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M.Kamal [1], V.I.Kukulin [2], V.T.Voronchev [3]

NUCLEAR-PHYSICS DIAGNOSTICS OF ION TEMPERATURE IN HOT DEUTERIUM-CONTAINING PLASMA

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[1] Permanent address: Physics Department, Faculty of Science, Cairo University, Cairo, Egypt

[2] Institute of Nuclear Physics, Moscow State University , USSR

[3] Institute of Crystallography, USSR Ac. of Sc.

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1. Finding ion temperatures in a hot plasma is essential in studying controllable thermonuclear synthesis (see for example reviews 1, 2). The nuclear physics activation methods based on reactions with charged particles are of particular importance among the various methods proposed by now for different temperature intervals because of their high sensitivity and effectiveness in the most interesting temperature interval of 1-10 keV /1,2/. The importance arises from the strong exponential dependence of the nuclear cross sections of charged particle induced reactions on the incident-particle energy in the subbarrier range.

One of the like methods proposed recently /3/ is based on measuring the yield of the annihilation γ-quanta ($E_\gamma = 0.511$ MeV) from the reaction $^{10}B + D \rightarrow {}^{11}C + n$ with subsequent β^+-decay of the produced ^{11}C isotope with lifetime $\tau = 20.5$ min. However, the proposed method requires that a thick boron-containing target should be placed in the hot deuterium plasma /3/, which is inconvenient for some reasons. In particular, the measurements will involve substantial errors /3/ because of rapid evaporation of such a target and, besides, deuterium plasma will contain some extremely undesirable impurities of heavy elements.

2. The present work proposes an alternative and, in our opinion, more attractive nuclear physics method for finding ion temperature T_i and, possible, even for determining the basic parameters of the function of deuterium ion distribution in a hot plasma. The method is based on a relatively low-concentration ^{6}Li ion injection into a hot plasma. We studied the basic parameters and the kinetics of hot D ^{6}Li plasma preliminarily /4,5/ and found, in particular, that admixture of ^{6}Li ions up to concentrations $n_{Li} \sim 0.1 n_D$, (where n_D is the concentration of deuterium and $n_D \sim 10^{15}$ cm^{-3}) to a deuterium plasma did not deteriorate the basic parameters of deuterium plasma (since an increase of loss is compensated by a respective increase of energy release owing to the strong exothermic reactions in the D + Li plasma which proceed with "proper" cross sections /4-7/). We mean here, first of all, that for DLi plasma with the given ^{6}Li-concentration, the ignition temperature

is turned relatively low (~ 50 keV) [4,5] . (It should be mentioned that several factors facilitating the reaction ignition were disregarded in the calculation and that extrapolated values of low-energy cross sections for $D + {}^6Li$ used were underestimated because in any way reliable experiments in the range of 30-50 keV had not been carried out yet). Nevertheless, under this condition the values of $n_i \tau_E$ (where n_i is the ion concentration and τ_E is the energy confinement time) were found to be quite comparable with the values for pure deuterium plasma.

Among several reactions proceeding in such a plasma, it is convenient to use the following two processes for ion diagnostics:

$$ {}^6Li + D \rightarrow {}^7Be^* \ (0.431 \ Mev) + n, \qquad \hookrightarrow {}^7Be + \gamma \tag{1}$$

$$ {}^6Li + D \rightarrow {}^7Li^* \ (0.478 \ Mev) + p, \qquad \hookrightarrow {}^7Li + \gamma \tag{2}$$

which give monochromatic γ-quanta of a well-defined energy*. (It is interesting to note that detection of 0.478 MeV γ-quanta emitted from ${}^7Li^*$ was proposed recently to be an accurate method for determining ${}^{10}B$ content in the absorbing elements of a nuclear reactor [8]). The γ-quantum yield in reaction (1) was recently measured [9] within a good accuracy at 63 keV $< E_d <$ 160 keV, whereas the second reaction (together with the first) was studied in [10].

3. For the purposes of plasma diagnostics at temperatures $T < 50$ keV, the experimental cross sections of reactions (1) and (2) must be extrapolated to low energies (with subsequent calculations of the reaction rate $<\sigma V>$).

In the present note the cross sections were extrapolated by the formula used extensively in nuclear physics and in astrophysics:

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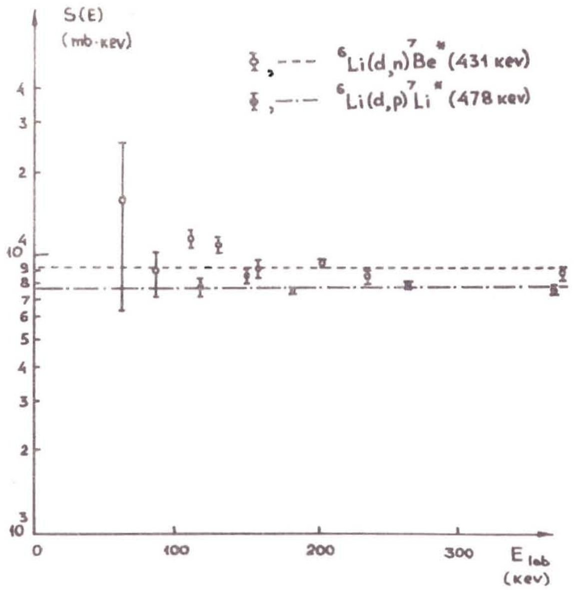
* *Doppler broadening of the corresponding γ-lines is small ($\Delta E_{Dop.} \simeq 10$ keV) and does not depend on the plasma temperature, since γ-quanta are emitted by the still unthermalized excited ${}^7Li$ and ${}^7Be$ nuclei ($\tau_{half-life} \ll \tau_{thermalization}$).*



The S-factors of reactions (1) and (2) calculated from the experimental cross section data. The approximation of the S-factors by the χ^2-criterium.

$$\sigma(E) = \frac{S(E)}{E} P(E) , \tag{3}$$

where S(E) is the S-factor depending little (in nonresonance case) on energy; P(E) is the Coulomb barrier penetrability. The penetrability P(E) was found directly in case of the $d + {}^6Li$ potential barrier calculated exactly in [4,5] , while the S-factors were found from the experimental results [9,10] by the fitting method (the detailed calculations may be found in [11]). The S-factors (which proved to be independent of energy to within a good accuracy) and the respective experimental results are shown in the Figure. A good quality of the approximation of the experimental values is quite evident. The corresponding values of the extrapolated cross sections are presented in Table 1. Assuming now the ion energy distribution is Maxwellian at temperature T, we may calculate the rates $<\sigma v>$ of reactions (1) and (2). In this case the $<\sigma v>$ values are found as

$$<\sigma v> = \frac{(8/\pi kT)^{1/2}}{m^2} M^{3/2} \int_0^\infty \sigma(E) \exp\{-\frac{M}{m}\frac{E}{kT}\}\frac{E}{kT} dE , \tag{4}$$

where M is the reduced mass of interacting pair, m and E are respectively the mass of incident particle and its energy in

Table 1

The values of the extrapolated low-energy cross sections of reactions (1), σ_1, and (2), σ_2

$E_{C.M.}$ (KeV)	σ_1 (mbarns)	σ_2 (mbarns)
10	6.04×10^{-11}	5.25×10^{-11}
20	1.31×10^{-6}	1.14×10^{-6}
30	9.87×10^{-5}	8.60×10^{-5}
40	1.23×10^{-3}	1.07×10^{-3}
60	—	1.99×10^{-2}
80	—	1.07×10^{-1}
100	—	5.28×10^{-1}

In the $0 \le E_{C.M.} \le 130$ keV range the cross sections σ_1 and σ_2 may be described properly by the analytical formula

$$\sigma_{1,2} = [A_{1,2}/E_L]\exp\{-B_{1,2}/E_L^{1/2}\},$$

where

$A_1 = 4210.1$	*barn. keV,*	$B_1 = 101.4$ (keV)$^{1/2}$
$A_2 = 4703.5$	*barn. keV,*	$B_2 = 133.07$ (keV)$^{1/2}$

$E_L = \frac{4}{3} E_{C.M.}$

the laboratory coordinate system. The results obtained are presented in Table 2. The data can be used further for estimating the values of γ-quanta flux in real thermonuclear reactors with magnetic confinement of plasma. The γ-quanta are amenable to being recorded by γ-ray detectors. The typical aperture of such a detector is ~ 10 cm^2. Therefore, at $T \sim 10$ keV the number N_γ of γ-quanta from either of reactions (1) and (2) entering a detector located at 1 m from a reactor in unit time is of the order of

$$N_\gamma \sim 10^{-20}\, n_D\, n_{Li} \frac{\text{(quant)}}{\text{sec}}$$

which gives quite an appreciable value $N_\gamma = 10^4 \frac{\text{quant}}{\text{sec}}$ at $n_D \sim 10^{14}$ cm^{-3} and $n_{Li} \sim 10^{10}$ cm^{-3}. In case of open traps with magnetic confinement of plasma, the γ-quantum yield increases substantially (at the same concentrations) because of the high values of the operative ion temperature /12/. The principal error in measuring the monochromatic γ-quanta fluxes will be introduced by the background γ-quanta produced in the neutron radiative-capture reactions occurring in the thermonuclear process and showing a continuous spectrum. Although at the present level of investigation the background is difficult to estimate, it can most probably be reduced considerably by shielding the detectors properly and selecting an optimal geometry of their arrangement. Besides quite a definite energy of the diagnostics γ-quanta can also raise the signal-to-noise ratio.

Table 2

The reaction rates $\langle\sigma_1 v\rangle$ and $\langle\sigma_2 v\rangle$

T keV	$\langle\sigma_1 v\rangle$ cm^3 sec^{-1}	$\langle\sigma_2 v\rangle$ cm^3 sec^{-1}
1	4.77×10^{-32}	4.15×10^{-32}
2	3.09×10^{-28}	2.68×10^{-28}
3	2.07×10^{-26}	1.83×10^{-26}
4	2.80×10^{-25}	2.58×10^{-24}
6	6.48×10^{-24}	6.91×10^{-24}
8	4.95×10^{-23}	5.34×10^{-23}
10	2.27×10^{-22}	2.28×10^{-22}
20	1.12×10^{-20}	9.82×10^{-21}
30	7.17×10^{-20}	5.69×10^{-20}
40	2.18×10^{-19}	1.67×10^{-19}
50	4.51×10^{-19}	3.55×10^{-19}

4. The last remark concerns the possibility, in principle, of using the described method to infer the ion energy distribution function. In the absence of background and assuming the Maxwellian ion spectrum, it is sufficient to measure the γ-yield of only one of reactions (1) and (2). The yield of other reaction can then be obtained from Table 2 as a mere consequence.

Therefore, any disagreement between the so predicted γ-yield from the second reaction and the measured γ-yield is indicative of a distortion of the Maxwellian distribution function and, in principle, permits the distorting parameters of strictly defined values to be introduced in the distribution function. Any comprehensive examination of the problem requires, however, that the intensity and the energy distribution of the continuous γ-background should be known at E_γ ranging from ~400 to 500 keV.

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Камаль М., Кукулин В.И., Ворончев В.Т. E4-88-802
Ядерно-физическая диагностика ионной температуры в горячей, содержащей дейтерий плазме

Предлагается ядерно-физический метод для нахождения ионной температуры в горячей, содержащей дейтерий плазме. Этот метод основан на использовании иона ^{6}Li и соответствующем измерении выхода γ-квантов в реакциях

$$^6\mathrm{Li(d,n)}\,^7\mathrm{Be}^* \to {}^7\mathrm{Be} + \gamma \quad (E_\gamma = 431\ \text{кэВ})$$

и

$$^6\mathrm{Li(d,p)}\,^7\mathrm{Li}^* \to {}^7\mathrm{Li} + \gamma \quad (E_\gamma = 438\ \text{кэВ}).$$

Работа выполнена в Лаборатории теоретической физики ОИЯИ.

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Kamal M., Kukulin V.I., Voronchev V.T. E4-88-802
Nuclear-Physics Diagnostics of Ion Temperature in Hot Deuterium-Containing Plasma

A nuclear-physics method for finding ion temperature of hot deuterium-containing plasma is proposed. The method is based on ^{6}Li ion injection and subsequent measurements of γ-quantum yield from the reactions

$$^6\mathrm{Li(d,n)}\,^7\mathrm{Be}^* \to {}^7\mathrm{Be} + \gamma \quad (E_\gamma = 431\ \text{keV})$$

and

$$^6\mathrm{Li(d,p)}\,^7\mathrm{Li}^* \to {}^7\mathrm{Li} + \gamma \quad (E_\gamma = 478\ \text{keV}).$$

The investigation has been performed at the Laboratory of Theoretical Physics, JINR.

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