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Research Article

Sonofusion: Ultrasound-Activated He Production in Circulating D_2O

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Abstract

Experiments over the last 25 years have demonstrated *sonofusion*: the formation of He by ultrasound incident on D_2O. The observed effect is described. Neither the characteristic gamma nor the neutron typically seen in the formation from two deuterons of ^{4}He and ^{3}He, respectively, is observed. The experimental arrangement is specified. A proposed model, based on cavitation-produced z-pinch jets in target-foil implants, is outlined. It involves formation in the implants of a BE condensate that provides the source of the deuterons and whose recoil ensures energy-momentum conservation. The model accounts for all experimental results. It also provides a guide for future work on sonofusion.

Keywords: Alpha, Bremsstrahlung, Gamma, Heatk, Sonoluminescence

1. Introduction

A summary is presented of over 25 years of the author's experimental results on the formation of ^{4}He initiated by a high-frequency acoustic wave incident on circulating D_2O in the presence of an exposed Pd, Ti or other lattice. ^{4}He analysis was also carried out in part by others [1–3], as summarized in the Appendix.

The observed effect is described in Section 2. The emitted heat correlates with the energy released in the counted number of 2D events. The process – termed *sonofusion* – produces, for each observed ^{4}He atom, excess heat slightly greater than the binding energy B (2D,^{4}He). Most applications of calorimetry to fusion have been based on electrochemistry [4–7], not on ultrasound. In both the ultrasound-generated and electrochemically generated calorimetry-based measurements, both ^{4}He and ^{3}He production were observed. Neither the characteristic 23.8 Mev gamma nor the 2.45 Mev neutron typically seen in $2^2H \rightarrow {}^4He + \gamma$ and $2^2H \rightarrow {}^3He + n$, respectively, has been observed in the ultrasound or electrochemical systems [3,8,9]. No gammas were found during sonofusion experiments when measured with GM and BF_3 detectors [8,9] and no ^{3}He was found in Pd target foil runs [3]. There was T detected via MS of a growing presence of ^{3}He over time from gases collected from Ti target foil runs [3].

The circulating D_2O system, comprising six major subsystems, is specified in Section 3.

A theoretical model for sonofusion is outlined in Section 4. It accounts for the process as a whole, including the absent gamma and neutron. The model is based on diverse experimental results [3,10,11]. It comprises the formation,

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by acoustic-driven cavitation, of bubbles that form a plasma containing deuterons and electrons. The plasma is compressed by a pinching magnetic field (Z-pinch), causing a sequence of picosecond sub-nanometer events consequent to implantation of D^+ ions in the lattice. The fusion occurs in a BE condensate formed in the lattice implantation. The single events are shown in a 1 μm^2 FE SEM photo [12]. Sonofusion differs from *bubble fusion*, which relies on neutrons producing fusion events *within the confines* of a cavitation bubble [13]. The model should provide a guide for future work, both experimental and theoretical, on sonofusion.

2. Observed Effect

An ultrasound pulse of energy Q_a, incident on a room-temperature system of circulating liquid D_2O, has been observed to produce ^{4}He and energy in the form of calorimetrically measured heat, Q_0,

$$m\mathrm{D}^+ + Q_\mathrm{a} \to (m-2)\,\mathrm{D}^+ + {}^4\,\mathrm{He}\ + Q_0$$

the number, m, of deuterons in the interacting cluster can range from about 100 to 2. The *excess* heat, Q_x, produced by the reaction is then

$$Q_x = Q_0 - Q_\mathrm{a}$$

The numerical values of (Q_a, Q_0, Q_x) given below will be those (delivered, measured, calculated) in one second [11].

The frequency of the acoustic wave is about 1 MHz; the pulse is on for about 120 s, then off for about 120 s. The temperature of the system reaches 90% of its steady-state value of about 15°C higher than the start temperature within about 60 s.

A single *cycle* of the ultrasound wave was found to produce about 10^7 events (an event is the production of a single ^{4}He atom [12]), observed spectra of sonoluminescent and bremsstrahlung photons, and measured heat in the amount $Q_0 = 58$ J for an acoustic energy $Q_\mathrm{a} = 15$ J, so that $Q_x = 43$ J. This translates into 10^{13} events/s and determined excess heat per event of $q_x = 4.3 \times 10^{-12}$ J = 26.9 MeV. The energy of an event is independent of the size of the number m of deuterons in the cluster. It is about 3 MeV higher than the binding energy of ^{4}He in terms of deuterons (the D_2O disassociation energy of 15.5 eV is neglected), which is related to the listed binding energies based on nucleons:

$$\mathrm{B}\left(2\mathrm{D};{}^4\,\mathrm{He}\right) = \mathrm{B}\left(2\mathrm{p},\ 2\mathrm{n};{}^4\,\mathrm{He}\right) - 2\,\mathrm{B}\,(\mathrm{p},\ \mathrm{n};\ \mathrm{D}) = 28.3 - 2\ \times\ 2.22 = 23.9\ \mathrm{MeV}.$$

The helium atoms were detected and counted by a mass spectrograph by B. Oliver [3,14]

3. Circulating D_2O System

The circulating D_2O system comprises six major subsystems, as shown in Fig. 1. The subsystems are next listed in the sequence in which D_2O circulates through them.

(1) A *bubbler* containing argon-saturated D_2O, with argon gas above the saturated liquid. The initial concentration of ^{4}He in the Ar, prior to circulation through the system, was measured in a mass spectrograph (see (7), below) at less than 2 ppm. The bubbler maintains constant pressure throughout the system; after the fluid has passed through the system, it also transfers any bubbles that have been formed from the liquid into the argon gas, separates the argon gas from the liquid D_2O, and collects about half the total ^{4}He produced; see (4) below. Calorimetric flow was determined through heat measurements in a system that used 1.6 MHz resonators. In another system, using a Mark I 20 kHz resonator, the amount of ^{4}He in the gases over the circulating D_2O was measured to be 551±1 ppm.

(2) An *FMI pump*, which pumps the circulating Ar/D_2O fluid and establishes a constant D_2O mass-flow rate.

(3) A *filter*, which eliminates any small particles.

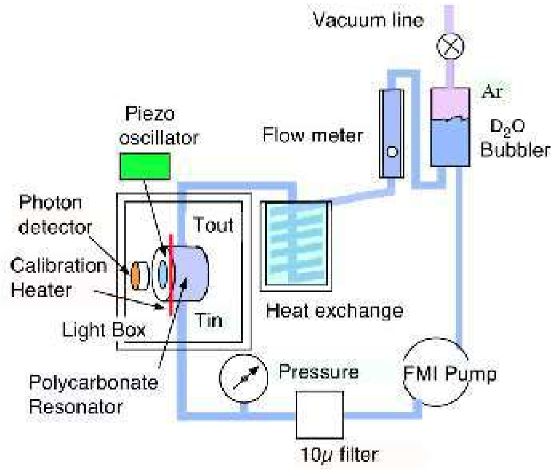

Figure 1. Typical D_2O Flow System.

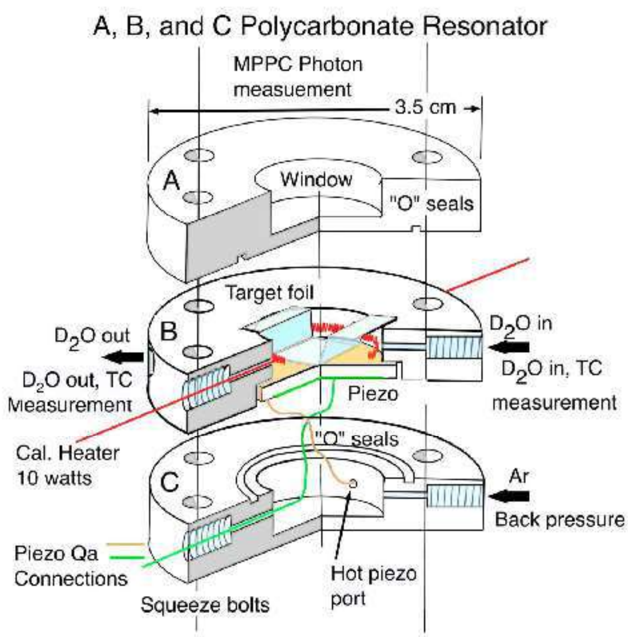

Figure 2. Typical resonator; see (4).

(4) A *light box* that contains a foil (target lattice), typically Pd, Ti or another material; a MHz piezo resonator; and thermocouples that measure the change in the D_2O temperature, $\Delta T = T_{\text{out}} - T_{\text{in}}$. The resonator produces a calibrated ultrasound pulse of magnitude Q_{a}, with a 120 s on/off mode; Q_{a} can be adjusted to deliver from 0 to 15J in 1 s. A typical resonator is shown in Fig. 2. The MHz ultrasound pulse creates cavitation bubbles in the circulating D_2O. The number of deuterons in a bubble is estimated reliably using the ideal-gas law for the collected portion of the total ^{4}He produced and the measured pressure and temperature. Each bubble grows and gains mass in the negative pressure of the acoustic input; at a maximum radius it collapses adiabatically to a final radius with a million-fold increase in energy density. 10^6 bubbles, each producing 10^3 photons, are counted by a multipixel photon counter (MPPC). The measured photon emission, shown in Fig. 3, includes two types of photon radiation: sonoluminescent and bremsstrahlung. The observed spectrum shows a single sharp peak of about 100 ns duration for each cycle [15].

(5) A *heat exchange*r, a heat sink that brings the temperature back to its initial base value.

(6) A *flow meter* that measures the flow rate, which together with ΔT determines the heat output Q_0. The excess heat produced by the reaction is determined from the delivered Q_{a} and mass-flow calorimetrically measured Q_0 by Eq. (2).

(7) A mass spectrograph (MS, not shown in Fig. 1) that measures the helium atoms in ppm concentration in the argon gas. A measured aliquot – known volume of gas at measured pressure and temperature – was transferred into the MS and compared to a known ppm standard. The number N of experimentally produced alphas was determined from *pV* = *NkT*.

4. Theoretical Model

The author has proposed a theoretical model to account for his 25-year collection of experimental results – with differing resonator sizes, frequencies, and acoustic inputs. The model involves a multi-stage process for the fusion of two deuterons into an alpha particle [9-2,14,15]. The discussion is carried through for ^{4}He, but it applies to T $\rightarrow^3$ He as well [10].

(A) The ultrasound pulse ionizes some of the D_2O and, in the first stage of a compression process, creates a population of transient cavitation bubbles with a wide spectrum of sizes. Bubbles whose size is in resonance with the

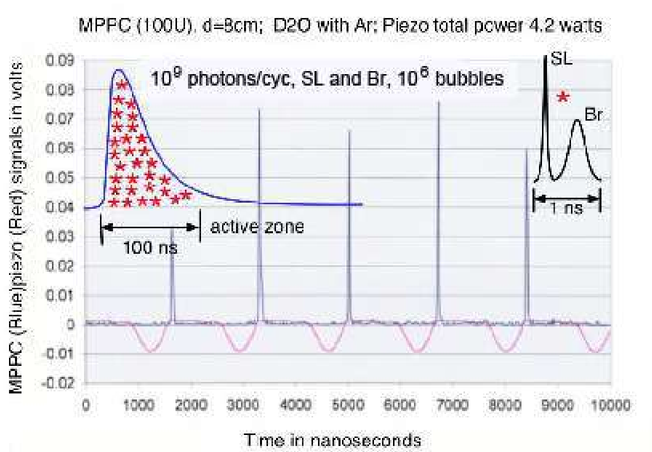

Figure 3. Measured photon spectrum, showing a single sharp peak of about 100 ns duration for each cycle. There is no activity in the region between peaks. Upper right shows the expected photon emission, which was not resolved experimentally, from one out of 10^6 bubbles/cycle.

acoustic wavelength grow in size and gain energy isothermally by picking up additional mass – deuterons and sheath electrons – from the D_2O and Ar [14], then collapse adiabatically in a few nanoseconds. The collapsing bubbles emit the observed sonoluminescent and bremsstrahlung photons. This sequence of events occurs on a time scale which is a tiny fraction of the time of a single ultrasound cycle, and millions of bubbles per cycle satisfy the resonance criterion for such pressure-driven growth in mass followed by its adiabatic collapse/emission. The supersonic collapse of sonoluminescent bubbles and photon emission on such a short time scale is itself a known phenomenon [16]. The collapsing bubbles also form a neutral plasma jet containing deuterons and sheath electrons.

(B) The jet is compressed further by a pinching magnetic field, produced by the jet's sheath electrons (Z-pinch), along the axis of the jet's motion [17].

(C) The compressed jet becomes implanted in the target foil, itself a two-stage process. The deuterons implant in the lattice inside the electron cloud. The free electrons accelerate towards and compress the less mobile deuterons. The oxygen and argon ions remain free of the lattice because O^- and Ar^+ are about 10^4 larger than the D^+, but the geometry of the jet is such that it is sufficiently close to the target foil for them to combine with the lattice material. The oxygen has been detected in the systems as thin oxide films, which were measured by EDS methods [10].

(D) To account for the absence of both a neutron and a gamma in the fusion process, the model postulates the formation, in the implanted deuteron cluster and electrons, of a system comprising two concentric components: a transient BE condensate M of deuterons and possibly another of Cooper pairs of electrons, with the latter on the outside. The number of deuterons in M can vary from 100 to 2. In the limiting case of 2, sonofusion corresponds to muon fusion. The Lawson criterion, L_c, for fusion to occur can therefore be approximated by that for muon fusion, for which it is $L_c > 10^{16}$ s/cm^3. In its simplest from the Lawson parameter is given by $L_c = n_D t_E$, where n_D is the deuteron density and t_E is the deuteron contact time. For sonofusion we have $t_E \sim 10^{-14}$ s, so the deuteron density has to satisfy $n_D > 10^{30}$ cm^3. At present there is no independent determination of n_D. The physical makeup of the two connected charged components results in two special conditions: (1) the M deuterons, with the condensate property of behaving as a single state in momentum space, will compress to astrophysical densities of picoseconds duration, with particle separation less than an Angstrom, whereas a group of individual charged particles, fermions or bosons, would resist this compression to the M center [18]; and (2) permittivities of the two charged components across their interface that have a ratio of 1000 due to the large difference in deuteron and electron mobilities. These two conditions work in tandem, along with the electric fields of the free-electron cloud surrounding M, to compress M.

(E) With increasing compression, the density becomes high enough for the M condensate to break up into a debris M' of D^+ ions, containing two fewer D^+ ions than the condensate M, and an alpha,

$$\mathrm{M} \rightarrow \mathrm{M}' + \mathrm{a} + \text{heat}.$$

Recoil is taken up by the D^+ ions in M'.

The fusion releases heat in the amount B(2D; ^{4}He) via bremsstrahlung; see Fig. 3.

(F) The heat released by the fusion of the deuterons vaporizes the region of the foil in which they are implanted, leaving a hemispherical heat footprint in the range of the binding energy and size of 50 nm and craters shown in Fig. 4. The transition (4a), with an initial temperature of 10^7 K, initiates a heat pulse in the lattice from a lattice depth of about 25 nm. The locations on the foil where the fusion events occur are termed *ejecta sites*. The site expands by 25 nm to the lattice surface as a radial heat pulse, ejecting 10^4 Pd lattice atoms; an FE SEM photo of surveyed sites [12] is shown in Fig. 4.

The temperature of the event is on the order of $10^4 - 10^5$ K at the surface. A portion of the heat pulse is released into the D_2O from ejecta sites. The remaining heat is released into the lattice, where it continues to expand hemispherically outward through the lattice, reaching its outer edge at 90 nm. As the heated portion of the lattice reaches the melting point of the target foil, 1825 K for Pd, it forms a melt zone – a footprint – that removes most old sites remaining from

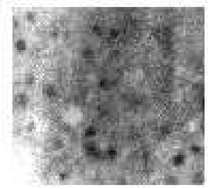

Figure 4. SEM photo of a Pd target foil, 1 mm square, showing ejecta sites with single DD fusion events for an acoustic pulse in the MHz range.

previous cycles. The sum of the heat released into the D_2O and the lattice is 20 ± 10 MeV, consistent with the 23.8 MeV of the alpha-producing event.

(G) While still in the foil, the alpha picks up two electrons from the plasma to form ^{4}He.

(H) The helium atoms are ejected into, and carried along and distributed with, the flow of the circulating D_2O and argon gas.

5. Conclusion

I conclude that the experimental results show the occurrence of the fusion process (2D, ^{4}He), producing $(43 \pm 3)\ \times 10^{-13}$ J of energy per event. (A similar treatment for the T measurements and its decay to ^{3}He is understood [10].) Theoretical analysis suggests that this process is enabled by the compression of deuterons and electrons squeezed to astrophysical densities of about 1ps duration. The compression is produced by the combination of a high-frequency acoustic pulse and a magnetically contained plasma comprised of the compressed deuterons and electrons to form BE condensates that terminate in the single-event fusion process and heat release. Corresponding results and analysis apply to T measurements and its decay into ^{3}He [10].

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This paper was a joint effort by Richard Spitzer who upon gaining some knowledge of sonofusion decided to write an explanation of my work in his words with my help.

Appendix

The author has many scanning-electron-microscope photos of target foils in various stages of heat-produced damage, and many videos and DVDs showing the temporal experimental progression and the actual melting or disintegration of the target foils discussed in refs. [8–12,14,15]. The extent of target-foil damage depends on the foil thickness and element composition, and resonant frequency and amplitude of Q_a.

Thomas used an adapted low-mass, KEV MS to measure ^{4}He in the presence of Ar and D_2 in the gas from the resonator during two weeks of testing in 1991–1992 at SRI [1]. The sampled gas at vacuum conditions was pre-treated by passing it from the bubbler to an evacuated 25 ml glass bulb, as shown in [7]; then through 60 g of heated CuO powder, removing hydrogen. The pre-treated gases were passed through an LN trap, removing the Ar and D_2O, and into the MS for analysis. Thomas found ^{4}He at a 2-sigma level.

Davidson analyzed gas samples for ^{4}He in 1992 at the Amarillo facility [2]. As in the SRI method, the sampled gases from the resonator were pre-treated by being passed through a heated granular CuO bed and collected in evacuated 25 ml glass bulbs. Gas standards from the Ar supply (gas prior to interacting with the acoustic pulse) and from the resonator (post interaction with the acoustic pulse) were shipped to Amarillo for analysis. There were fewer than 2 ppm of ^{4}He in the Ar supply, well below the 5 ppm generally accepted for helium in background air. Davidson found ^{4}He at 20 ppm in the sampled gases from the resonator. This represents a partial pressure of the total ^{4}He present. No complementary calorimetry measurements were made.

In May and June, 1994, T. Claytor, D. Tuggle, R. Stringham, and R. George at Los Alamos National Laboratory (LANL) prepared seven gas samples in 50 ml stainless-steel sampling cylinders for analysis: three samples from target-foils runs and four standards. At 20 kHz, no gammas were observed using Geiger-Muller counters during sonofusion runs. The sample gases were not pre-treated. The target-foil experiments were performed using the M2 20 kHz resonator described in Section 3. The gas samples were then shipped to B. Oliver for the He analysis at the Rocketdyne facility [3]. The foil gases were cleaned in a 12-inch long $1/4$-inch diameter charcoal-packed "U" tube column, before injection into the MS chamber. This absorbed the hydrogen and froze out the Ar and D_2O vapors. Oliver used three successive aliquot injections, determining the ^{4}He present in each aliquot by the technique described in Section 3. The three measurements showed consistent results, 552 ± 1ppm. These measurements were complemented by a calorimetric measurement of 65 W for the 19 h run, matching the counted number of alphas, 552 ± 1 ppm. The ^{4}He results were reported in "Helium Analysis of Target Metals", B.M. Oliver, 1994.

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