JET–P(98)25

A A Korotkov et al

Measurement of Energy Distribution of Deuterium-Tritium Fusion α-particles and MeV Energy Knock-on Deuterons in JET Plasmas

JET–P(98)25

Measurement of Energy Distribution of Deuterium-Tritium Fusion α-particles and MeV Energy Knock-on Deuterons in JET Plasmas

A A Korotkov[1], A Gondhalekar, R J Akers[2].

JET Joint Undertaking, Abingdon, Oxfordshire, OX14 3EA,
[1]A F Ioffe Institute, St. Petersburg, Russia.
[2] UKAEA Fusion, Abingdon, Oxon, OX14 3DB, UK.
(UKAEA/Euratom Fusion Association)

September 1998

ABSTRACT

We report first non-perturbing measurements of energy distribution function $f_\alpha(E_\alpha)$ of confined DT fusion α-particles, made in the Joint European Torus (JET) using a neutral particle analyzer. We demonstrate significant direct neutralization of α-particles in charge-exchange reactions with helium-like ions of main intrinsic plasma impurities in high temperature plasmas. We have also measured for the first time in a tokamak plasma MeV energy deuterons produced by close collisions between fusion α-particles and plasma fuel ions, which are neutralized by hydrogen-like ions of the impurities. Both processes contribute to measured flux to the analyzer and allow $f_\alpha(E_\alpha)$ to be determined.

PACS numbers: 52.55.Pi, 52.20.Hv, 52.55.Fa

The dominant process for neutralization of MeV energy protons in JET plasmas was shown to be charge-exchange with hydrogen-like ([H]) ions of main intrinsic low-Z impurities, carbon and beryllium [1]. Application of this Impurity Induced Neutralization (IIN) model to quantitative interpretation of neutral particle analyzer (NPA) measurements of energy distribution function of hydrogen isotope ions heated by waves in the ion cyclotron range of frequencies [2,1], has established IIN as a reliable neutralization model for high energy ions in JET plasmas. It was anticipated that in DT experiments in JET helium-like ([He]) two-electron species $A^{(Z-2)+}$ of C, Be and He would analogously neutralize MeV energy α-particles in double charge-exchange reactions $He^{2+} + A^{(Z-2)+}(1s^2) \rightarrow He^0(1s^2) + A^{Z+}$ [3]. Feasibility of using such reactions for making plasma measurements was first confirmed during ion cyclotron resonance frequency heating of ^3He minority ions in deuterium plasmas [4]. In this Letter we describe measurements of DT fusion α-particles in energy range $0.8 \le E_\alpha(MeV) \le 3$ and of deuterons in range $0.4 \le E_d(MeV) \le 1.5$, using a NPA where impurity induced neutralization produced the measured atomic flux.

Experimental set-up and a description of the NPA are given in [1]. The NPA was located on top of the torus with its vertical line-of-sight intersecting deuterium atomic beams from octant 4 neutral beam injection (NBI) at the plasma center. A spectrometric detector set-up [4] has enabled measurements of atomic efflux from the plasma in the presence of a neutron flux of up to $6\times10^{14} m^{-2} s^{-1}$ at the NPA. The NPA is of the conventional E||B type in which the dispersion system separates ^4He atoms from all hydrogenic atoms except deuterium, making ^4He atoms of energy E_α indistinguishable from deuterium atoms of energy $E_d = E_\alpha / 2$. The measurement yields line-of-sight integrated energy distribution function $\overline{F}(E)$ of trapped plasma ions with pitch-angle $\frac{\pi}{2} \pm 5\times10^{-3}$ on the NPA line-of-sight. Measurements were made in hot-ion H-mode plasmas [5] as in fig.1 which shows a pulse with toroidal field on axis B=3.5T plasma current I=3.5MA, using only NBI, comprising 80kV D-atoms from octant 4 and 140 kV T-atoms from octant 8, for additional heating, giving fuel isotope density mixture $n_D / (n_D + n_T) \approx 0.5$. A note-worthy feature of these pulses is that the time-scale of increase of α-particle birth rate, $\tau = (d \ln R_{DT} / dt)^{-1}$ = 0.25s-0.4s, is shorter than the slowing-down time [6] τ_S for 3.5MeV a-particles, with $<\tau_s>=0.7s$ in interval I and $< \tau_S >= 1s$ in interval II. We therefore expect $f_\alpha (E_\alpha)$ to be far from equilibrium, and the defining characteristic of the distribution to be a strong depletion at energies much less than the α-particle birth energy.

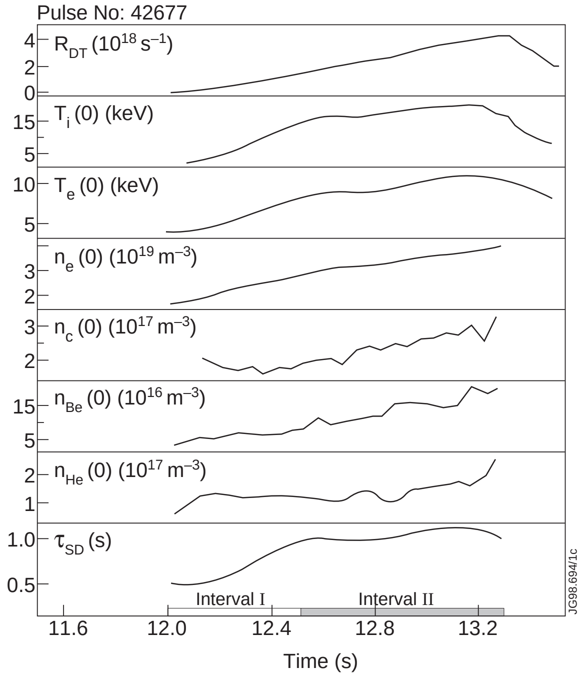

Fig.1: Temporal evolution of key plasma parameters in typical hot-ion H-mode plasma pulse. R_{DT} is rate of 14 MeV neutron production, equal to the DT fusion a-particle birth rate at $E_\alpha (MeV) = 3.5 \pm 0.5$; $n_e(0), T_e(0)$ and $T_i(0)$ are respectively central electron density, electron temperature and ion temperature; and n_{C6+}, n_{Be4+} and n_{He2+} are central densities of bare carbon, beryllium and helium ions measured using charge-exchange spectroscopy. τ_{sd} is α-particle slowing down time in the plasma core. Measurements discussed later in this paper were integrated over time interval I and interval II shown.

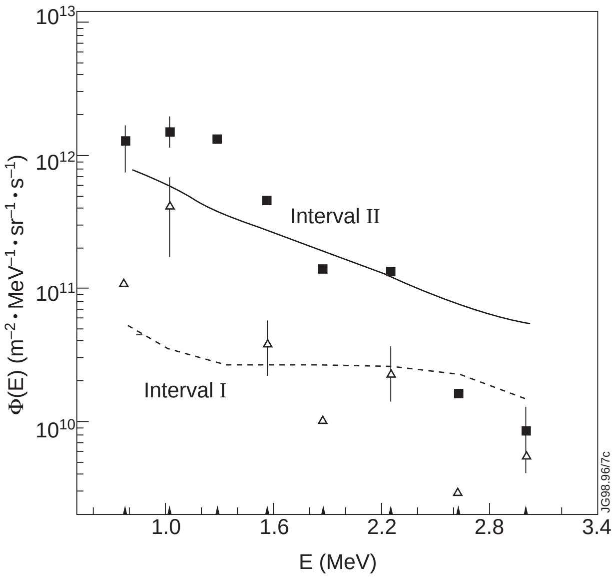

Fig.2: Normalized atomic flux $\Phi(E)$ at NPA detectors, integrated over the time interval I(D) and interval II(,) shown in fig.1. The NPA was set-up for a-particle measurements, the energy setting of the eight NPA channels is shown by thorns on the energy axis. Errors in measured flux, due to uncertainties in subtracting neutron noise and due to statistical fluctuations in count rate, are shown. The two curves are the result of simulation of $\Phi(E)$, which will be discussed later in the paper.

Fig.2 shows normalized atomic flux $\Phi(E_i) = N(E_i) / (S \cdot \Delta\Omega \cdot \Delta E_i)$ measured by the NPA, integrated over time interval I and interval II, where $N(E_i)$ is count rate in NPA channel *i=1,..8*, S is surface area of view at the plasma mid-plane, $\Delta\Omega$ is solid angle of view and ΔE_i is energy-width of the channel. $\Phi(E_i)$ shows two anomalies with respect to prediction of it based on classical evolution of slowing-down α-particle population, (i) in interval I the low energy channels are filled in a time much less than τ_S after birth of the α-particles, and (ii) at $t >> \tau_S$ deduced $\overline{F_\alpha}(E)$ decays too rapidly with energy. Both indicate that the measured $\Phi(E_i)$ contains more contributions to flux than neutralized α-particles. We attribute the additional flux to neutralized high energy deuterons produced in close nuclear elastic scattering collisions (knock-on) between fusion α-particles and fuel ions.

Formation of suprathermal deuterons by close collisions between a-particles and thermal plasma ions is an inherent property of fusion plasmas [7,8]. Such collisions are relatively infrequent and do not greatly perturb the energy distribution of α-particles or that of thermal plasma ions. The slowing-down velocity distribution functions for α-particle and knock-on deuteron populations, $f_\alpha(\upsilon_\alpha)$ and $f_d(\upsilon_d)$ respectively, were calculated using two time-dependent Fokker-Planck equations as in [9]. For $f_\alpha(\upsilon_\alpha)$ the time-dependent radial α-particle source $S_\alpha(r,\upsilon_\alpha,t)$ was derived using measured fusion reactivity [9]. For $f_d(\upsilon_d)$ the source $S_d(r,\upsilon_d,t)$ of knock-on deuterons was obtained by integrating over $f_\alpha(\upsilon_\alpha)$. As in [9] we assume that for both ions the source is isotropic in velocity, ions are confined, collisionality is classical, and the ion orbit width is small compared to its mean radial position. The source $S_d(r,\upsilon_d,t)$ becomes [8]

$$S_d(r,\upsilon_d,t)=\frac{8\pi m^2 n_d}{\upsilon_d}\int_u^\infty \frac{d\sigma}{d\Omega}\, f_\alpha(\upsilon_\alpha,t)\upsilon_\alpha d\upsilon_\alpha$$

where $m=(m_d+m_\alpha)/2m_\alpha$, $u=m\upsilon_d$ is minimum α-particle speed required to create deuterons of speed υ_d, and n_d is thermal deuteron density. The differential scattering cross-section $d\sigma/d\Omega$, derived from data in [10], is also isotropic. Fig.3 shows the calculated $f_\alpha(E)$ and $f_d(E)$ at the plasma center at different times in interval I. We see that knock-on deuterons preferentially populate the lower energy regime. Calculations were performed for different flux-surfaces within the α-particle birth volume from which line-integral distributions $\overline{f_\alpha}(E_\alpha)$ and $\overline{f_d}(E_d)$ were constructed. Later in the paper we shall determine two unknowns, the contributions of neutralized α-particles and knock-on deuterons to the measured flux, from one NPA measurement. We shall reduce the number of unknowns using, $K(E_\alpha)=\overline{f_d}(E_d)\big/\,\overline{f_\alpha}(E_\alpha)$, the ratio of the two distributions computed here which we consider to be exactly determined.

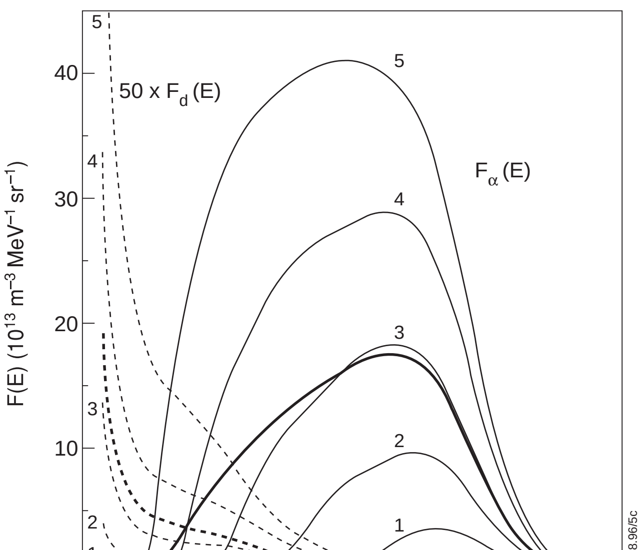

Fig.3: Temporal evolution in the plasma core of $f_\alpha(E)$ (solid curves) and $f_d(E)$ (dashed curves), in the interval I. Curves are labeled j =1,2,...5 *corresponding to time $t_j(s)=(12+0.1\mathrm{j})$ into the pulse in fig.1. Bold curves show $f_\alpha(E)$ and $f_d(E)$ averaged over the interval I.*

Neutralization probabilities $P_{v\alpha}(E_\alpha)$ **and** $P_{vd}(E_d)$ **for** α**-particles and knock-on** deuterons required to determine $\overline{F_\alpha}(E_\alpha)$ and $\overline{F_d}(E_d)$ from the NPA measurements were computed using the IIN model. Calculation of P_{vd} for deuterons was given in [1]. Similarly, $P_{v\alpha} = \sum n_{Z-2} < \sigma\upsilon >$, where n_{Z-2} is density of two-electron ions, $< \sigma\upsilon >$ is rate coefficient for double charge-exchange reactions and the summation is over all contributing species, n_{C4+}, n_{Be2+} and n_{He0}. The rate coefficients were derived using cross-sections presented in [3]. Densities n_{Z-2} in the plasma core were calculated using the ionisation balance model developed in [1], using measured bare impurity ion densities n_Z as input. Due to the transient conditions in pulses we have employed time-dependent forms of eq.6 and eq.7 in [1]. Rearranging the equations and recognizing the ordering $n_Z >> n_{Z-1} > n_{Z-2}$ for ion densities and associated fluxes, we obtain n_{Z-2} in terms of evolution of n_Z,

$$\frac{dn_Z}{dt} = n_{Z-2} \cdot I_{Z-2} \cdot n_e - div\Gamma_Z - S_{Z-2} \qquad \text{Eq.1}$$

In this expression $S_{Z-2} = \lambda \cdot n_Z n_b^2 \langle\sigma\upsilon\rangle_{CXZ}^b \langle\sigma\upsilon\rangle_{CXZ-1}^b / I_{Z-1} n_e$ represents a two-step process for creating [He] ions from bare impurity ions by successive single charge-exchange reactions between bare ions and deuterium NBI atoms, I_{Z-1} and I_{Z-2} are rate coefficients for ionization of [H] and [He] ions by electrons, Γ_Z is radial flux of bare impurity ions, n_b is density of deuterium NBI atoms in octant 4, and $\langle\sigma\upsilon\rangle_{CXZ}^b$ and $\langle\sigma\upsilon\rangle_{CXZ-1}^b$ are rate coefficients for single charge-exchange reactions between bare impurity ions and NBI atoms, and similarly for [H] impurity ions. It can be shown that strongly trapped bare impurity ions, in two-step charge-exchange process with deuterium atoms, are the most important source of [He] ions when full power NBI from octant 4 is employed, as in the pulses described. Thus λ is the fraction of trapped bare impurity ions which stay long enough in the region of NBI atoms to undergo the two-step process, giving $\lambda \approx (\pi\sqrt{2\varepsilon} / 3q) \cdot (\Delta l / 2\pi R)$, where $\varepsilon = \rho / R$, ρ is radial extent of the α-particle source, R is the plasma major radius, q is safety factor averaged over extent of α-particle source, and Δl is toroidal length of the deuterium beam from octant 4 NBI.

In eq.1 for determining n_{Z-2} the most uncertain term is the radial impurity ion transport term $div\Gamma_Z$, no reliable basis for quantifying it is available. For the pulses analyzed the measured density $n_Z(r)$ increased continuously in time, implying that $div\Gamma_Z < 0$, due either to growing impurity ion influx or to impurity ion transport. Two limiting cases were considered, (i) $|div\Gamma_Z| << {dn_Z}/{dt} + S_{Z-2}$, and (ii) ${dn_Z}/{dt} + div\Gamma_Z = 0$. The former gives an upper limit for n_{Z-2} while the latter gives a lower limit due to 'coronal' equilibrium in the presence of deuterium NBI atoms.

Fig.4 presents resulting neutralization probabilities $P_{v\alpha}$ and P_{vd}, showing that $P_{vd} \approx 150 P_{v\alpha}$. It is this circumstance that makes possible a flux of neutralized knock-on deuterons comparable in magnitude to that of neutralized α-particles to arise, although the density of knock-on deuterons is $\sim 10^{-2}$ that of α-particles. Strong NBI causes P_{vd} to increase by a factor 10-20 due to a shift in the ionization balance, whereas $P_{v\alpha}$ increases only by factor two at the highest energies due to the two-step charge-exchange process. When $n_e < 2\times10^{19} m^{-3}$ and strong NBI is applied, the term S_{Z-2} dominates. The two limiting assumptions about impurity transport then give close results, enabling determination of absolute magnitude of $f_\alpha(E_\alpha)$ to within a factor two, and hence a more accurate $f_\alpha(E_\alpha)$.

We next compute evolution in time of expected relative contribution of deuterium flux to the total flux to the NPA $\Phi_d/(\Phi_d+\Phi_\alpha)$, in time interval I. Using calculated distributions $\overline{f_\alpha}(E_\alpha)$, $\overline{f_d}(E_d)$, neutralization probabilities $P_{v\alpha}(E_\alpha)$ and $P_{vd}(E_d)$, and eq.5 in [1], gives for the flux of neutralized α-particles $\Phi_\alpha(E_{\alpha i}) = \overline{f_\alpha}(E_{\alpha i})P_{v\alpha}(E_{\alpha i})\mu_\alpha(E_{\alpha i})\gamma_\alpha(E_{\alpha i})$ and analogously $\Phi_d(E_{di})$ for knock-on deuterons. Here μ and γ are energy and ion species dependent NPA detection efficiency and plasma transparency coefficients. Transparency coefficients for atoms exiting the plasma were calculated using the model developed in [11] which incorporates electron losses from excited states of the atoms. Fig.5 gives the result, showing that in the two lowest energy channels of the NPA nearly the whole flux is due to knock-on deuterons, while 70% of flux in the highest energy channels is due to α-particles. Relative Φ_d decreases at lower energies and increases at higher energies as the pulse progresses. The

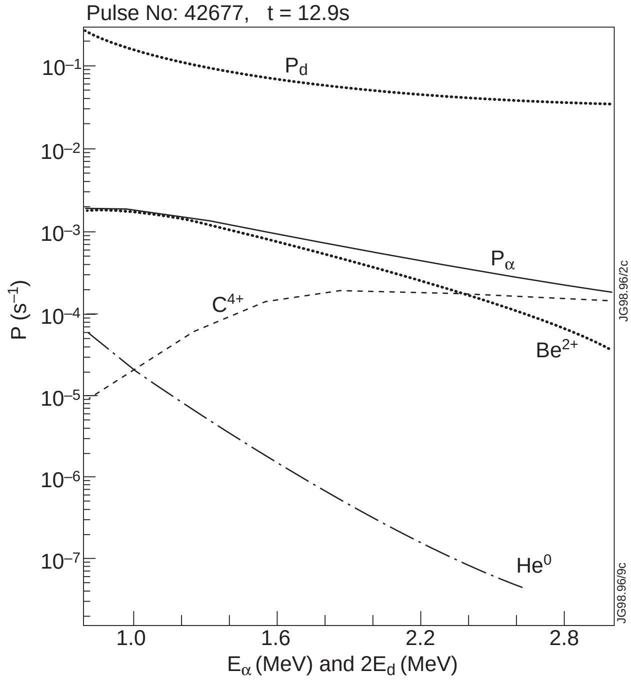

Fig.4: Comparison of total neutralization probabilities P_{vd} for knock-on deuterons and $P_{v\alpha}$ for α-particles, as function of ion energies. The lower part of the figure shows partial contributions of C^{4+}, Be^{2+}, and He^0 to total neutralization probability for α-particles, using the upper limit on n_{Z-2}. The magnitudes shown for $P_{v\alpha}$ and P_{vd} are typical for hot-ion H-mode plasmas in JET.

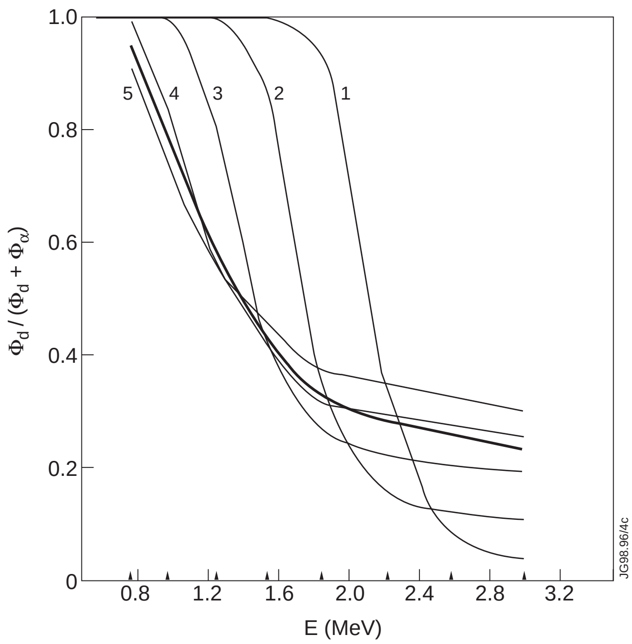

Fig.5: Temporal evolution of fractional contribution of flux of neutralized knock-on deuterons to the NPA flux in interval I, as function of energy. The five labeled curves correspond to the five time points mentioned in fig.3.

curves in fig.2 show total flux $\Phi(E_{\alpha i}) = \Phi_\alpha(E_{\alpha i}) + \Phi_d(E_{di})$, where $E_{di} = E_{\alpha i}/2$ as explained earlier. We see that there is approximate agreement between the measured flux and that calculated using predicted distributions $\overline{f_\alpha}(E_\alpha)$ and $\overline{f_d}(E_d)$. This demonstrates that the IIN model incorporates the required atomic physics of neutralization to reproduce in absolute magnitude the measured NPA flux.

The Measured line-integral distribution functions $\overline{F_\alpha}(E_\alpha)$ **and** $\overline{F_d}(E_d)$ were finally deduced using the measured flux $\Phi(E_i)$ of fig.2, and eq.2 which allows for an admixture of helium and deuterium atoms detected in the NPA,

$$\overline{F_\alpha}(E_{\alpha i}) = \frac{\Phi(E_i)}{G_\alpha(E_{\alpha i})P_{v\alpha}(E_{\alpha i}) + K(E_{\alpha i})G_d(E_{di})P_{vd}(E_{di})} \qquad \text{Eq.2}$$

where $G_\alpha(E_{\alpha i}) = \mu_\alpha(E_{\alpha i})\gamma_\alpha(E_{\alpha i})$ and similarly for $G_d(E_{di})$. Fig.6 gives the result, showing $\overline{F_\alpha}(E_\alpha)$ and $\overline{F_d}(E_d)$ in interval II. The hollow circles and triangles show the deduced $\overline{F_\alpha}(E_\alpha)$ corresponding respectively to the upper and lower limits for n_{Z-2}. As seen from eq.2 the uncertainty in $\overline{F_\alpha}(E_\alpha)$ is reduced with increasing contribution of deuterons. Because n_{Z-1} can be determined independently of ion transport considerations [1] P_{vd} can be known much more accurately than $P_{v\alpha}$, with the consequence that the dominance of the second term in the denominator containing P_{vd} in eq.2 leads to more accurate determination of $\overline{F_\alpha}(E_\alpha)$. Curves in fig.6 show $\overline{f_\alpha}(E_\alpha)$ and $\overline{f_d}(E_d)$ for comparison. We see that the magnitudes of $\overline{f}(E)$ and $\overline{F}(E)$ for both ions are close, only the last two energy points differing significantly. Such anomalies seem to be a feature only of pulses with high (≥5MW) NBI power at octant 4. This suggests that anisotropy of $f_\alpha(E)$ at birth, due to the stronger beam-plasma fusion source which is not taken into account in the kinetic calculation, could be a reason for the anomaly.

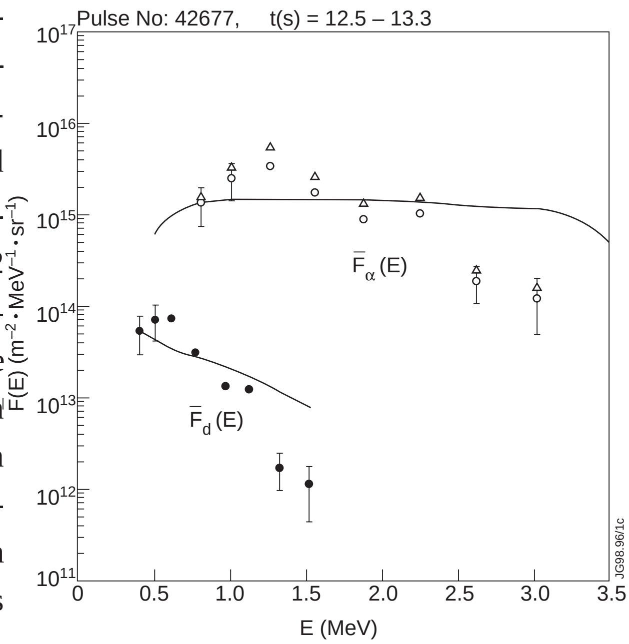

Fig.6: Line-of-sight integrated energy distribution function for a-particles and knock-on deuterons deduced from NPA measurements in interval II. Circles (o) and triangles (Δ) denote lower and upper limits on deduced $\overline{F_\alpha}(E_\alpha)$, corresponding to the two limiting values of n_{Z-2}. The error bars incorporate counting statistics, uncertainties in subtraction of neutron noise, and uncertainties in key plasma parameters. Solid circles (•) show deduced $\overline{F_d}(E_d)$ with error bars arising for the same reasons as above. For comparison calculated distributions $\overline{f_\alpha}(E_\alpha)$ and $\overline{f_d}(E_d)$ are shown as solid curves.

In conclusion, we have demonstrated non-perturbing measurements of energy distribution function of DT fusion α-particles in JET, using a NPA. Direct neutralization of α-particles in double charge-exchange reactions with impurity ions and creation of high-energy deuterons in close nuclear elastic collisions has been found. Both processes are shown to be effective methods for measurements of α-particle distribution function. In the direct measurement powerful hydrogenic NBI is found to greatly reduce uncertainties arising from lack of knowledge of impurity ion transport. Measurements of knock-on deuterons and the direct measurements of α-particles, when used together, enlarge the measurement energy range and can increase the accuracy of determining $\overline{F_\alpha}(E_\alpha)$.

The authors thank P.J.Lomas and his team for preparing and carrying out the high DT fusion yield experiments in JET on which this work is based, S.S.Kozlovskij and A.Detch of the Technical University of St.Petersburg, Russia for developing the spectrometric detector set-up which was indispensable, D.Testa for help with the NPA measurements, R.Kînig for careful analysis of measurements of impurity ion densities, R.V.Budny for TRANSP analysis of plasma data in support of this work, P.Helander and J.Wesson for clarifying discussions about deuteron tail formation due to close collisions, and P.R.Thomas for support of this work. The work of the UKAEA Fusion was funded jointly by the UK Department of Trade and Industry and by Euratom.

REFERENCES:

[1] A.A. Korotkov, A. Gondhalekar and A.J. Stuart, Nuclear Fusion **37**, 35 (1997).

[2] K.G.McClements, R.O.Dendy and A.Gondhalekar, Nuclear Fusion **37**, 473 (1997).

[3] A.A.Korotkov and A.M.Ermolaev, Proceedings of 22nd EPS Conference on Controlled Fusion and Plasma Physics, July 1995, UK. Europhysics Conference Abstracts, **19C,** III-389 (1995).

[4] A.A.Korotkov and A. Gondhalekar, 5th IAEA Technical Committee Meeting on Alpha Particles in Fusion Research, JET Joint Undertaking, September 1997, UK.

[5] P.Lomas, ‘ELM-Free H-Modes in D-T’, 39th Meeting of the Division of Plasma Physics of the American Physical Society, USA. Bulletin of the American Physical Society. **42**,1860 (1997).

[6] J.Wesson, *Tokamaks*, Clarendon Press, Oxford, 1997.

[7] D.Ryutov, Physica Scripta, **45**, 153 (1992).

[8] P.Helander, M.Lisak and D.D.Ryutov, Plasma Physics and Controlled Fusion **35**, 363 (1993).

[9] K.G.McClements, R.O.Dendy and A.Gondhalekar, JET Report JET-R(97)02, and 5th IAEA Technical Committee Meeting on Alpha Particles in Fusion Research, September 1997, UK.

[10] S.T.Perkins and D.E.Cullen, Nuclear Science and Engineering **77**, 20 (1981).

[11] A.A.Korotkov and R.K.Janev, Physics of Plasmas **3**, 1512 (1996).