First Gamma-Ray Measurements of Fusion Alpha Particles in JET Trace Tritium Experiments

V. G. Kiptily,[1] Yu. F. Baranov,[1] R. Barnsley,[1] L. Bertalot,[2] N. C. Hawkes,[1] A. Murari,[3] S. Popovichev,[1] S. E. Sharapov,[1]
D. Stork,[1] and V. Yavorskij[4,5]
[1]*Euratom/UKAEA Fusion Association, Culham Science Centre, Abingdon, Oxon, OX14 3DB, United Kingdom*
[2]*Associazione Euratom/ENEA/CNR sulla Fusione, Frascati, Rome, Italy*
[3]*Consorzio RFX - Associazione Euratom-Enea sulla Fusione, I-35127 Padova, Italy*
[4]*Euratom/OEAW Association, Institute for Theoretical Physics, University of Innsbruck, Austria*
[5]*Institute for Nuclear Research, Kiev, Ukraine*
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Gamma-ray spectra from nuclear reactions between fusion-born alpha (α) particles and Be impurities were measured for the first time in deuterium-tritium plasmas in the Joint European Torus. The time dependence of the measured spectra allowed the determination of the density evolution of fast α particles. Correlation between the decay time of the γ-ray emission and the plasma parameters in different plasma scenarios was established. Results are consistent with classical slowing down of the α particles in discharges with high plasma currents and monotonic q-profiles. In low plasma current discharges and in the discharges with large on-axis current holes (extreme reversal central magnetic shear), the γ-ray emission decay times are shorter than the classical slowing down times, indicating an α-particle confinement degradation in such discharges in line with theoretical predictions.

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The nuclear reaction D(T, n)^{4}He between deuterium (D) and tritium (T) is the main source of energy in a thermonuclear fusion reactor with magnetic confinement. The power for the self-sustained DT-plasma burn is provided by the ^{4}He-ions (α particles), which are born with an average energy of 3.5 MeV and transfer the energy to the thermal plasma during their slowing down. Investigation of the α-particle behavior is a crucial task for the International Thermonuclear Experimental Reactor (ITER) [1] and the development of the magnetic fusion reactor concept. The α particles have been studied in the full-scale DT-plasma experiments on the Tokamak Fusion Test Reactor (TFTR) [2] and on JET [3] tokamaks, which are fusion devices, where plasma is confined in a toroidal vessel by means of an applied toroidal magnetic field and a poloidal field mainly induced by the plasma current. In these experiments, several plasma diagnostics provided the measurement of temperature changes and some other effects, caused by fast α particles [4–6].

This Letter reports the first γ-ray measurements of fusion-born α particles in JET "trace tritium" discharges, i.e., in majority deuterium-plasma after seeding with a small population of tritium Neutral Beam Injection (NBI) fast ions. The γ-ray emission from the nuclear reaction ^{9}Be(α, $n\gamma$)^{12}C is used to measure changes in the density of the fast α particles with energy $E_\alpha > 1.7$ MeV in the post-NBI period. This important diagnostic nuclear reaction has already been applied to detect the presence of the fast α particles in JET experiments, where ion-cyclotron-resonance heating of ^{4}He-beam ions was used to accelerate ^{4}He to the MeV range [7]. In this Letter we demonstrate how a nuclear diagnostic based on the γ-ray spectrometry of the interaction between α's and Be impurity in plasmas [8] could be used in future magnetic fusion machines to obtain essential information on the slowing down and confinement of the fast α particles.

In present JET experiments γ-ray energy spectra are measured with a calibrated bismuth germanate (BGO) scintillation detector with diameter of 75 mm and a height of 75 mm [8]. The detector is located in a well-shielded bunker and views the plasma quasitangentially. In order to reduce neutron and γ-ray background, the

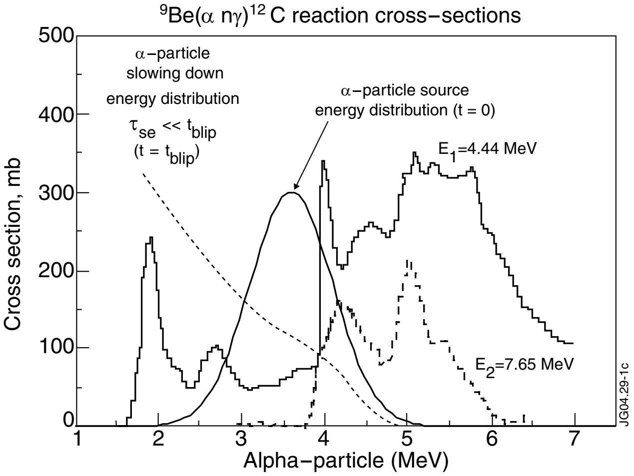

FIG. 1. Excitation functions of ^{12}C levels, 4.44 MeV and 7.65 MeV, which are populated in the reaction ^{9}Be(α, $n\gamma$)^{12}C. The α-particle source energy distribution was calculated for the 105-keV tritium beam injected in 6-keV deuterium-plasma. The steady-state α-particle energy distribution calculated for the case $\tau_{se} \ll t_{\rm blip}$. Both distribution functions have arbitrary normalization.

front collimator is filled with polythene to a depth of 0.5 m. Behind the detector there is an additional 1.5-m long dump of polythene and steel. The detector line of sight lies in a horizontal plane about 30 cm below the plasma magnetic axis. During these experiments the γ rays were continuously recorded with integration time 250 ms over the energy range 1–28 MeV, with an energy resolution of about 4% at 10 MeV.

Diagnostic capabilities of the nuclear reaction $^9\mathrm{Be}(\alpha,n\gamma)^{12}\mathrm{C}$, the significance of which for the fusion α particles has already been reported in [9], are determined by the specific reaction cross section. The excitation functions of first two levels of the final nucleus, $^{12}\mathrm{C}$, populated in this reaction, are shown in Fig. 1. The resonance structures, which are clearly seen in both cases, provide the energy selectivity for the α-particle measurements. The first energy level, 4.44 MeV, is excited by α particles with energies exceeding 1.7 MeV, and the second one, 7.65 MeV, is populated by α's with energies in excess of 4 MeV. The α-particle energy probability distribution for α born in a typical deuterium-plasma JET discharge due to DT-fusion reaction with a 105 keV triton-beam injected ion is also presented in Fig. 1. It is seen that the beam-plasma α particles can give rise to 4.44-MeV gammas ($4.44 \rightarrow 0$ transition), and α particles in the high-energy wing of the distribution can also excite the second level, giving rise to γ rays with energy 3.21 MeV ($7.65 \rightarrow 4.44$ transition). As an example, Fig. 2 shows two γ-ray spectra, recorded in the same discharge: the left-hand side plot shows the spectrum during 300-ms T-beam blip, the right one shows the spectrum just after the NBI blip. During the injection, two γ-ray peaks, 4.44 MeV and 3.21 MeV, are observed, however, in the post-blip time slice the 3.21-MeV peak becomes rather weak. This is an effect of changes in the distribution function, i.e., the result of a shift of the high-energy tail to the low-energy range due to the α particle slowing down.

Clear variations in the intensity of the 4.44-MeV γ-ray emission were observed in the post-beam-blip period of many discharges. Figure 3 shows decays of the 4.44-MeV γ-ray intensity, recorded by the spectrometer in discharges with different NBI heating power. The measured rate of 14-MeV neutrons, which are born during the T-beam injection, is shown as well. It is important to note that the main plasma heating (deuterium NBI) is kept constant for several seconds after the T NBI-blip, ensuring steady plasma conditions. This applies to all the shots in our database. The γ-ray decays are thus measured against unchanging plasma conditions. In these experiments the duration of T-beam blips was $t_{\mathrm{blip}} \leq 300$ ms.

Neutrons with energy that exceeds 5 MeV could give rise to the background 4.44-MeV γ rays due to the nuclear inelastic scattering $^{12}\mathrm{C}(n, n'\gamma)^{12}\mathrm{C}$. The main source of this background γ-ray emission is the polythene plug, which is placed in front of the detector and contains carbon as the main chemical element in the compound. Extraction of the neutron background is an important part of the data processing. This factor is the main source of uncertainties in the interpretation of the present measurements.

More than 20 discharges were analyzed, comparing two parameters: τ_γ-decay-time of the 4.44-MeV γ-ray intensity from the reaction $^9\mathrm{Be}(\alpha,n\gamma)^{12}\mathrm{C}$, and $\tau_\alpha + \tau_\mathrm{T}$-classical slowing down time of the fast α particles and the beam tritons on electrons, where $\tau_{\alpha,\mathrm{T}} = (\tau_{se}/3) \times \ln[(E_i^{3/2} + E_c^{3/2})/(E_f^{3/2} + E_c^{3/2})]$, $E_c \propto AT_e(0)$ is "critical energy" at which energy transfers from fast particles to electrons and ions are equal. For the calculation of τ_α, τ_T the slowing down of α particles from 3.5 MeV to 1.7 MeV and T-beam ions from 105 keV to 40 keV are accepted as possible contributions to the effective decay-time, τ_γ. Here, T-beam ions produce a source of α particles during

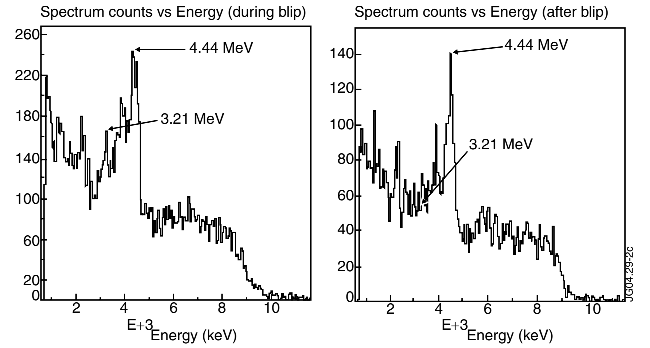

FIG. 2. Gamma-ray spectra measured in 2.0 MA/2.25 T discharge 61046 with deuterium 15-MW NBI heating and tritium 300-ms blip $P_{\mathrm{TNBI}} \cong 1.5$ MW; $T_e(0) \cong 6$ keV, $n_e(0) \cong 6 \times 10^{19}$ m^{-3}.

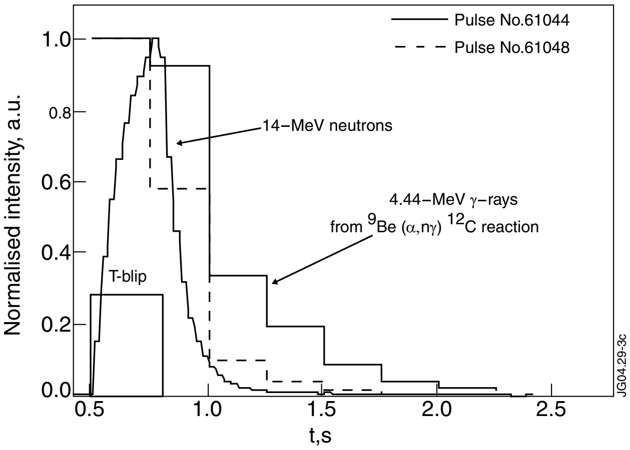

FIG. 3. Comparison of time evolutions of 4.44-MeV γ-ray emission measured in the discharges 61044 and 61048. Pulse No. 61044: 2.0 MA/2.25 T, $P_{\mathrm{DNBI}} \cong 14.5$ MW $P_{\mathrm{TNBI}} \cong 1.5$ MW; $T_e(0) \cong 5$ keV, $n_e(0) \cong 4.8\ 10^{19}$ m^{-3}. Pulse No. 61048: 2.0 MA/2.25 T, $P_{\mathrm{DNBI}} \cong 2.9$ MW $P_{\mathrm{TNBI}} \cong 2.3$ MW; $T_e(0) \cong 5$ keV, $n_e(0) \cong 3.2 \times 10^{19}$ m^{-3}.

T-beam slowing down to 40 keV when the cross section for production of fusion reactions from triton-beam atoms decreases by an order of magnitude. The variation of the γ-ray intensity after the T-blip, as shown in Fig. 3, can be approximated as $I_\gamma(t) \propto \exp(-t/\tau_\gamma)$. The time variation of the 4.44-MeV γ-ray emission after the end of the T-beam blip was modeled. The γ rate (R_γ) is proportional to:

$$R_\gamma(t) \propto n_{\mathrm{Be}} \int F(E_\alpha, t)\sigma(E_\alpha)v_\alpha dE_\alpha, \tag{1}$$

where n_{Be} is the Be density in the plasma; $F(E_\alpha, t)$ is the slowing down energy distribution of α's; $\sigma(E_\alpha)$ is the energy dependence of the reaction cross section for $^9\mathrm{Be}(\alpha, n\gamma)^{12}\mathrm{C}$; v_α is α-particle velocity. The slowing down distribution in Eq. (1) was assumed to follow the classical formula with slowing down on the plasma electrons characterized by time $\tau_{se} \propto T_e^{3/2}/n_e$ [10], where T_e and n_e are the temperature and density of electrons in plasma. The distribution function $F(E_\alpha, t)$ would of course be altered by any nonclassical α-losses. In the case $\tau_{se}/3 < t_{\mathrm{blip}}$, modeling revealed that the expected rate $R_\gamma(t)$ was approximately exponential with time constant $\sim\tau_\gamma$. This follows from the fact that the expected distribution function $F(E_\alpha, t)$ is a result of the α particle slowing down within the T-beam blip period close to the function related to the case $\tau_{se}/3 \ll t_{\mathrm{blip}}$ shown in Fig. 1.

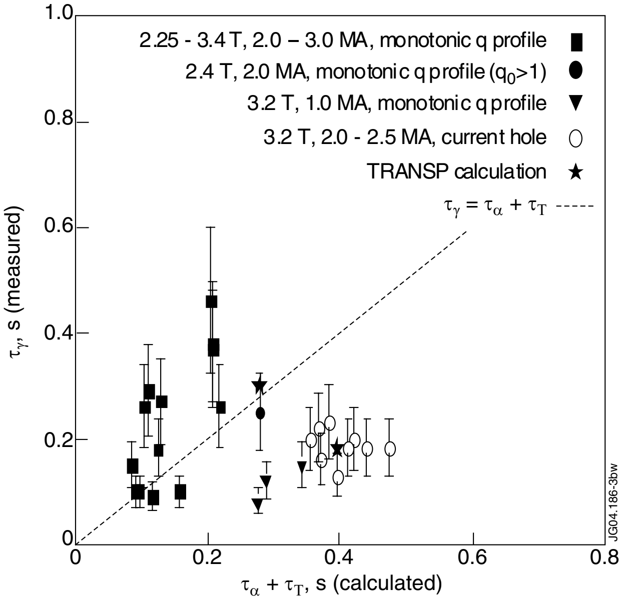

FIG. 4. Measured 4.44-MeV γ-ray decay-times, τ_γ, for different plasma scenarios: $B_T = 2.25$–3.2 T, $I_p = 1.0$–3.0 MA. A characteristic time of evolution of the α-particle energy distribution ($E_\alpha > 1.7$ MeV) calculated by TRANSP is shown for two discharges. The slowing down times, τ_α, τ_T were calculated with the electron density $n_e(0)$ and the electron temperature $T_e(0)$, measured in the plasma center.

In the case $\tau_{se}/3 \gg t_{\mathrm{blip}}$, the initial α-distribution after the blip and prior to the measurement phase is similar to the α-particle source distribution, which is presented in Fig. 1. A simple exponential decay for $R_\gamma(t)$ would not then be observed, but these conditions did not apply in any of the experimental shots studied.

Results of the comparison of measured τ_γ against calculated classical $\tau_\alpha + \tau_T$ for the plasmas are presented in Fig. 4. For the calculation of the slowing down times, the electron density $n_e(0)$ and the electron temperature $T_e(0)$, measured in the plasma center were used. One can see from the figure that in most of the discharges with toroidal magnetic field and plasma current in the ranges 2.25–3.2 T and 2.0–3.0 MA the slowing down is characterized by the scaling $\tau_\gamma \gtrsim \tau_\alpha + \tau_T$. The fact that τ_γ's lies above the estimated values is explained by the broad α-particle source distribution $S(E_\alpha)$ and more complicated link between τ_γ and $\tau_\alpha + \tau_\gamma$. The discharges displaying classical behavior are all ELMy H-modes with monotonic q-profiles. Modeling of the fast α particle slowing down was performed using the TRANSP code [11] for several discharges. The results of these calculations are in agreement with the experimental data, within the error bars.

There are two groups of discharges that do not follow the classical behavior, i.e., have $\tau_\gamma < \tau_\alpha + \tau_T$. One of the explanations of the fast decay of the γ-ray emission in these plasmas is the effect of a poor α-particle confinement due to the significant wide orbit effects. Our modeling assessments show that a minimal critical plasma current $I_{cr} > 1.5$–2 MA is required to avoid significant first orbit (FO) losses of 3.5-MeV alphas and consequently wide orbit induced transport in the discharges with monotonic plasma currents. Therefore, in discharges with $I_p^{\max} = 1$ MA the γ-ray decay-times are expected to be lower than classical. Another similar anomalous behavior of the γ-ray emission decay was observed in discharges with hollow current profiles. These discharges have strongly reversed magnetic shear in the plasma center. Measurements based on the motional Stark effect (MSE) [12] show very small central current density in the plasma core area, the so-called "current hole," in these discharges. The typical size of the current holes in the analyzed discharges is around $0.35a$, where a is a minor radius of the plasma. According to the confinement criteria [13] developed for α particles born in a plasma with a hollow current profile, the current hole effect is equivalent to an increase of the critical plasma current, $I_{cr} \approx 1.5(1 - x_h^{1/2})$ (MA), where $x_h = r_h/a$ is an effective radial size of the current hole. For the discharges with the current hole as large as $x_h \approx 0.35$, the critical current value is equal to $I_{cr} \approx 3.7$ MA. In the case of discharges with $I_p^{\max} = 2 - 2.5$ MA, the FO losses of 3.5-MeV alphas are therefore rather significant, 20%–30%. These estimates explain the faster observed decay-times of the

γ-ray emission measured in the discharges with calculated slowing time for the fast α particles derived classically.

To summarize, the time-dependent γ-ray spectra from the nuclear reaction between the fast fusion α particles and Be impurities, $^9\mathrm{Be}(\alpha, n\gamma)^{12}\mathrm{C}$, were measured for the first time in deuterium-tritium plasmas. The time evolution of the MeV α-particle density was obtained, and a correlation between the decay-time of the γ-ray emission and the characteristic α-particle slowing down time in different plasma scenarios was established. The majority of the results are consistent with classical slowing down of the MeV α particles and the parent tritons; however, in discharges with low plasma current and in discharges with hollow current profiles, the γ-ray emission was found to decay on a much shorter time scale, $\tau_\gamma \ll \tau_\alpha + \tau_\mathrm{T}$. This is attributed to wide orbit effects (enhanced losses and transport), which determine the α-particle behavior, and this interpretation is consistent with preliminary theoretical predictions [13], which indicate that only larger machines with higher currents, such as ITER with 10 MA, can cope with the current hole effect on fusion-born α particles. It is necessary to emphasize that application of this γ-ray technique with dedicated multichannel devices could provide the time- and spatial-resolved fusion α-particle measurements in next-step fusion machines, such as ITER or other burning plasma experiments.

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