

LETTERS TO THE EDITORS

PACS numbers: **28.90.+i**, **52.90.+z**, 78.60.Mq

On the prospects of bubble cavitation-induced fusion

A A Goverdovskii, V S Imshennik, V P Smirnov

DOI: 10.3367/UFNe.0183.201304k.0445

Contents

1. **Introduction** **423**
2. **Analysis of bubble fusion experiments** **424**
3. **Underlying feasibility of cavitation fusion** **425**
4. **Conclusion** **425**

References **425**

Abstract. Experimental and theoretical work on cavitation-induced fusion reactions in bubbles is critically analyzed. It is shown that the existing data are internally inconsistent. The yield of hypothetical thermonuclear neutrons is found to be at least three orders of magnitude overestimated and therefore inconsistent with the tritium yield observed. A simple estimate shows that any power system using the principle discussed is unfeasible.

1. Introduction

Russia, at that time part of the USSR, entered the field of controlled nuclear fusion (CNF) more than sixty years ago, closely preceded by a number of other nations. Soon after, following I V Kurchatov's landmark lecture in the UK,[1] two major relevant concepts — thermal insulation and the magnetic confinement of high-temperature plasma — were declassified, and about twenty years later, the possibility of igniting the explosion of a fusion microtarget, a device sharing much of its physics with an explosive charge of a weapon, came under broad discussion (inertial confinement). Since then, the active international exchange of results and ideas coupled with the cooperation of prominent scientists from leading countries, has provided great advances in the field, giving rise to the discipline of high-temperature plasma physics and contributing greatly to many adjacent areas of physics. The need for a temperature of tens of millions of degrees spurred the development of new diagnostics tools, new materials, and new technologies, which, when integrated, yield in economic terms more than was originally invested in CNF research.

However, despite all the successes in developing the technology and physics of high-temperature plasmas, the primary goal — building a fusion reactor — has not yet been achieved. It is only relatively recently that the construction of the ITER (International Thermonuclear Experimental Reactor) tokamak complex began, with the reliable physical demonstration of an energetically favorable reaction being planned for as far away as the early 2030s. Next in the plan is the demonstration reactor DEMO (Demonstration Power Plant), a preliminary stage of commercial reactors. Thus, even if the ITER and DEMO are a successes, we cannot expect fusion power to be commercialized before the second half of this century. This is, of course, disappointingly far away, and the question arises of whether we are on the right path at all; not surprisingly, uneducated or poorly educated inventors come in large numbers (and usually with support from those in power) with 'simple' recipes as to how the fusion problem can be solved (a situation that incidentally imposes the daunting time-consuming task of replying on the leading fusion experts).

On the other hand, world-renowned scientists and even well-staffed research groups (usually from other fields) sometimes offer original and interesting solutions to the CNF problem, which cannot be outright discarded as wrong and should instead be subjected to close scrutiny and careful analysis. One example approach is the so-called 'ultrasonic nuclear fusion', or more commonly, bubble fusion.

The theoretical analysis of cavitation in a liquid dates back to Rayleigh. Hopes for obtaining high temperatures and high densities from the spherically symmetric collapse of a bubble were enhanced by the observation of sonoluminescence, a phenomenon in which light in the form of pulses with duration up to tens of picoseconds is produced in a liquid. Some studies in the 1960s–1970s discussed theoretically whether an imploding bubble can produce high temperatures. Establishing the limiting parameters of the problem requires assessing such factors as dissipation due to electronic

[1] The lecture was given at the British atomic center Harwell Laboratory during Kurchatov's 1956 UK trip as a member of a Soviet government delegation.

A A Goverdovskii State Scientific Centre of the Russian Federation "Leypunskii Institute for Physics and Power Engineering," pl. Bondarenko 1, 249033 Obninsk, Kaluga region, Russian Federation
E-mail: gaa@ippe.ru
V S Imshennik Keldysh Institute of Applied Mathematics, Russian Academy of Sciences, Miusskaya pl. 4, 125047 Moscow, Russian Federation
E-mail: imshenik@itep.ru
V P Smirnov Joint Institute for High Temperatures, Russian Academy f Sciences, ul. Izhorskaya 13/2, 125412 Moscow, Russian Federation
E-mail: vpsmirnov@rosatom.ru

Received 14 February 2013
Uspekhi Fizicheskikh Nauk **183** (4) 445 – 448 (2013)
DOI: 10.3367/UFNr.0183.201304k.0445
Translated by E G Strel'chenko; edited by A M Semikhatov

conductivity, radiation, and a nonsymmetric bubble shape. A deviation from perfectly symmetric compression can manifest itself in the collapse process either as a result of the mutual interactions between the bubbles as they develop en masse or due to emergent instabilities. Based on the analysis of the bubble formation process, it cannot be ruled out either that the development of instabilities and the broadening of the liquid–vapor transition region — two factors that influence the limiting maximum compression values achievable for the plasma parameters — occur during the nucleation stage. The amount of vapor in a bubble is also difficult to control, as is the vapor charge composition needed for reducing radiative loss during compression. Direct experiments on emission from a single bubble reported low temperatures of a few electron volts; the corresponding figures for multibubble cavitation were found to be an order of magnitude smaller. Given all the above, it is not surprising that the bubble fusion concept was found to show little or no promise.

2. Analysis of bubble fusion experiments

It was experiments [1] at the Oak Ridge National Laboratory, which, importantly, is well known for its reputation, that rekindled — and indeed generated a heated debate on — the subject of bubble fusion. In these experiments, a sample (of 0.6 liters) of deuterium-enriched acetone C_3D_6O exposed to both neutrons (of 14 MeV) and ultrasound at 0 °C produced neutrons (of 2. 5 MeV) and a considerable quantity of tritium, indicating the occurrence of D–D fusion in the respective equal-probability processes $D(d,n)^3He$ and $D(d,p)^3H$. The neutron detector, a small-size (50 × 50 mm) NE213 liquid oscillator, was placed immediately next to the dish and 15 cm from the head of a neutron generator (NG) (with the intensity $\Phi_0 = 5 \times 10^5$ neutrons per second (n/s)). The layout exploited the large solid angle difference to improve the geometric efficiency of detection of the sought neutrons against the intense NG background. The magnitude of the effect, determined as the difference of large numbers, was found to be about $\delta = 2\%$ of the total number of neutrons counted by the detector.

In Ref. [1], the hypothetic D–D source was estimated to have a surprisingly high intensity $\Phi_{DD} = 10^5$ n/s, and the later study [2, 3] gave a value of even 4×10^5 n/s. Such values of neutron yield from cold acetone are fully consistent with the tritium yield rate equivalent to the neutron field intensity of 5×10^5 n/s [1, 3]. These results are highly important: under the geometry conditions used in Refs [1–3], the NG flux at the dish surface did not exceed $\Phi_1 = 10^4$ n/s, suggesting that the neutron flux in acoustically treated deuterium-enriched acetone increases with a coefficient $K = \Phi_{DD}/\Phi_1 = 10$ (!). An increase in the volume of the medium should give rise to an increase in K and, hence, to an increased energy release, with all the consequences that follow. Returning to numbers, however, if the discoverers' value $\Phi_{DD} = 10^5$ n/s [1], which corresponds to two percent of the total number of neutrons, is considered correct, then the background source of neutrons — mainly those produced directly by the NG and those scattered on the hydrogen-containing cuvette — should have the intensity $\Phi_2 \sim \Phi_{DD}[\varepsilon/(1-\delta)]$. Here, $\varepsilon \sim 10$ is the geometric detection efficiency ratio of the fusion to NG neutrons. The final value $\Phi_2 = 5 \times 10^7$ is two orders of magnitude larger than the total possible number of neutrons in the system. This absurdly high value relates to the fact that the authors of the 'discovery' in Refs [1–3] clearly underestimated the self-efficiency of the detection of neutrons by the NE213 detector. According to Refs [1–3], the detection efficiency is only 0.1%, in sharp contrast to the realistic value of the order of 10% (see Ref. [4] for a review).

Papers [1–3] use the same underestimated efficiency to analyze the results in [5] from an independent Oakridge team that the lab management set up to check the results in Ref. [1]. The team control experiments detected no D–D neutrons in a setup similar to that used in Ref. [1]. However, in the interpretation of the authors of Ref. [3], in which their own estimate of the 'desired' detection efficiency is taken to apply to somebody else's detector, the Oakridge results brilliantly confirm the existence of intense fusion neutron emission.

Deserving special mention in this connection is Ref. [6], which, while formally and verbally confirming the data in Ref. [1], produces more skepticism than optimism or confidence concerning the existence of the phenomenon in principle. Both the original and differential NE213 spectra thoroughly detailed in Fig. 5 in Ref. [6] exhibit quite distinct, variously directed, similar-amplitude fluctuations in the low-energy region (below 2.5 MeV), which is fairly characteristic of a poorly stabilized electronic channel of a detector, especially in the exponential region of the spectrum. This implies that both the results in Ref. [6] and those in Ref. [5] should be considered to refute the results in Refs [1–3].

Defining the neutron detection efficiency in an error-free manner yields the upper boundary at a level for which the required source intensity of hypothetical neutrons is only 10^3 n/s, in obvious contrast to the tritium yield data in Refs [1–3] (5×10^5 n/s). It should be noted that according to the data in Ref. [1], the entire observed increase in 'tritium' activity as measured by a standard dosimetric gamma camera is only one third of the device self-background (which, incidentally, differed by a factor of three in the studies of irradiated samples of deuterium-enriched and normal acetone). Unfortunately, the authors of Ref. [1] failed to analyze what factors other than those related to D–D fusion could contribute to the appearance of tritium in the deuterium-enriched acetone. But these factors are obvious. A hydrogen-containing sample acts as a decelerator, with the result that slow neutrons are radiatively captured by deuterium nuclei, leading to the formation of tritium. Ultrasonic vibrations can influence the volume distribution of tritium or its compounds in the dish, thus creating the 'enriched' regions from which the samples (1 cm^3 in volume) were taken — and giving the impression of a massive production of tritium due to fusion. Such fantastic scenarios may be many, and any of them has the right to exist until a decisive and professionally performed experiment shows otherwise.

Putting the above criticisms together, fusion reactions cannot be regarded as an actually observed event. Indeed, the internally contradictory studies in Refs [1–3] rather disprove the possibility of cavitation-induced fusion, at least for external neutron source experiments. Rather simple energy balance considerations can be used to assess whether such a layout is possible in principle. The most energetically favorable external neutron source is the spallation of high-energy protons on heavy nuclei, with an energy expenditure of only 50 MeV (electric) per neutron of the beam. To return at least this amount to the system, it is necessary, given the 33% conversion efficiency of thermal to electrical energy and 20% conversion efficiency of electrical energy to that of a beam, that the fusion reactions produce no less than 750 MeV (thermal). This suggests that the working medium should produce $M = 100$ neutrons per source neutron. In the language of nuclear reactors, the effective neutron multiplication coefficient in the medium should be $K_{\text{eff}} \sim 0.99$. For comparison, the energy breakeven condition for the accelerator driven system (ADS) technology is already satisfied at $K_{\text{eff}} \sim 0.9$. For an accelerator-based hybrid system with conventional atomic reactors or fusion facilities, the energy amplification coefficient should exceed 50–100. In this case, the neutron amplification in a fusion reactor should reach $M = 10^4$ but not $M = 0.1$, as can be determined under strong assumptions from the data in [1–3]. Finding an extra five orders of magnitude does not seem to be possible.

3. Underlying feasibility of cavitation fusion

We now proceed from the analysis of experiments to discussing whether a vapor plasma with fusion-level parameters can in principle be produced by a collapsing bubble. If bubble fusion advocates are pinning most their hopes on cumulative processes occurring during the collapse of bubbles, it makes sense to look at an estimate of how the process of cumulation occurs for shock waves (SWs) that are quite likely to arise during the collapse. We suppose that bubbles, as they emerge in large numbers in the liquid, are spaced sufficiently far apart for the spherical symmetry to remain intact. We also suppose that the non-one-dimensional instabilities of the hydrodynamic collapse process can be suppressed. We consider a convergent shock wave in the process of spherically symmetric cumulation. In the present context, we note, first, that there is an automodel solution [7–9] and, second, that this solution is realized in a sufficiently close vicinity of the center of symmetry for an arbitrary initial impact. In particular, the temperature behind the shock front depends on the front radius r_{f} according to the automodel solution,

$$T_{\text{f}} \sim r_{\text{f}}^{2(1-k)} = r_{\text{f}}^{-0.911} , \tag{1}$$

for the simplest equation of state with the adiabat exponent $\gamma = 5/3$. Here, $k = 1.453$ is the automodel index ($r_{\text{f}}^k \sim -t$, where time t is measured from the instant of SW cumulation). Relation (1) determines, in a way, the cumulation rate and readily gives the value of the SW front radius for which the temperature reaches fusion values T_{f}^{TF} (TF is an abbreviation for thermonuclear fusion). Of course, such an estimation requires that initial values be specified for the temperature T_{f} and radius r_{f0} in the initial conditions for the applicability of the automodel solution. Roughly speaking, T_{f0} and r_{f0} should be of the same order of magnitude as their bubble surface counterparts. We take $T_{\text{f0}} = 300$ K and $r_{\text{f0}} = 1$ cm in the relation

$$\frac{r_{\text{f}}^{\text{TF}}}{r_{\text{f0}}} = \left(\frac{T_{\text{f0}}}{T_{\text{f}}^{\text{TF}}}\right)^{1.098} , \tag{2}$$

which follows from Eqn (1) and where $T_{\text{f}}^{\text{TF}} = 3 \times 10^6$ K. Inserting the above three values into Eqn (2) gives the very small value $r_{\text{f}}^{\text{TF}} = 0.4055$ μm. This tiny sphere, according to solution (1), contains only a very small number (10^7) of particles with energies of 0.3 keV or more and has a negligibly small energy (10^{-9} J) if the initial water vapor concentration in the bubble is taken to be less than the water molecule concentration by a factor of 10^2.

Nor can we avoid concluding, further, that the automodel cumulation regime cannot be sustained if an SW radius varies by a factor of more than 10^4. We note that the limiting conditions for this regime relate to the dissipative processes in the plasma behind the shock front [10]. In Ref. [10], the hydrodynamic problem including dissipative processes was studied in detail computationally by introducing ionic viscosity, electronic and ionic heat conductivities, and the electron–ion heat difference (see also the references in Ref. [10]). Thus, the cumulation process, in fact, breaks up into three stages: the initial 'push', the automodel regime, and the dissipative 'cutoff' of infinite cumulation. Although possible, we did not find it necessary here to simulate all the three states numerically, but we can firmly conclude that the third stage is entered at a much larger SW radius, $r_{\text{f}}^{\text{DP}} \gg r_{\text{f}}^{\text{TF}} \approx 1$ μm, amply demonstrating that a plasma with fusion parameters is unachievable in this context.

There is one point to note, however. Paper [10] shows at a physical level of rigor that an automodel process cannot cumulate indefinitely. But at a rigorous mathematical level, only the boundedness of the radial derivative for the electron temperature was shown, although numerical work demonstrated the boundedness of all the other radial thermodynamic and hydrodynamic derivatives, including those at the last, the fourth, stage, where the shock front is reflected from the symmetry center. To return to the complete formulation of the problem, it is worth emphasizing the essential role of non-one-dimensional instabilities of a spherically symmetric process in restricting the cumulative process involved in bubble collapse [11].

4. Conclusion

Drawing on Ref. [1], the experimental data on and calculations intended to account for the bubble collapse phenomenon have been analyzed to show that bubble fusion holds no promise for power applications. There are other factors of relevance — the low energy release density, deviations from the symmetry of collapse, vapor composition, and many others — which, although secondary, serve to enhance the main conclusion. However, putting bubble power aside and concentrating on the physics of bubble collapse, it should be recognized that this subject is interesting enough to warrant separate research attention.

References

1. Taleyarkhan R P et al. *Science* **295** 1868 (2002)
2. Taleyarkhan R P et al. *Phys. Rev. E* **69** 036109 (2004)
3. Nigmatulin R I et al. *J. Power Energy* **218** 345 (2004)
4. Klein H, Brooks F D *PoS* (FNDA2006) 097 (2006)
5. Shapira D, Saltmarsh M *Phys. Rev. Lett.* **89** 104302 (2002)
6. Xu Y, Butt A *Nucl. Eng. Design* **235** 1317 (2005)
7. Guderley G *Luftfahrtforschung* **19** 302 (1942)
8. Zel'dovich Ya B, Raizer Yu P *Physics of Shock Waves and High-Temperature Hydrodynamic Phenomena* (New York: Academic Press, 1966 – 1967) [Translated from Russian: *Fizika Udarnykh Voln i Vysokotemperaturhykh Gidrodinamicheskikh Yavlenii* (Moscow: Fizmatgiz, 1963)]
9. Brushlinskii K V, Kazhdan Ja M *Russ. Math. Surv.* **18** (2) 1 (1963) [*Usp. Mat. Nauk* **18** (2) 3 (1963)]
10. Imshennik V S *J. Appl. Mech. Tech. Phys.* **21** 748 (1980) [*Prikl. Mech. Tekh. Fiz.* (6) 10 (1980)]
11. Zababakhin E I *JETP Lett.* **30** 87 (1979) [*Pis'ma Zh. Eksp. Teor. Fiz.* **30** 97 (1979)]