Nucleation by Cosmic Rays in Ultrasonic Cavitation

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Nucleation in ultrasonic cavitation is due to cosmic rays. The neutron component seems sufficient to explain the experiment in water, through the creation of oxygen recoil nuclei which would act as nucleating agents; energy deposit and radiolytic effects produce small overheated and oversaturated regions in which cavities of radius larger than the critical one may originate. The microcavities would be created in the absence of a sound field and grow to visible size when an adequate sound field is applied. Enclosing the tank in which the liquid is contained with lead or paraffin screens results in threshold variations which are due to absorption and slowing down of primary neutrons and, probably, to nuclear reactions induced by the gamma and meson components of cosmic radiation in the screen material through the production of secondary neutrons.

1. INTRODUCTION

THE majority of experiments on sound-induced cavitation can be explained by assuming that the process consists mainly of the growth of pre-existing nuclei to visible size through evaporation during the negative part of the pressure cycle. The size of nuclei would be of the order of 0.1–10 μ, and to maintain them in the liquid, the presence of one or more stabilizing mechanisms has been suggested.[1]

The origin of the nuclei, however, has defied for a long time any attempt at investigation. One of the authors investigated the possibility that cosmic radiation could be responsible for nucleation and reported[2] some results obtained in water which support such an hypothesis. At the same time, Libermann and Rudnick[3] in trying to clarify how bubble chambers work performed an experiment in pentane and acetone and obtained a strong decrease of the sonic cavitation threshold in the presence of a neutron source. Their results point out that C or O recoil nuclei may be responsible for the creation of cavitation nuclei, i.e., gaseous bubbles having a radius larger than the critical one, as a consequence of energy deposit in small regions (thermal spikes) which subsequently explode with a mechanism similar to that suggested by Seitz[4] to explain the action of ionizing radiation in bubble chambers. The presence of sound would be necessary for the production of cavitation nuclei.

The present paper reports an investigation of the relation between penetrating radiation and ultrasonic cavitation in water, which supports evidence that cosmic radiation may be responsible for the origin of cavitation nuclei in ordinary water, and makes possible the identification of recoil oxygen nuclei as the nucleating agents. In addition, there has been developed a new method for the examination of the influence of radiation on the cavitation threshold which also appears of interest for the detection of nuclear particles.

[1] M. Strasberg, J. Acoust. Soc. Am. **31**, 163 (1959); F. E. Fox and K. F. Herzfeld, J. Acoust. Soc. Am. **26**, 984, (1954); E. N. Harvey *et al.*, J. Appl. Phys. **18**, 162 (1947); W. R. Turner, Vitro Laboratories, Silver Spring Laboratory, Maryland, Technical Note N 4329–12960, 1960 (unpublished).

[2] D. Sette, Third Meeting of the International Commission on Acoustics, Stuttgart, 1959 (unpublished).

[3] D. V. Liberman and I. Rudnick, Third Meeting of the International Commission on Acoustics, Stuttgart, 1959 (unpublished); D. V. Liberman, Phys. Fluids **2**, 466 (1959).

[4] F. Seitz, Phys. Fluids **1**, 2 (1958).

2. EXPERIMENTAL METHODS

The cavitation threshold in commercial distilled water was measured at 1 Mc/sec in a tank (volume about 20 liters) with a procedure similar to that followed in previous research[2]: the voltage at the quartz source was increased by steps and applied for 30 sec, after a rest time of 30 sec; at the onset of cavitation the sound was quickly removed and a minimum of 5 min was allowed before a new run was started. The sound intensity for which cavitation was visually detected was taken as the cavitation threshold. All measurements were performed at room temperature (23°–25°C). The threshold found in aerated distilled water was about 1 w/cm². Figure 1 gives a general scheme of the experimental disposition. In order to avoid possible cavitation at the interface quartz-water, a focusing device[5] formed of conical and parabolic mirrors was used; the cavitation always starts in this region well separated from any solid walls. The distribution of sound energy in the field has been checked by direct measurement obtaining a calibration to pass from the voltage applied to the source to the sound density in the focal region. The equivalent average intensity used in the following refers to plane waves giving the same sound density. The onset of

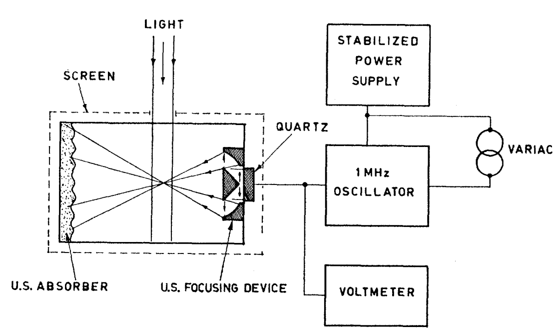

FIG. 1. Block diagram of experimental setup.

[5] A. Barone, Acustica **2**, 221 (1952).

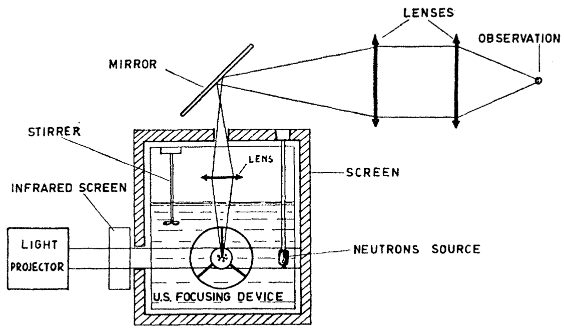

FIG. 2. Optical observation of cavitation.

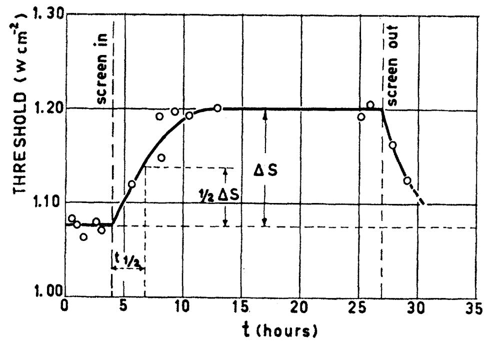

FIG. 4. Threshold in distilled water surrounded by a 5-mm lead screen.

cavitation has been observed visually by means of an optical disposition (Figs. 1 and 2) at a distance of about 2 m from the tank for safety purposes when a neutron source is used. A stirrer slowly (60 rpm) moves the water. Figures 1 and 2 show the position of a screen. A simple mechanical support has been devised to use screens of various thicknesses singly or in combinations.

The definition of cavitation threshold used by us is an operative one. There is, in fact, no sharply defined power density necessary for the cavitation onset; there is instead for each power density a probability that the phenomenon occurs during a fixed time interval. Such a probability is finite already at power densities well below the operative threshold and increases to a value of one for densities larger than the threshold. The operative threshold can be taken, in first approximation, as a weighted average of sound intensities at which the onset may occur, the weights being the probabilities that cavitation starts during the fixed time interval T. To clarify the definition of threshold we have performed some preliminary experiments trying to evaluate the average delay with which onset follows the application of the sound field; in this experiment the sound was applied at a fixed intensity and held until cavitation set in. In Fig. 3 (curve a) the reciprocal (F) of the average delay has been plotted as a function of sound intensity (I); curve b will be discussed later. The probability of observing the cavitation in the time T at a certain power can be put equal $F\times T$. The variation of F with power is due to (1) an increase of volume in our experimental setup in which the sound level may easily produce the growth of nuclei, and (2) the possibility of the growth of nuclei of smaller radii. If one calculates $\sum_i I_iF_iT/\sum_i F_iT$, using an adequate number of points of curve a (Fig. 3) between the intensity I_1 and I_2 for which, respectively, $F\times T$ is appreciably larger than zero and has value 1 ($F=0.033$, T being 30 sec), one obtains a sound intensity of 1.01 w/cm^2 which is practically coincident with the threshold measured in the operative way (1 w/cm^2).

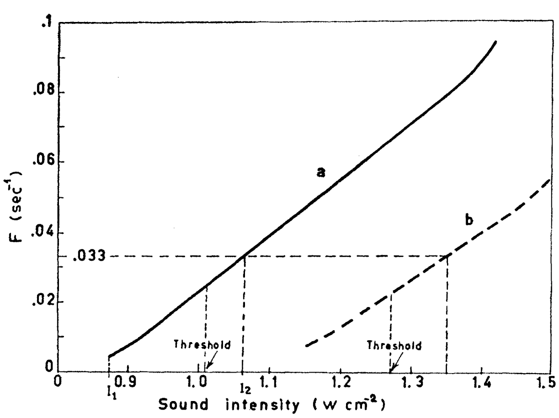

FIG. 3. Inverse of average delay of cavitation onset in distilled water; a sound field of constant intensity is applied to the liquid. (a) Unscreened tank; (b) 20-mm lead screen surrounding the tank.

3. EXPERIMENTAL RESULTS

(a) Lead Screen

Sette[2] has found that the cavitation threshold in ordinary as well as in aerated distilled water is considerably increased if the tank is surrounded by a lead screen of 15-mm thickness. In order to determine better the

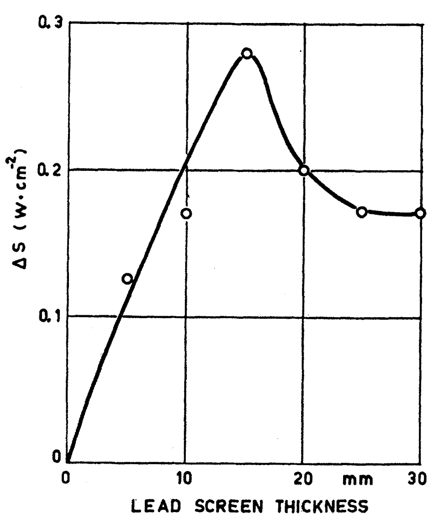

FIG. 5. Threshold variation in distilled water as a function of lead screen thickness.

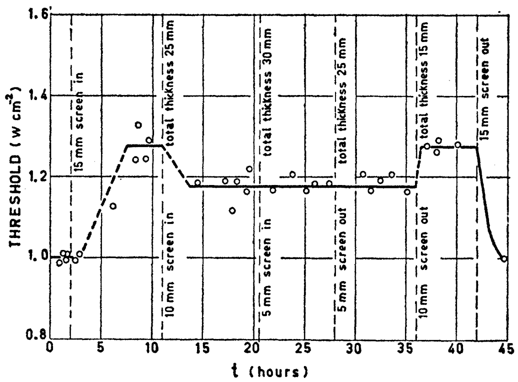

FIG. 6. Threshold in distilled water with lead screens of different thicknesses.

effect of lead screens, three parallelepiped enclosures of the tank have been prepared. They have removable sides and can operate in combination; the lead thicknesses of the enclosures are from the inner one 15, 10, and 5 mm. With this disposition it is possible to study the cavitation threshold when the lead screen surrounding the tank has a total thickness of 5, 10, 15, 20, 25, and 30 mm.

Figure 4 gives a typical run with a 5-mm lead screen. Each point is the average of five determinations. In each run new distilled water has been used; the cavitation threshold has been measured a few hours before screening the tank in order to ensure that no disturbing effects were present. The cavitation threshold increases as a consequence of the presence of the screen and returns to the starting value when sufficient time has elapsed after the removal of the enclosure.

From the observation of the various curves an approximate evaluation of the time required for $\frac{1}{2}$ variation of the threshold when the screen is inserted or removed has been obtained: $\tau_{\frac{1}{2}}=70$ min. This value is only to be taken as indicative of the order of magnitude, and as such it is valid for all thickness and for the increase and decrease of the threshold. Very probably, however, differences are present, but they cannot be exactly evaluated at present.

In Fig. 5 the variations of threshold obtained in runs with different lead thicknesses are collected. It has been already pointed out that the threshold can be associated with the average delays with which cavitation follows

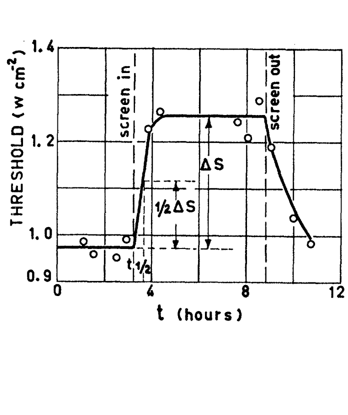

FIG. 7. Threshold in distilled water surrounded by a 15-mm paraffin screen.

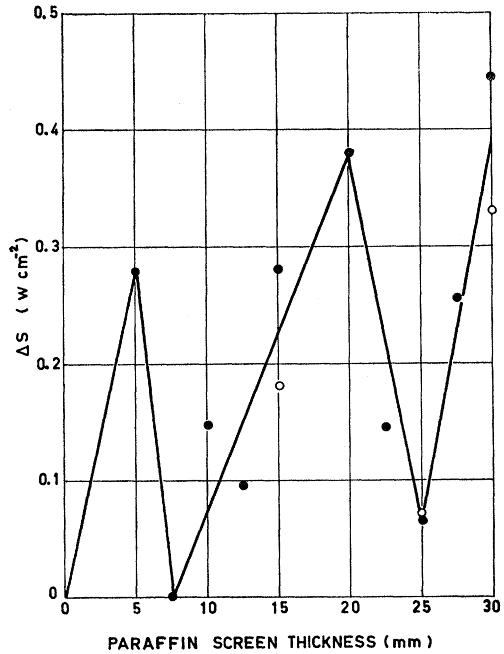

FIG. 8. Threshold variation in distilled water as a function of paraffin screen thickness.

the application of sound of different intensities (experiment of Fig. 3). At the threshold intensity an average delay of about 40 sec was found.

In order to confirm the existence of the maximum in the curve of Fig. 5 an experiment has been performed using the same water specimen and changing the screen

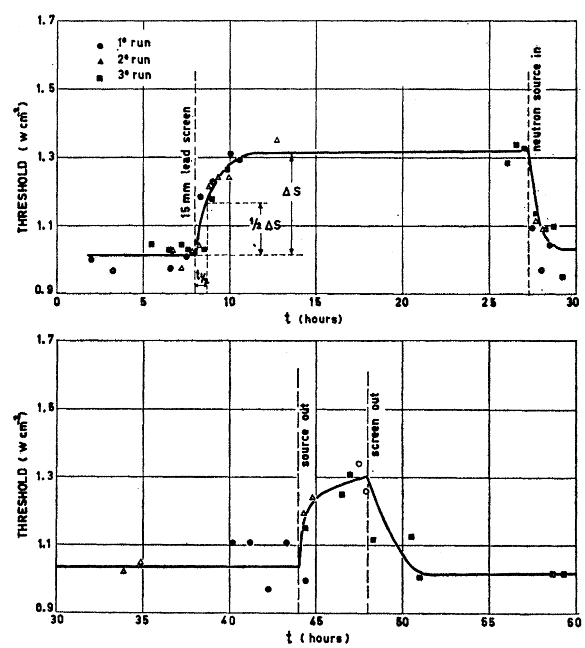

FIG. 9 Threshold in distilled water surrounded by a 15-mm lead screen and in the presence of a Ra–Be neutron source.

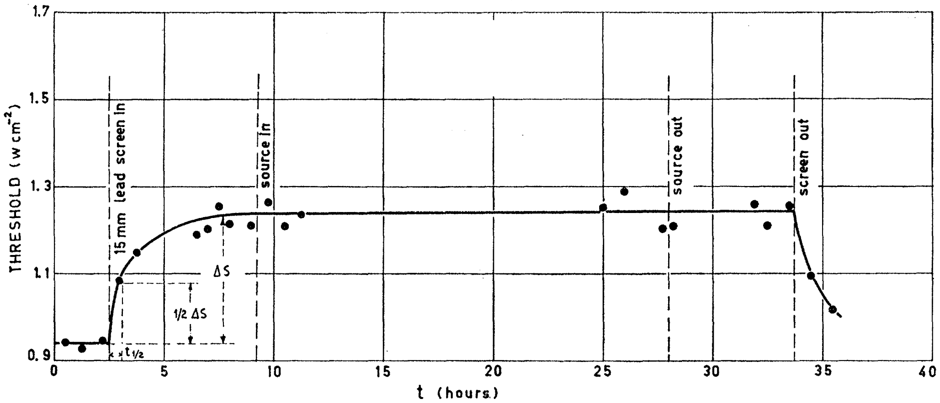

FIG. 10. Threshold in distilled water surrounded by a 15-mm lead screen and in the presence of a source of neutrons (in a paraffin container) with energies lower than 1 Mev.

thickness in the order 0, 15, 25, 30, 25, 15, and 0 mm (Fig. 6).

(b) Screens of Highly Hydrogenated Materials

Four enclosures of paraffin having 5, 7.5, 10, and 15 mm wall thickness have been built making possible experiments with the following screen thicknesses (mm): 5, 7.5, 10, 12.5, 15, 20, 22.5, 25, 27.5, and 30. Figure 7 gives the result for 15-mm screen. The time for $\frac{1}{2}$ variation of threshold is about 25 min. Figure 8 shows the results obtained with the paraffin screens: dots refer to experiments with different water specimens, circles to experiments with the same water filling. An experiment has also been performed with a 5-mm enclosure of perspex (polymethyl methacrylate) obtaining an increase of the threshold in water of about 19%, and a $\tau_{\frac{1}{2}}$ value of the same order than with paraffin screens.

(c) Neutron Irradiation

A 10-mC equivalent Ra–Be neutron source has been used: the flux is 1.5×10^5 neutrons/sec. The maximum neutron energy is about 10 Mev; the energy distribution is approximately Gaussian and it has a maximum around 4 Mev. The concomitant emission of γ rays has no consequence on cavitation as will be discussed later.

To find the influence of neutrons on the cavitation threshold the latter has been measured during the following steps: (1) no screen; (2) 15-mm lead screen; (3) neutron source in the liquid; (4) neutron source excluded; (5) lead screen removed. The source was fixed at one end of an aluminum rod which could enter into the tank through a hole in the lead screen (diameter 1 cm). Figure 9 gives the results obtained with various specimens.

Figure 10 refers instead to the case in which a paraffin cylinder, having walls and bottom of 25-mm thickness (Fig. 11), has been fixed into the tank at the beginning of the experiment and receives the neutron source. In this second experiment the energy of the neutrons reaching the liquid as reduced by a factor of 10. In fact, the mean-free path of neutrons having energies between 1 and 10 Mev in paraffin is 10 mm; this means that the neutrons emitted with energy E undergo on the average 2.5 collisions during their path through paraffin, reducing their energy (E') according to $\ln(E/E')=2.5\xi$, the slowing down power ξ for paraffin being 0.913. Thus the result is $E'=0.1\ E$.

It is evident that while the fast neutrons emitted from the source bring the threshold to the original value for unscreened water, the neutrons having energies smaller than 1 Mev are not able to produce any change in the cavitation threshold.

4. DISCUSSION OF NUCLEATION MECHANISM

The preceding results show that elementary particles as neutrons may, and cosmic radiation does, influence ultrasonic cavitation. The simplest hypothesis seems to be that penetrating radiation may lead to the formation of cavitation nuclei, i.e., of gaseous bubbles with very small radii.

Seitz[4] suggested a mechanism for nucleation in bubble chambers i.e., in a liquid near the critical point, which has been used also by Libermann and Rudnick[3] to furnish an interpretation of their results on ultrasonic cavitation in pentane and acetone. It would seem, therefore, interesting to see if Seitz' mechanism can explain the results of the experiments on ultrasonic cavitation in water and, if necessary, what changes may be reasonably introduced in the theory.

According to Seitz the primary penetrating particles produces, inside the liquid contained in a bubble chamber, small hot regions (thermal spikes) as a consequence of energy deposits either of the same primary particles or of secondary ionizing particles. The hot regions may explode in cavities of a radius larger than the critical one required for stability; these cavities can grow subsequently through evaporation of the liquid. In the case of hydrogen and propane bubble chambers in normal working conditions, Seitz's analysis indicated that the knocked-on electrons of about 1 kev produced by high-energy particles along their path are responsible for nucleation. Libermann and Rudnick, in the analysis of their results on sound cavitation in pentane and acetone at room temperature and in the presence of a neutron source, indicate C and O recoil nuclei as the nucleation agents.

When a thermal spike explodes into a nucleus, effects due to inertia, viscosity, and thermal conductivity of the liquid come into play and they are very difficult to be evaluated exactly. An approximate discription of the process may be obtained simply by considering the energy balance for the bubble formation without taking into account dynamic effects. By these calculations one obtains a lower evaluation of the energy that the particles have to deposit in a length equal to the diameter of cavities of critical size in order to produce a nucleus. Such calculations were done by Seitz for the bubble chambers situation and extended by Libermann and Rudnick to the case in which a sound wave is present, delivering energy for the cavity formation during the negative part of the pressure cycles. The formula that these authors find is

$$U=0.21(4\pi\sigma^2/P) \times[-1+2(10^{-6}n_vH-P_{gi})/P] \text{ Mev cm}^{-1}, \quad (1)$$

where $U=-dE/dx$ is the density of energy deposited by the ionizing particles, σ the surface tension (dynes cm^{-1}), $P=p_a+p_{go}+p_{gi}$ (bars), p_a the amplitude of acoustic pressure, p_{go} the pressure of gas above liquid, p_{gi} the pressure of gas inside cavity, n_v the number of moles of vapor per unit volume at temperature and pressure inside the cavity, and H the heat of vaporation per moles (erg mole^{-1}). Pressures are positive if they contract the bubble. On the right side of Eq. (1) there is the sum of three terms which represent, in order, the contributions to energy balance of surface, evaporation, and sound energies.

In the case of water[6] $\sigma=72.75$ dyne cm^{-1}; $p_{gi}=2.66\times10^{-2}$ bar; $H=44\times10^{10}$ erg mole^{-1}, $n_v=10^{-6}$ cm^{-3} (at pressure p_{gi} and $T=25°\text{C}$). Equation (1) yields for water:

$$U\simeq13.97\times10^3(0.80/P^2-1/P) \text{ Mev cm}^{-1}. \quad (2)$$

The maximum densities of energy deposit for possible primary particles are not larger than those for protons. The energy loss as a function of energy (E) for protons moving in water may be evaluated by means of the semi-empirical method suggested by Hirschfelder and Magee.[7] One finds a maximum for U which is about 800 Mev cm^{-1} at an energy between 0.05 and 0.1 Mev. Because the method is not reliable below proton energies of 0.1 Mev, the results are to be taken only as indicative: they show however, that the maximum energy deposit occurs at an energy lower than 0.1 Mev. The determination of U for O^{16} nuclei may be obtained starting from the value calculated for U in air according to Livesay[8] and converting it to the case of water using Evans' curves[9] of stopping power per electrons vs atomic number of the material. One can estimate for O^{16} nuclei in water a $U_{\max}$ of 6000–7000 Mev cm^{-1} for energies between 4 and 5 Mev.

In ordinary water other elements are present as impurities which may yield recoil nuclei when struck by high-energy particles. Since, however, the number of impurity atoms is extremely low in comparison with the number of water molecules, and since the cavitation threshold is usually not greatly influenced by a small variation of impurity content (the threshold is about the same for distilled and tap water), we assume that the presence of impurity atoms can be at this stage ignored, and that the maximum possible value of U is that experienced in the case of O^{16} nuclei (6000–7000 Mev cm^{-1}). Using this value in Eq. (2) the acoustic pressure needed for nucleation would be about 3.6 bars, which differs from the results of these experiments because the cavitation threshold under ordinary conditions in water is about 1.20 bars (1 w cm^{-2}). The disagreement between Seitz's theory and these experiments is more strongly emphasized if one remembers that by bringing into account dynamic effects the acoustics pressure needed for cavitation, according to this scheme, increases noticeably.

It is also to be observed that the mechanism now under examination would require the simultaneous presence of sound and ionizing event for the onset of cavitation. This does not seem to be in agreement with the experiment under our conditions of observation. First of all it would be difficult to explain the observed long time constants with which the threshold changes as a consequence either of screening or of the presence of the neutron source. In addition, cavitation should be a much rarer process than it is, if the nucleation is to be attributed, as it seems, to cosmic rays. In fact the total number of cosmic particles at sea level[10] being of the order of 2×10^{-2} cm^{-2} sec^{-1} and the section of our tank being 500 cm^2, and assuming that each particle entering the tank produces on average one cavity and that the events are equally distributed in the liquid mass (volume 2×10^4 cm^3), one can calculate an approximate value for the number of events happening in the liquid volume in which the acoustic pressure can produce cavitation (few cm^3). One gets 10^{-3} event per second, and therefore, one should observe on the average one cavitation process every 1000 sec while the observed delay of the onset of cavitation following the application of the sound field is about 40 sec at the cavitation threshold intensity. In addition, in the experiment with the neutron source inserted inside the lead screen (Fig. 9), the threshold returns to the original value of un-

[6] *Handbook of Chemistry and Physics*, edited by C. D. Hodgman (Chemical Rubber Publishing Company, Cleveland, Ohio, 1952).
[7] J. Hirschfelder and J. Magee, Phys. Rev. **73**, 107 (1948).
[8] D. Livesay, Can. J. Phys. **34**, 203 (1956).
[9] R. Evans, *The Atomic Nucleus* (McGraw-Hill Book Company, Inc., New York, 1955).
[10] B. Rossi, Revs. Modern Phys. **20**, 537 (1948); D. J. Montgomery: *Cosmic-Ray Physics* (Princeton University Press, Princeton, New Jersey, 1949).

screened water, although the number of neutrons active in the liquid is much higher than the number of high-energy particles of cosmic radiation reaching the tank (also the neutrons seem to be more effective particles). It could be that either only a few neutrons are emitted from the source with sufficient energy for the formation of nuclei, or that the equilibrium density of nuclei in the liquid is controlled by elements other than radiation, such as impurities present in the liquid.

It seems, therefore, plausible to assume that in the conditions under which we observe cavitation in water, the creation of nuclei occurs without requiring the presence of sound. Therefore Liberman and Rudnick's modification of Seitz's treatment does not apply, and one deduces from Seitz's formula

$$2rU=4\pi\sigma r^2+\tfrac{4}{3}\pi r^3 n_v H+\tfrac{4}{3}\pi r^3 P_{go}, \qquad (3)$$

that to produce cavities of about 1 μ, densities of energy deposit of the order of 47 500 Mev cm^{-1} are necessary. If the dynamic effects were taken into account the value would be enlarged appreciably. Because there are no events produced by 10-Mev neutrons which can give such densities and while the experiment with the neutron source inside the tank enclosed with lead screen (Fig. 9) shows that nuclei are instead originated we conclude that Seitz's treatment in the way in which it was developed for the bubble chamber situation is inadequate to explain normal cavitation in water.

It is to be noted that the penetrating radiation produces in water intense radiolytic effects as well as local heating. When radiolysis[11] is caused by a particle having a mass equal to or larger than the proton mass, OH free radicals are formed along the path of the ionizing particle, while H free radicals are distributed at about 150 A from the same line (they are originated by δ rays). This situation leads to reactions among free radicals of the same kind with a copious production of H_2 and O_2 molecules.

The region in proximity to the path of particles is, therefore, in a very peculiar condition which is not properly described as simply overheated. The possibility of evolving a better theory is bound to an adequate description of the status of molecules in this region. It does not seem satisfactory to use parameters which are normally introduced to describe situations of a quite different nature. If, however, in the absence of such a theory, one wishes to approximately describe the situation, one should assume that the ionizing particles create in water small overheated and oversaturated regions which originate nuclei. The above analysis would indicate that in the case of water oversaturation plays a major role. This seems plausible because an increase of solved gases may help the formation of nuclei directly and drastically reduce the surface tension.[12]

It seems therefore to us that the experiment indicates the following conclusions on the nucleation mechanism in water:

(1) Primary particles of cosmic radiation as well as neutrons from a Ra–Be source can create nuclei directly or through secondaries; cavities originate in small regions in which very special conditions exist as a consequence of the heating and the radiolytic effects produced by ionizing paritcles.

(2) Nucleation does not require the presence of sound, and when nuclei are created they have a finite life in the liquid.

The secondary particles which may originate in water are recoil H or O nuclei. Both of them are produced by neutrons from the Ra–Be source in the experiment with the screened tank (Fig. 9); the maximum density of energy deposit for protons is about 800 Mev/cm and it occurs at an energy lower than 0.1 Mev; the maximum density of energy deposit for O recoil nuclei is 6000–7000 Mev/cm at about 4 Mev.

In order to determine if protons may act as nucleation agents we have performed the second experiment (Fig. 10) with the neutron source, surrounding the latter with a paraffin enclosure of 2.5 cm (the maximum energy of neutrons being reduced to 1 Mev). In this case protons of energy higher than 0.1 Mev (which therefore will pass during their flight into the liquid through the energy of maximum deposit density) are still produced in large number while the maximum value of energy for O recoil nuclei is 0.25 Mev which correspond to a maximum density of energy deposit of about 1000 Mev/cm. No variation in the cavitation threshold has been observed when neutrons with a maximum energy of 1 Mev are shot into the liquid, thus showing that protons, as well as ionizing particles which deposit energy into the liquid at a rate lower than 1000 Mev/cm are not able to produce nucleation.

The oxygen recoil nuclei are, therefore, the only secondary particles which may produce cavitation nuclei in water. To do so they muct have an energy which surely is higher than 0.25 Mev; energies somewhat lower than 2.5 Mev are, however, sufficient. The latter energy value[13] has been obtained from the results of the first experiment with the Ra–Be source when neutrons with maximum energy of 10 Mev produce nucleation.

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[11] *Proceedings of the Second United Nations International Conference, on the Peaceful Uses of Atomic Energy, Geneva, 1955* (United Nations, Geneva, 1958), Vol. 7, Report on Session 12B, pp. 513–610; M. Haissinsky, *La Chimie Nucleaire et ses Applications* (Masson, Paris, 1957).

[12] Concentrations of the order of 5×10^{19} gas molecules dissolved per cm^3 would be easily produced (Haissinsky) to which a pressure of 120 atm corresponds. Assuming in first approximation the validity of C. G. Kuper and D. H. Travena [Proc. Phys. Soc. (London) **A65**, 46 (1952)] calculation on the influence of small gas solution on the surface tension of liquids also for high values of gas content, a reduction of about 50% would result in σ.

[13] The corresponding value of U is 5000 Mev/cm.

5. CREATION OF CAVITATION NUCLEI BY COSMIC RADIATION

According to the above discussion the creation of cavitation nuclei should be possible by ionizing particles which during their life in the liquid may deposit energy at a rate of the order of a few thousand Mev cm^{-1} (5000 Mev/cm is surely sufficient). The analysis has shown that 2.5-Mev oxygen recoil nuclei are in these conditions.

We wish now to examine if cosmic particles either directly (when charged) or through secondaries, may explain quantitatively the experiment in ordinary water. The direct nucleation by charged particles (proton, electrons, mesons) can be excluded. The maximum densities of energy deposit of protons (800 Mev/cm) are not sufficient for the creation of nuclei and the densities of energy deposit for electrons and mesons are much lower than for protons. Moreover, the free radicals created by these particles take part mainly in recombination reactions.[11]

Turning now to nucleation produced through secondaries, we observe that energetic electrons and mesons could produce recoil nuclei, but it can be easily seen that events of this kind are rare and so can be ignored. In fact the cross section for these collisions[14] is

$$\sigma = 8\pi a^2 Z^2 E_R^2 / M c^2 E_D, \tag{4}$$

where a = Bohr radius, 5.3×10^{-9} cm, E_R = Rydberg energy, 13.6×10^{-6} Mev, Z = atomic number of the struck nucleus, E_D = minimum required for the energy given to the nucleus (2.5 Mev for O in our case), and M = rest mass of the nucleus. We obtain for the oxygen nuclei:

$$\sigma = 2\times10^{-4} \text{ barn}.$$

These conclusions are in agreement with the results of Sette[2] for water irradiated with gamma rays (Compton electrons of about 1 Mev) and of Libermann[3] in pentane irradiated with 20-Mev β^+; no effect on the cavitation threshold was found.

Cosmic neutrons with energy equal to or higher than 10 Mev can produce oxygen recoil nuclei with an energy higher than 2.5 Mev, and they are present in the cosmic radiation at sea level with a density of about 2×10^{-4} cm^{-2} sec^{-1}.[10] High-energy neutrons appear, therefore, as the particles in cosmic radiation which may lead to the formation of small cavities near the surface of the liquid and which diffusing into the volume, may act as cavitation nuclei.

An approximate calculation can be carried out to see if their density in the cosmic radiation reaching the tank may be sufficient to explain the experiment. The geometrical cross section of our liquid mass is about 5×10^2 cm^2, and we can assume that about 10^{-1} neutron having energy higher than 10 Mev reaches the liquid per second. We suppose also that each neutron produces at least one cavity which has a finite mean life. The experiments with lead and paraffin screens give different values for $\tau_{\frac{1}{2}}$. In order to make an orientative calculation we assume the intermediate value of $\tau_{\frac{1}{2}} = 3\times10^3$ sec, for the time required to reach the $\frac{1}{2}$ variation of threshold as a consequence of inserting the screen. Assuming an exponential law for the decrease of the number of nuclei, λ being a constant, we have

$$\tau_{\frac{1}{2}} = (\ln 2)/\lambda = 3\times10^3 \text{ sec}.$$

When the screen is removed the increase of the number of nuclei will proceed according to

$$dN = Kdt - \lambda N dt, \tag{5}$$

N being the total number of nuclei in the liquid (volume about 2×10^4 cm^3) at time t and K (sec^{-1}) the rate of creation of cavities.

From (5), we have

$$N = (K\tau_{\frac{1}{2}}/\ln 2)(1 - 2^{-t/\tau_{\frac{1}{2}}}).$$

As equilibrium value of N, we have

$$N = K\tau_{\frac{1}{2}}/\ln 2 = 3\times10^3 K/\ln 2. \tag{6}$$

Assuming that each fast neutron reaching the liquid produces at least one nucleus, we take for K the value 10^{-1}. The result is

$$N = 4.34\times10^2,$$

and per unit volume

$$n = 2.17\times10^{-2}. \tag{7}$$

In our experiment the volume in which the sound field was sufficient to produce cavitation (growth of nuclei) was about $V = 2$ cm^3. In addition, the fluid under sound radiation changes continuously as a consequence of motion due to the stirrer and to the gradient of radiation pressure. Velocities of the order of 0.5 cm/sec have been observed in the focal region; and one can calculate that the fluid in this zone is renewed every 2 sec. The volume of the fluid which passes through the region in which suitable conditions for the growth of nuclei exist in t seconds is $Vt/2 = t$ cm^3 and the resultant number of nuclei in it is

$$n^* = 2.17\times t\times10^{-2}. \tag{8}$$

The average delay of cavitation onset is obtained from (8) for $n^* = 1$ as $t = 46$ sec, which is quite in agreement with the observed value (40 sec).

In this calculation approximate values have been used. One has to consider, however, two circumstances which have not been taken into account although they may favor the formation of nuclei: (1) Neutrons with energy not much lower than 10 Mev are probably active; (2) neutrons with very high energy are present in cosmic radiation which could produce more than one oxygen recoil nuclei.

It seems, therefore, that the neutron component of cosmic radiation is sufficient to explain the observed

[14] G. J. Dienes and G. M. Vineyard, *Radiation Effects in Solid* (Interscience Publishers, Inc., New York, 1957).

cavitation in ordinary water, through the production of oxygen recoil nuclei which would be the agents creating cavities.

6. DISCUSSION OF SCREEN EXPERIMENTS

Figures 5 and 8 show that small thicknesses of lead or paraffin screens produce an increase of threshold and that one (15-mm lead) or two (7.5- and 25-mm paraffin) maxima are found as the thickness grows to 30 mm. The increase of threshold is connected with a decrease of efficient primaries in the radiation reaching the liquid and therefore in microcavity density, as a consequence of absorption and slowing down in the screen. In Fig. 3, curve b has been obtained by the same procedure as curve a, in this case enclosing the tank with a 20-mm lead screen. The corresponding value of the threshold is about 1.27 w/cm². The shift of the curve F vs power when the lead screen is inserted corresponds to an increase of threshold which is associated with a reduction of nuclei present in the liquid.

The maxima in the threshold screen thickness curves indicate the presence of processes which facilitate nucleation, and depend on screen thickness. Although further experimentation and more nuclear data are needed to clarify the process, a tentative suggestion is that mesons and γ rays of cosmic radiation could induce nuclear reactions in the screen material with the emission of secondary particles, as for instance, neutrons.

In paraffin one could have the reaction[15,16] $C^{12}(\gamma,n)$-C^{11}, whose differential cross section has a maximum for a γ energy of 22 Mev. The total cross section is 0.05 barn.

Similar reactions[15–17] induced by gamma rays in paraffin and lead are: $C^{12}(\gamma,p3n)B^8$, $C^{12}(\gamma,2n)C^{10}$, $Pb^{204}(\gamma,n)Pb^{203}$, $Pb^{206}(\gamma,n)Pb^{205}$, $Pb^{207}(\gamma,n)Pb^{206}$, and $Pb^{208}(\gamma,n)Pb^{207}$.

Moreover mesons may react with protons in nuclei according to

$$\mu^- + p \rightarrow n + \nu,$$

giving rise to neutrons having energies of 10–20 Mev; as a consequence, one or more particles, mainly neutrons, escape from the excited nucleus. Average emission of 1.6 neutrons per absorbed meson in lead and of 0.8 neutrons per meson in carbon with cross sections of 0.02 barn and 0.002 barn, respectively, have been reported.[18] From these data it seems that mesons are more effective in lead than in paraffin. It is to be noted that cross sections of the order of 10^{-2} barn assume interest in meson or gamma reactions because the meson component of cosmic radiation is about 10^2 times the proton and neutron component, and because the gamma component is still higher than the nuclear one by a factor of 30–50.

The importance of reactions of this kind in producing secondary neutrons reaching the liquid will depend on thickness, increasing with the thickness to a maximum for each reaction when the probability of reaction is maximum and the probability of subsequent absorption of secondaries in the screen is low. A process of this kind may compensate for and overcome the absorption of primary particles in the screen and qualitatively explain the observed threshold dependence with screen of lead and paraffin. In the latter case more than one reaction should be present. It is to be mentioned that (γ,n) reactions have significant cross sections only for narrow energy bands.

The more rapid increase of threshold for the paraffin screens than for the lead ones seems in agreement with the conclusion that neutrons are responsible for nucleation, taking into account the more effective slowing-down of neutrons in paraffin.

More research is in progress in order to increase the knowledge of the mechanism responsible for the screening action.

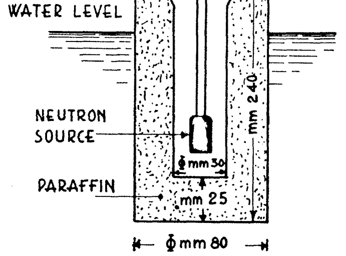

FIG. 11. Paraffin enclosure used for slowing down neutrons.

7. CONCLUSIONS

The experimental results presented in this paper confirm the suggestion given by one of the authors in a previous communication and establishes that the nucleation responsible for ultrasonic cavitation is connected with cosmic radiation.

More theoretical work is needed to fully clarify the mechanism of production of gaseous nuclei using an adequate description of the status of molecules in the small regions in which high-energy particles are absorbed. In order to explain the experiment in ordinary water it seems necessary to take into account heating and radiolytic effects which produce small overheated and H_2 and O_2 oversaturated regions along the path of radiation inside which cavities may be produced. In addition, cavities originated in the absence of sound seem to be stabilized with processes associated with impurities which eventually would control the density of nuclei in ordinary water.

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[15] W. Kunibald and J. Schintlemeister, *Tabellen der Atomkerne* (Akademische Verlagsgesellschaft, Berlin, 1958), Vol. 1, Part I.
[16] K. Strauch, Ann. Rev. Nuclear Sci. 105, 2 (1953).
[17] H. Palevsky and A. O. Hanson, Phys. Rev. **79**, 242 (1950); R. Scherr, *ibid.* **84**, 387 (1951).

[18] R. D. Sard and M. F. Crouch, in *Progress in Cosmic-Ray Physics* (North-Holland Publishing Company, Amsterdam, 1954), Vol. II.

The analysis of possible nucleation processes indicates that oxygen recoil nuclei produced by the neutron component of cosmic rays act as nucleating agents.

The effects of lead or paraffin screens on the cavitation threshold are probably due to a decrease of the present neutron component reaching the liquid and to the production of secondaries in nuclear reactions induced by mesons and gamma rays in the screen material.

A cell formed by a liquid in an adequate sound field and suitably screened, constitutes a device which allows the examination of the influence of various penetrating particles entering the cell through a hole, on cavitation threshold. The device also allows one to distinguish the various types of particles: for example, its response to neutrons depends on their energy.

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Harmonics of the Kruskal Limit and Field Diffusion in a Toroidal Pinch Discharge*

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Measurement of the magnetic fields in a toroidal pinch discharge have shown that when the applied toroidal magnetic field (B_{z0}) is comparable with or less than the self-field of the discharge (B_θ), the B_θ field penetrates into the discharge more rapidly than expected by simple electromagnetic theory, and also the B_z flux is enhanced within the discharge. This second effect was very marked in these experiments because of the high impedance of the supply circuit connected to the B_z coils. In addition, the magnetic field oscillograms show steps which commence when the magnetic pitch ($\lambda_B=2\pi rB_z/B_\theta$) satisfied $\lambda_B\simeq L/n$ or $2L/n$, where L is the torus circumference and n is an integer. If it is assumed that instabilities prevent the formation of a large pressure gradient in the discharge, then $j_\perp \ll j_{\|}$, and the field configurations predicted for an applied electric field (E_z) are in good agreement with those observed experimentally after field penetration is complete. In particular, the enhancement of B_z is explained. Further, the assumption of small $j_{\|}$ leads to the prediction of more rapid B_θ penetration at low B_z. The most likely instabilities which would cause the limitation in pressure gradient and produce the waveform steps are thought to be interchange modes.

1. INTRODUCTION

THEORY indicates that most pinch discharge configurations should be unstable to the $m=1$ mode of the magnetohydrodynamic kink instability. Even in discharges in which the currents are confined to a thin skin, the outer layers should be unstable to the $m=1$ mode unless the axial magnetic field (B_z) varies with radius according to stringent conditions and in particular changes sign within the current layer.[1] Experimentally, when discharges have been produced with little or no initial B_z, large amplitude kink instabilities have been observed by many workers following the initial discovery by Carruthers and Davenport[2] and Granovskii and Timofeeva.[3] In discharges with very high initial B_z, theory[4] predicts that the $m=1$ mode will be unstable for wavelengths in the z direction ($2\pi/k$) greater than the pitch of the magnetic lines of force at the edge of the discharge, namely greater than $\lambda_B\equiv 2\pi aB_z/B_{\theta a}$, where a is the radius of the discharge column and $B_{\theta a}$ the value of B_θ at this radius. When a toroidal discharge tube is used, a boundary condition is imposed limiting the possible wavelengths for the $m=1$ instability to the torus circumference (L) and submultiples of L. Hence, the onset of the $m=1$ mode will occur when B_θ has risen to the value which makes $\lambda_B=L$. (This is often referred to as the Kruskal limit.) Striking confirmation of the theory was obtained in experiments on the Stellarator by Kruskal *et al.*[5] More recently the higher m modes have been detected[6] and these modes again appear at the critical values of B_θ predicted by theory; they cease at higher value of B_θ, also in accordance with theory.

In the intermediate range where the initial B_z is of

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[1] M. N. Rosenbluth, *Proceedings of the Second United Nations International Conference on the Peaceful Uses of Atomic Energy, Geneva, 1958* (United Nations, Geneva, 1958), Vol. 31, p. 85. See also B. R. Suydam, *ibid.*, Vol. 31, p. 157.

[2] R. Carruthers and P. A. Davenport, Proc. Phys. Soc. (London) **B70**, 49 (1957).

[3] V. L. Granovskii and G. G. Timofeeva, J. Exptl. Theoret. Phys. (USSR) **28**, 378 (1956).

[4] M. D. Kruskal and J. L. Tuck, Proc. Roy. Soc. **A245**, 222 (1958).

[5] M. D. Kruskal, J. L. Johnson, M. B. Gottlieb, and L. M. Goldman, reference 1, Vol. 32, p. 217.

[6] W. Bernstein, A. Z. Kranz, and F. Tenney, Phys. Fluids **3**, 1019 (1960).