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The physics of a thermonuclear explosion of a normal-density liquefied deuterium sphere

(On the impossibility of a spherically symmetric thermonuclear explosion in liquid deuterium at normal density)

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Contents

Abstract. The hydrodynamic problem of a thermonuclear explosion in a sphere of normal-density liquid deuterium was solved (Institute for Physics and Power Engineering, Obninsk) in 1952 – 1954 in the framework of the Soviet Atomic Project. The principal result was that the explosion shockwave in deuterium strongly decayed because of radiation energy loss and nonlocal energy release by fast neutrons. At that time, this negative result implied in essence that the straightforward approach to creating a thermonuclear weapon was in fact a blind alley. This paper describes a numerical solution to the stated problem, obtained with the modern DEIRA code developed for numerical modeling of inertially confined fusion. Detailed numerical calculations have confirmed the above 'historic' result and shed additional light on the physical causes of the detonation wave decay. The most pernicious factor is the radiation energy loss due to the combined effect of bremsstrahlung and the inverse Compton scattering of the emitted photons on the hot electrons. The impact of energy transfer by fast neutrons — which was already quite adequately accounted for in the above-cited historical work — is less significant. We present a more rigorous (compared to that of the 1950s) study of the role of inverse Compton scattering for which, in particular, an independent analytic estimate is obtained.

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1. Introduction

More than half a century has passed since the time the problem of a thermonuclear explosion in deuterium was investigated in 1952 – 1954 at the Institute for Physics and Power Engineering in Obninsk (FEI in *Russ. abbr.*). In those long-gone years, this problem was a component of the program of developing nuclear weapons, so that the entire research effort was conducted in conditions of strictest secrecy — classified as the 'special dossier' (sd). The results of this research project carried out by a team of physicists and mathematicians was a detailed report which has most likely survived in the archives of what used to be the USSR Ministry of Medium Machine Building (Minsredmash in *Russ. abbr.*). Nonetheless, very clear information on this work can be found in a brief report presented by V I Chitaikin [1] to the International Symposium ISAP-96 (ISAP standing for the *Russ. abbr.* of the History of the Soviet Atomic Project) in Dubna (May 1996) at Section 4 (Nuclear Weaponry).

The administration of Minsredmash formulated for the FEI team the task of thoroughly analyzing the feasibility of producing a thermonuclear explosion of a spherical mass of liquid deuterium under the most favorable conditions of initiation: with a tritium – deuterium (TD) sphere containing a sufficient amount of tritium placed at the center of the deuterium sphere. The mass of the equimolar deuterium–tritium mixture was given as approximately 4500 g, which was probably close to the entire strategic amount of tritium stored in the USSR at the beginning of the 1950s. Furthermore, the central TD core was assumed to be heated to an initial temperature above the threshold for starting fusion in the TD mixture, equal to ~ 5 keV; in other words, the initiating explosion of a small atomic bomb was tacitly assumed. Specific computations simply assumed a uniformly distributed initial 30-keV temperature of ions and electrons in the TD sphere, which corresponds to an initial internal energy of 3.7 kilotons of trinitrotoluene equivalent (TNT). The reader will recall that 1 kg TNT amounts to 4.184 MJ.

The design aspects of this spherical and totally untransportable hydrogen bomb were not discussed, and neither were preparations for a demonstration explosion of a deuterium sphere under cryogenic conditions. The principal question formulated for the team headed by D I Blokhintsev, then Director of FEI, thus concerned clarification of whether a thermonuclear explosion in a purely deuterium sphere at a radius of 100 cm could be effectively ignited; this radius implied that the total mass at a density of liquefied deuterium of 0.16 g cm^{-3} would be approximately 670 kg (we know now that the liquid deuterium density varies in the interval 0.16 – 0.17 g cm^{-3} depending on temperature $T = 19 - 25$ K.[1] The research team was enhanced by a large group of laboratory assistants, approximately 50 people equipped with several dozen Mercedes and Reinmetal electrical calculators. The team also included more than ten mathematicians headed by Professor E S Kuznetsov and young Candidates of Physico-mathematical Sciences G I Marchuk and N I Buleev. The physicists were headed first by D I Blokhintsev himself but from 1953 onwards by A S Davydov. The physicists in the team were Yu P Raizer, B B Kadomtsev, V S Imshennik, and N N Lukinykh, as well as A Ptitsyn, D Serdobol'skii, and N Legoshina. It can be said that very few people at FEI knew of the existence of this research team or of its activities; this is clear from numerous memoirs of former FEI research officers who designed atomic reactors — this was the principal task of FEI.

2. Main results of the research effort in 1952 – 1954

This section briefly describes the main results obtained by the team in 1952 – 1954, as summarized in the resulting report dated 1954 [1].

The following processes were taken into account in the physical formulation of the hydrodynamic problem: (a) the kinetics of thermonuclear reactions in the TD sphere and deuterium sphere with known reaction cross sections (obtained, in addition to other sources, from 'made in Dubna' experimental data); (b) the equation of state of an ideal plasma and its electron thermal conductivity (classical theory of nonuniform gases as given in the Chapman and Cowling monograph [2][2]; (c) energy losses caused by emission of radiation due to bremsstrahlung mechanism (FF) and the inverse Compton effect (CS) which had at the time just been theoretically analyzed (in A S Kompaneets' famous paper [3]); (d) the nonlocal thermonuclear energy release in the form of fast particles (neutrons, alpha-particles, protons) — reaction products, and (e) boundary conditions at the explosion shockwave front treated as rupture. All these processes were included in the equations of one-dimensional spherically symmetric hydrodynamics taking account of heat conduction; these were solved numerically by the method of characteristics developed specifically for the problem in hand — the Cauchy problem for hyperbolic equations with terms representing energy sources and sinks in the entropy equation.

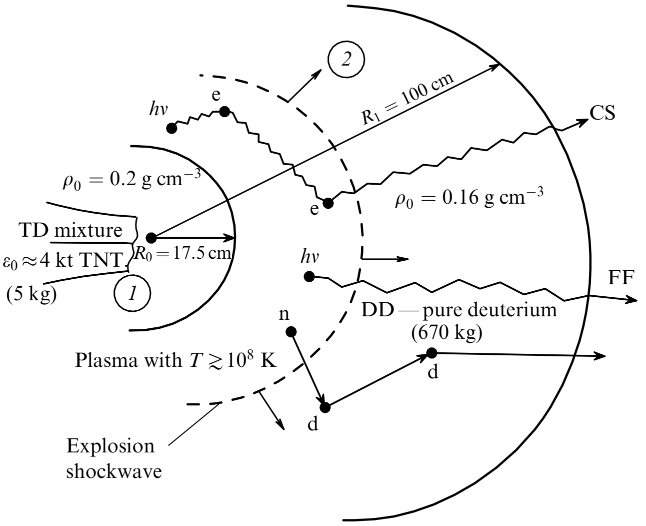

Figure 1. Schematic diagram of thermonuclear explosion of a deuterium sphere (see explanation in the text).

A schematic diagram of the deuterium sphere in question (*2*) with the initiating tritium – deuterium sphere (*1*) is shown in Fig. 1. The dashed curve traces the shockwave front within the confines of the deuterium sphere. Behind this front we see the high-temperature plasma at a temperature of 10 – 100 keV (or $10^8 - 10^9$ K) that emits photons, and fast particles that are products of thermonuclear reactions in the plasma. The 14-MeV neutrons play the main role among fast particles that release energy nonlocally.

The negative result of two years of work on the numerical solution to the problem as formulated consisted, in crude terms, in very fast damping of the explosion shockwave as it propagated through the deuterium sphere. The total energy release was found to be only about 400 kt TNT, of which about one-third was released inside the DD sphere, and two-thirds in the TD sphere. Notice that if the deuterium were burnt completely, much more energy would be released: nearly 60 megatons (Mt) TNT! It became clear in the process that the fusion wave damps out mostly owing to net losses by radiation (FF+CS) and to the nonlocal nature of the thermonuclear energy release, most of all the 14-MeV neutrons of the TD reaction (in complete agreement with the conclusions made in Ref. [1]). Nevertheless, a quantitative description of the inverse Compton effect left much to be desired despite the huge amount of preparatory work done to tabulate the kernel of the integral equation of comptonization with the Klein – Nishina – Tamm cross section taken into account literally.[3] This result seems to have nipped in the bud any possible applications of the design in question for creating thermo-

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[1] It is worth recollecting that the task for our team at FEI was formulated by D I Blokhintsev personally. We can only hypothesize to what extent this formulation was his creation. From the physics point of view, it was indubitably interesting, and not only for possible applications.

[2] It is worth remarking that we had very limited access to scientific literature at the time. Among these 'sources', this monograph by two British scientists, exceptionally rich in content, was singularly useful; there was, alas, no haste in translating it into Russian (here we cite the original publication).

[3] We can reconstruct, albeit with great effort, that taking into account the inverse Compton effect in the physical formulation of the hydrodynamic problem consisted in merely increasing severalfold the power of radiative cooling for each point of the fusion zone. As for this constant coefficient, it was extracted from the data in the report of the All-Union (now All-Russian) Research Institute of Experimental Physics (VNIIEF), among whose authors were N A Dmitriev, an outstanding specialist in computational physics, and L P Feoktistov, one of the creators of thermonuclear weapons in the years to come.

nuclear weapons in the ‘Sturm und Drang’ period. The research team at FEI was in fact dissolved as early as 1955.

The estimate cited above as net calculated energy release is somewhat reduced in comparison with the data given in the report [1]: nearly 800 kilotons TNT. However, this discrepancy with Ref. [1] does not appear to be significant as far as the conclusions of the present paper are concerned, since the deuterium burnup is also very low (about 2%).

The entire work on the task described inevitably involved the participation of several research establishments, first of all the RF Nuclear Center (RFYaTs) VNIIEF (current designation) in Sarov. We remember, for instance, a very useful visit to FEI by Ya B Zel’dovich, D A Frank-Kamenetskii, Yu A Romanov, and A I Zhukov. In addition to physics consultations organized at the Institute for Physical Problems (IFP) with L D Landau’s group, which also included E M Lifshitz, I M Khalatnikov, and S D’yakov, we had frequent contact with the Division of Applied Mathematics (OPM) just organized at the V A Steklov Mathematical Institute, which was headed by M V Keldysh (the OPM was later reorganized into the Institute of Applied Mathematics of the USSR Academy of Sciences). These were particular mathematical consultations with I M Gel’fand, S K Godunov, O V Lokutsievskii, and V F D’yachenko.

3. State-of-the-art numerical solution to the problem of a thermonuclear explosion of a deuterium sphere

It is of certain scientific interest to redo the numerical calculation of the problem formulated above, while applying currently available modern physico-mathematical models of controlled thermonuclear fusion (CTF). Among other things, it is possible to use for the purpose the sufficiently rich DEIRA code developed by one of the authors of the present article (M M Basko) for studying targets of the inertial heavy-ion synthesis (IHIS) [4]. This numerical solution not only is independent of the FEI computations in the past but also implements a definitely better physico-mathematical model (although it is oriented to modeling ‘microscopic’ IHIS targets). Since such ‘intensive’ parameters of a thermonuclear explosion as temperature T and retention parameter ρR have similar values in IHIS targets and in the design we are now discussing, there is every reason to expect that the DEIRA code should provide correct answers to our problem, too. Furthermore, since one-dimensional hydrodynamic calculations take very little time with modern computers, we could easily conduct a whole series of computations to find out the role played by the most important physical processes, and most of all — the energy loss by the emission of radiation.

Table 1

Variant No.	FF	CS	$E_{\rm fin}$, MJ	$E_{\rm fin}$, Mt TNT	$f_{\rm b,DD}$
3000	+	+	1.30×10^9	0.31	0.0018
3005	+	−	2.39×10^9	0.57	0.0062
3006	−	−	4.05×10^{10}	9.68	0.17

A series of computation runs was thus performed using the DEIRA code, for which Table 1 lists the value of total energy release in a thermonuclear explosion of a deuterium sphere with an initial external radius $R_{\rm DD,0} = 100$ cm, deuterium density $\rho_{\rm DD,0} = 0.16$ g cm^{-3}, and seed energy deposition within the radius $R_{\rm DT,0} = 17.5$ cm for a tritium–deuterium equimolar sphere of density $\rho_{\rm DT,0} = 0.20$ g cm^{-3}: $E_{\rm DT,0} = 1.55 \times 10^{13}$ J $= 3.7$ kt TNT, $T_{\rm e0} = T_{\rm i0} = 30$ keV, $T_{\rm r0} = 0.5$ keV. The DEIRA code distinguishes between the electron and ion temperatures $T_{\rm e}$ and $T_{\rm i}$, while radiation is taken into account in the approximation of a separate temperature $T_{\rm r}$. In addition to the data on energy release, Table 1 collates the physical processes taken into account: FF — bulk energy losses due to plasma bremsstrahlung, and CS — additional energy losses by the emission of radiation through the inverse Compton effect. The minus sign in the 2nd and 3rd columns signifies that a particular process was artificially turned off in this model run, while the plus sign marks that it was turned on. The next two columns (3rd and 4th) list the total energy release in the explosion in units of MJ and Mt TNT, respectively. Finally, the last column presents the fraction $f_{\rm b,DD}$ of the burnt up deuterium relative to its total mass in the outer sphere. If all channels of energy loss through radiation are turned off (minuses in both columns 2 and 3), i.e., in variant No. 3006, very high energy release is achieved, nearly 10 Mt TNT, while if they are turned on (+ and + in variant No. 3000), then it drops to 0.31 Mt TNT at a negligible deuterium burnup (one-hundredth of that in variant No. 3006); the energy release does not differ as much (by a factor of ~ 30) by virtue of energy release in the TD sphere. Variant No. 3005 with the comptonization of radiation turned off occupies an intermediate position between the above variants (energy release grows by a factor of 1.84, and the fraction of deuterium burnup by a factor of 3.4).

The thermonuclear explosion is thus appreciably less efficient in variant No. 3000 than in variant No. 3005. It is important to emphasize that the analog of the former calculation at the FEI with a total energy release equal, as we mentioned earlier in this paper, to ~ 0.4 Mt TNT, is variant No. 3000. We can make a conclusion — a flattering one for the first two authors of the present article — that the historically first calculation [1] was very satisfactorily confirmed. At the same time, we conclude, according to Table 1, that judging by the negligible deuterium burnup in variants Nos 3000 and 3005, there is practically no thermonuclear explosion in the deuterium sphere. Notice that if the deuterium were completely burnt, energy release would reach an enormous level: 56.7 Mt TNT. It does grow very substantially in variant No. 3006 toward this limiting value, even though it still remains lower by a factor of 5.86, in exact agreement with the fraction of burnt up deuterium listed in Table 1.

When discussing the data of Table 1, we chose not to discuss the results of some other variants in which nonlocal effects in energy release from fast particles (products of DD and TD reactions) were described in a different manner. These effects were, of course, taken into account in the variants displayed (see Table 1): for α-particles and protons, the energy release was described in terms of the diffusion approximation (in fact, this nonlocal effect played virtually no practical role); the slowdown of neutrons with an energy of 2 MeV was considered to be local (their range is relatively short and therefore nonlocality could be neglected), and the energy of 14-MeV neutrons was ‘spread’ over a special diffusion profile which was calculated separately at each instant of time.

Additional variants of calculations showed that the nonlocal energy release of 14-MeV neutrons plays in this particular problem a quantitative role at least as important

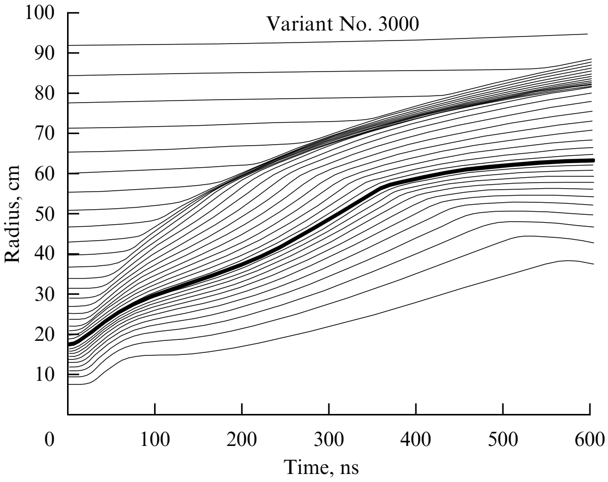

Figure 2. Trajectories of mass elements in computation variant No. 3000. The heavy curve traces the interface between the inner TD sphere and the bulk of pure deuterium.

as energy losses by radiation. The physical cause of this lies in the value of the range of these neutrons in deuterium: as it equals 4.1 g cm^{-2}, it practically coincides with that of photons in Compton scattering, equal to 5 g cm^{-2} (as follows from the Thomson cross section), plus both these ranges are only slightly shorter than the mass thickness $\rho_{\mathrm{DD},0}(R_{\mathrm{DD},0} - R_{\mathrm{DT},0}) = 13.2$ g cm^{-2} of the deuterium sphere. In this way, the formal localization of 14-MeV neutrons (with radiative losses unchanged) resulted in the total energy release increasing by a factor of 2.4 in comparison with that in variant No. 3000, and the fraction of burnt up deuterium by a factor of 5.4 (cp. with the respective values 1.8 and 3.4 in above-drawn comparison with variant No. 3005 based on Table 1). It should be remarked, however, that in the FEI calculations the nonlocality of fast products of reactions was physically better justified than the way inverse comptonization was taken into account.[4] In view of this, problems with the description of energy losses through radiation were considerably more serious than those in describing energy transfer by neutrons produced in the TD reaction. At the moment, too, both effects are described by the DEIRA code not by rigorously solving the corresponding kinetic equations but by using simplified, albeit sufficiently sound, models which are — we already stressed this point — totally independent of the methods and approximations used at FEI in the 1950s.

Figures 2 and 3 exhibit $r-t$ diagrams of the first two variants in Table 1; the thick curve traces the contact border between the tritium – deuterium mixture and pure deuterium. We clearly see that the front of the igniting shockwave in deuterium, which is represented by the kink and closeness of $r-t$ trajectories, undergoes a substantial slowdown from the very beginning. The main cause of this slowdown is radiative cooling of the zone of thermonuclear fusion due to the combined effect of bremsstrahlung emission and the inverse Compton effect. Figure 3, in which the inverse Compton effect is omitted, shows less pronounced braking of the shockwave than in Fig. 2, where both effects were taken into account.

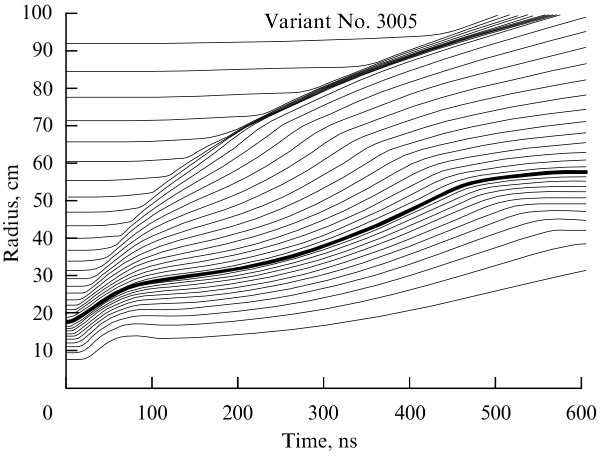

Figure 3. Same as in Fig. 2 but for variant No. 3005.

Figures 4 and 5 display temperature profiles for all three temperatures at several characteristic instants of time — from the initial ($t = 0$) to the final ($t = 1000$ ns) in which the fusion wave (steep front of ion temperature) almost reaches the maximum initial radius $r = 100$ cm. Figure 4, which plots the temperatures for the main variant No. 3000, even demonstrates a fine structure: a small preceding peak of ion temperature up to $T_{\mathrm{i}} \sim 2$ keV appears at the instant of time $t = 200$ ns on the shock density jump ahead of the main front of thermonuclear burning at $T_{\mathrm{i}} \sim 6$ keV. The electron temperature differs from the ion temperature only within the inner TD sphere (cf. Fig. 2). The behavior of the radiation temperature T_{r}, which is very different from the substance temperatures T_{i} and T_{e}, is very important: the value of T_{r} never exceeds the low value of about 1 keV and, while being almost constant along the entire radius, decreases gradually after $t = 100$ ns. As is well known, this difference — more than tenfold — indicates that energy losses by radiation differ very little from losses in the bulk mode of emission (amplified by the inverse Compton effect). In Fig. 5, this effect manifests itself even more strongly, owing to a relative increase in the temperature of the substance under conditions where the effect of inverse comptonization is turned off. The time needed for the fusion front to reach the external boundary was very substantially reduced.

Another feature of the above-considered temperature profile needs pointing out. A long precursor of fairly high temperatures (of several keV) appears ahead of the fusion front singled out by the steepest rise in temperatures T_{i} and T_{e} directed inward along the radius. It is quite clear that this is caused by fast particles generated in thermonuclear reactions, most of all by 14-MeV neutrons. Electron heat conduction also makes a certain contribution, but not the emission of radiation.

4. Evaluation of the relative role of radiative cooling through the inverse Compton effect

It was recognized at the early stages of the development of nuclear weapons that an efficient thermonuclear explosion could only be produced in pure liquid deuterium under the

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[4] The calculation of the nonlocality of energy release by fast particles, first and foremost by 14-MeV neutrons, was based in this particular problem on the original work by B B Kadomtsev, who developed the algorithm of numerical solution of the appropriate integral transport equations for neutrons in a nonuniform medium.

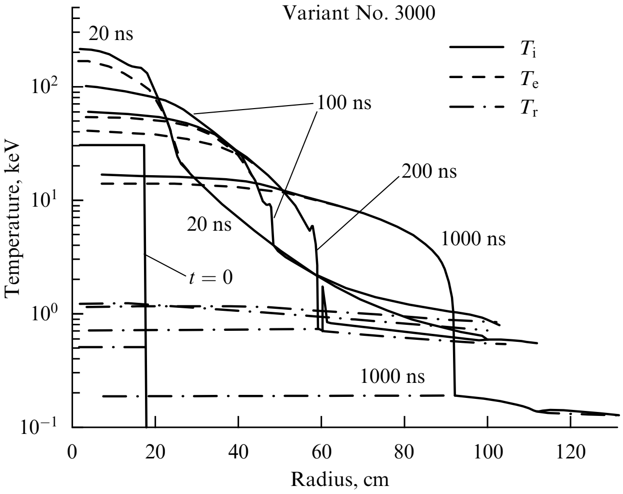

Figure 4. Radial profiles of three temperatures — ion T_i, electron T_e, and radiation T_r — at various instants of time in variant No. 3000.

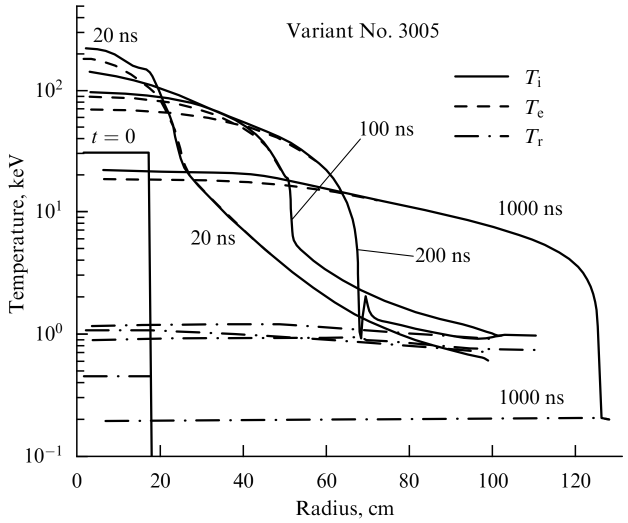

Figure 5. Same as in Fig. 4 but for variant No. 3005.

conditions of nonequilibrium radiation, at which the actual density of radiation energy is substantially lower than the equilibrium Planck density with the radiation temperature $T_r = T_e = T_i$. For this reason, radiative cooling was taken into account in the formulation of the problem on the explosion of a deuterium sphere as bulk bremsstrahlung radiation with a quantitative description of the case of fully ionized high-temperature deuterium plasma, which was well known at the time. However, a simple evaluation of the optical depth of a deuterium sphere with a reasonable mass of several dozen or hundred kilograms showed that bremsstrahlung photons inevitably go through several Compton scattering events before they escape from the thermonuclear combustion zone (see the diagram in Fig. 1). Since the scatterers were plasma electrons with very high temperatures — several dozen or hundred keV — energy exchange in such scatterings led to a considerable increase in the energy of bremsstrahlung photons. This, in the nutshell, is the gist of the inverse Compton effect (see, however, the terminological remark below).

The following question arises naturally when describing this effect: how adequate is the use of the three-temperature approximation in the DEIRA code (based, among other concepts, on introducing separate radiation temperature $T_r \neq T_e$) for describing the above increase in radiative cooling of deuterium plasma? It is clear that if these temperatures differ greatly (in fact $T_r \ll T_e$!), then the real spectrum of nonequilibrium radiation cannot be described by the Planck formula. However, under closer scrutiny it becomes clear (see below) that it is precisely in the optically thin case, in which the above-indicated strong inequality holds, that the approximation of separate radiation temperature T_r turns out to be perfectly adequate — provided the goal was to have a correct description of the radiative cooling of the thermonuclear plasma.

A justification of the three-temperature approximation to the description of radiative cooling of thermonuclear plasma was the subject of a short note [5], even though the assumption made in it reduced to only a small deviation from the equality $T_r = T_e$.

Now we shall give an evaluation of the relative role of the specific power W_{CS} of the inverse Compton effect in comparison with the specific power W_{FF} of bremsstrahlung radiation in the case of deuterium plasma (or a deuterium–tritium mixture) — that is, of the quantity $W_{\mathrm{CS}}/W_{\mathrm{FF}}$ as a function of temperatures T_r and T_e. (Note that assuming different values for the temperatures T_e and T_i is general practice when describing thermonuclear plasma.)

The main processes of interaction with the emitted photons in the deuterium plasma possessing electron temperature T_e of about several dozen (hundred) kiloelectronvolts are as follows:

• Bremsstrahlung radiation whose specific power is independent of the spectrum of photons present in the plasma; it is given by the expression [6]

$$\begin{aligned} W_{\mathrm{FF}} &= \frac{32\pi}{3}\left(\frac{2\pi T_e}{3m_e}\right)^{1/2}\frac{Z^2e^6}{m_e c^3 h}\,n_i n_e \\ &= 1.43\times10^{-27}Z^2(T_{e,\mathrm{K}})^{1/2}n_i n_e \\ &= 4.86\times10^{-24}Z^2(T_{e,\mathrm{keV}})^{1/2}n_i n_e\,, \end{aligned} \tag{1}$$

where the electron temperature is given in units of K and keV, and power in erg cm^{-3} s^{-1}. Expression (1) also uses the quasiclassical approximation which differs very little from the Born approximation — another limiting approximation (the latter's result is greater than the quasiclassical one only by a factor of 1.103). In the case of the deuterium plasma, one has $Z = 1$, $n_i = n_e = \rho/2m_0$, where ρ is the plasma density, $m_0 = 1.66\times10^{-24}$ g is the nuclear unit of mass. If $\rho = \rho_0 = 0.16$ g cm^{-3}, then $n_{e0} = 4.82\times10^{22}$ cm^{-3}.

• Compton scattering whose cross section for $h\nu \ll m_e c^2$ is with sufficiently high accuracy independent of the photon energy $h\nu$ and equals the Thomson cross section $\sigma_T = (8\pi/3)\times(e^2/m_e c^2)^2$.

The process of inverse bremsstrahlung of the emitted photons plays no role in our conditions since the appropriate mean free path is much greater than the radius of the deuterium sphere.

The role of Compton scattering reduces to two basic effects: (a) partial confinement of the emitted photons in the deuterium sphere whose optical depth for scattering is $\tau_{\mathrm{CS}} = \sigma_T n_e(R_{\mathrm{DD},0} - R_{\mathrm{DT},0}) = 2.6$, and (b) cooling of electrons through the inverse Compton effect whose specific power for $T_r < T_e$ is also practically independent of the spectrum of photons in the plasma and is dictated exclusively by the local density of radiant energy U_r (per unit volume); it is expressed by a formula given by Ya B Zel'dovich in the review paper [7]:

$$W_{CS} = \frac{4\sigma_T n_e T_e}{m_e c} U_r . \quad (2)$$

Since the cross section σ_T is independent of the photon frequency ν, a correct description of both effects outlined above does not need knowledge of the spectrum of nonequilibrium radiation. It is sufficient to calculate the temporal and spatial distributions of its total energy density U_r, which can be implemented in terms of the three-temperature model by using the solution of a separate nonstationary diffusion equation for the quantity $U_r = a_r T_r^4$ with the diffusion coefficient $l_{CS}c/3 = c/(3\sigma_T n_e)$ independent of radiation frequency (this is the procedure that the DEIRA code implements); here, $a_r = \pi^2/(15\hbar^3 c^3)$ is a constant that characterizes the heat capacity of the Planck radiation at the temperature T_r. Note that the only meaning carried by the radiation temperature $T_r < T_e$ is that the expression $a_r T_r^4$ describes the bulk density of the nonequilibrium radiation contained in the plasma but does not signify at all that the spectrum of this radiation is governed by the Planck formula at the temperature T_r. The accuracy of this description is only restricted by the condition of applicability of the diffusion approximation: it is quite satisfactory at the above values of $\tau_{CS} \geqslant 1$ and enhances with increasing τ_{CS}.

Using formulas (1) and (2), we can readily evaluate the sought-after relative role of the inverse Compton effect in the radiative cooling of the deuterium plasma:

$$\frac{W_{CS}}{W_{FF}} = 4.4 \times 10^{21} n_e^{-1} T_{e,\,keV}^{1/2} T_{r,keV}^4 = 0.46 \left(\frac{T_e}{25\ keV}\right)^{1/2} T_{r,\,keV}^4 , \quad (3)$$

where we used the value of $n_e = 4.82 \times 10^{22}$ cm^{-3}. Expression (3) immediately shows that if $T_e = 10-100$ keV, the inverse Compton effect begins rapidly to dominate once the radiation temperature T_r rises even slightly above the value of $T_r = 1$ keV. This explains why the radiation temperature T_r in Figs 4 and 5 does not — ever or at any point — appreciably exceed this level. Notice also that as the deuterium burning zone spreads out, the relative role of the inverse Compton effect increases further owing to the decrease in electron density n_e in expression (3).

One remark of a terminological nature is in order here. According to the established tradition, we refer to the specific power (2) as cooling through the inverse Compton effect. In reality though — and this is easily demonstrated by following the derivation of the Kompaneets equation in Refs [3, 6] — the rate of cooling (2) of hot electrons originates with the purely classical Doppler effect in the Thomson scattering of photons by hot electrons with Maxwellian velocity distribution, not by electrons at rest. When $h\nu \ll m_e c^2$ and $T_e \ll m_e c^2$, the quantum Compton effect always results in energy transfer from photons to electrons, not the other way around. In this sense, the plasma cooling through the inverse Compton effect that we discuss here represents essentially cooling that stems from the Doppler effect under Thomson scattering (see also Ref. [8]).

The destructive role of Compton cooling in the thermonuclear explosion of deuterium can be demonstrated with greater clarity by considering a deuterium sphere of greater diameter, for example, with an initial radius $R_{DD,\,0} = 300$ cm. In this geometry, with the radius of the TD 'igniter' $R_{DT,\,0} = 30$ cm ($E_{DT,\,0} = 18.7$ kt TNT), all the descriptive details of energy transfer by 14-MeV neutrons become of secondary importance since the mass thickness of deuterium $\rho_{DD,\,0}(R_{DD,\,0} - R_{DT,\,0}) = 43.2$ g cm^{-2} now greatly exceeds the neutron range equal to 4.1 g cm^{-2} and we approach the most favorable conditions of local energy release for all products of thermonuclear reactions of DD fusion. The results of two appropriate calculations are given in Table 2. A comparison of two variants in this table shows unambiguously that turning on the Compton radiative losses completely dampens the wave of thermonuclear combustion in deuterium: the fraction of deuterium burnup reduces from the respectable level of 48% (variant No. 3011) to the negligible value of $f_{b,\,DD} = 1.3 \times 10^{-4}$ (variant No. 3010).

Table 2

Variant No.	FF	CS	E_{fin}, MJ	E_{fin}, Mt TNT	$f_{b,\,DD}$
3010	+	+	5.40×10^9	1.29	1.3×10^{-4}
3011	+	–	2.99×10^{12}	715	0.48

5. Conclusion

Two co-authors of this article (G.I.M. and V.S.I.), who took part in the FEI work in those days long ago (1952–1955), found more than merely pleasure in the qualitative confirmation of their main result; however, we were also curious to clarify what was one of the main reasons for essentially the impossibility of producing any significant thermonuclear explosion in a cryogenic deuterium shell. We have to accept that the main reason is the steep rise in energy loss through emission of radiation driven by inverse comptonization of bremsstrahlung photons in high-temperature deuterium plasma. It should be emphasized that the way this effect was taken into account in the past in FEI calculations was poorly justified in comparison with that in the modern DEIRA code. In view of this, the authors of the present article believe that the above independent checking of old results is desirable, especially taking into account the very important progress achieved in the physico-mathematical model by the computations of the third author of this article (M.M.B.).

We also need to remark that the explosion of a deuterium sphere was considered as an option for the 'igniter' of the so-called 'deuterium pipe' — a superpowerful nuclear bomb described, for example, in an interview of B L Ioffe [9] and in the monograph [10] devoted to L P Feoktistov's 80th anniversary of birth. It appears to us that lacking such an igniter (because it is impossible to initiate the thermonuclear combustion, as was shown in FEI calculations and confirmed here for a deuterium sphere), it is difficult to find a 'positive' solution to igniting the pipe itself (note that the pipe radius was also about 100 cm). As for the deuterium pipe proper, the propagation of a stationary wave of thermonuclear detonation through it is again precluded by the inverse comptonization effect [10]. For these reasons, we still consider designing a deuterium pipe absolutely out of reach.

By way of self-criticism, we need to remark that more complete calculations of the problem in question are available nowadays, which include kinetic equations for neutrons and spectral equations for photon transfer; these, in principle, could be utilized to improve the accuracy of the results obtained using the DEIRA code given above. Nevertheless, it appears that conducting such computations aimed at checking the main conclusion of this paper (the impossibility of detonating deuterium in a spherically symmetric sphere with liquid deuterium at normal density) is hardly advisable since this result was obtained here with huge 'overkill'.

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