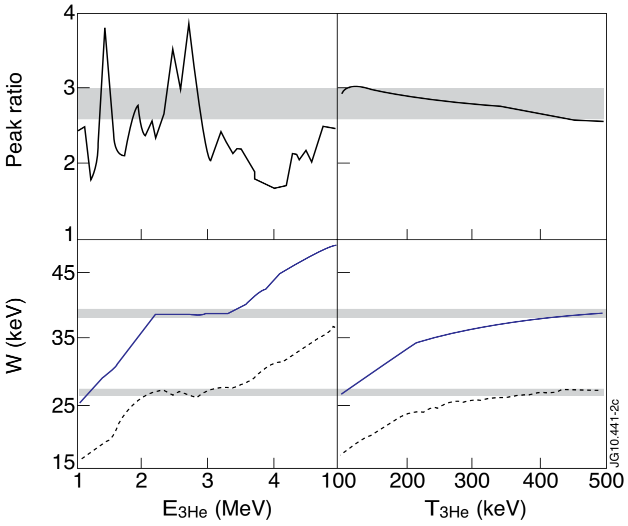


Figure 1: (colour on line) Top: experimental and fitted (blue) peak shapes for the $E_{\gamma 1}$ (left) and $E_{\gamma 2}$ (right) γ-ray emission peaks. The unshifted $E_{\gamma 1}$ = 2313 keV and $E_{\gamma 2}$ =1635 keV values are marked with vertical dashed lines. Bottom: Normalized simulated $E_{\gamma 1}$ (left) and $E_{\gamma 2}$ (right) peak shape for monoenergetic ^{3}He ions with Gaussian pitch angle distribution centred at θp=90° and with FWHM=10°.

Figure 2: Peak ratio (top) and width (bottom) of the simulated $E_{\gamma 1}$ and $E_{\gamma 2}$ γ-ray emission peaks for monoenergetic ^{3}He ions of different energies (left) and Maxwellian ^{3}He ions of different temperature (right). The horizontal bands are the experimental values.

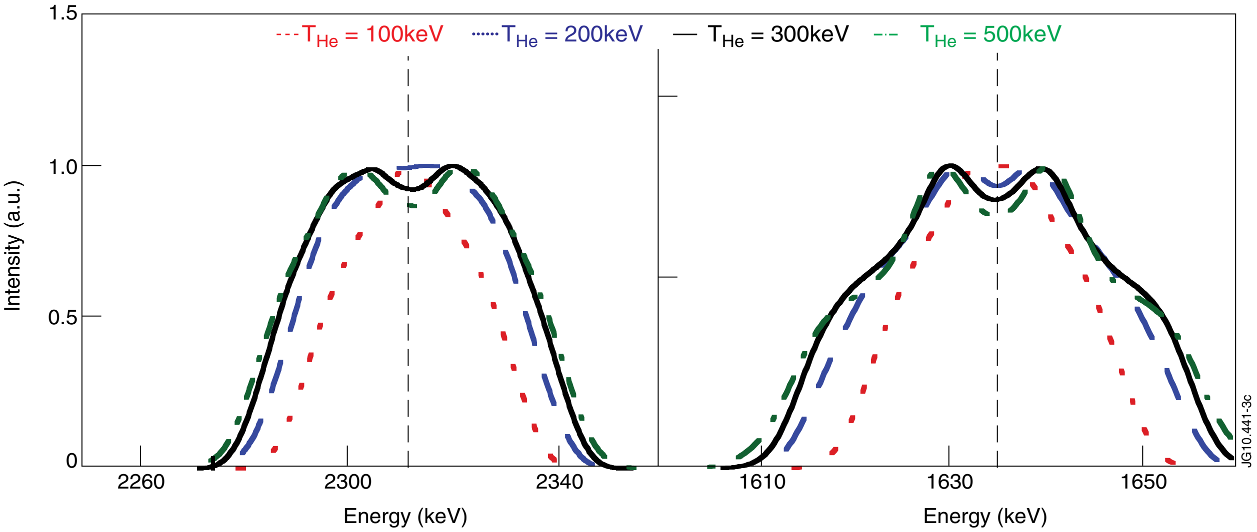


Figure 3: (colour on line) Simulated $E_{\gamma 1}$ (left) and $E_{\gamma 2}$ (right) γ-ray emission peak shapes normalized to unit height for ^{3}He ions described by a Stix distribution with several asymptotic tail temperatures T_{3He}. The unshifted $E_{\gamma 1}$ = 2313 keV and $E_{\gamma 2}$ = 1635 keV values are marked with vertical dashed lines.