POSSIBLE ANTI-MATTER CONTENT OF THE TUNGUSKA METEOR OF 1908

By Prof. CLYDE COWAN
Department of Physics, Catholic University of America
AND
C. R. ATLURI and Prof. W. F. LIBBY
Institute of Geophysics and Department of Chemistry, University of California, Los Angeles

PERHAPS the most spectacular meteor fall to be observed in modern times occurred on June 30, 1908, at 0h 17m 11s U.T. in the basin of the Podkanemaia Tunguska River, Siberia (60° 55′ N, 101° 57′ E), some 500 miles to the north of Lake Baykal[1]. It was seen in a sunlit cloudless sky over an area of about 1,500 km in diameter and was described as the flight and explosion of a blindingly bright bolide which "made even the light of the sun appear dark". The fall was accompanied by exceptionally violent radiation and shock phenomena. Although seismic, meteorological and geomagnetic field disturbances were registered at points around the world at the time, and descriptive accounts of the phenomena accompanying the fall were collected from witnesses during the years following, the first inspection of the place of fall was not made until 1927. No trace of a crater was found, though great damage of the forest was still evident due to thermal and blast effects.

Various hypotheses have been advanced to explain the massive phenomena as having been caused by a large meteor, a small comet or a nuclear explosion. All are argued cogently, for and against. Estimates of the total yield of energy, made from the records of the disturbances already mentioned and from deductions based on blast and thermal damage at the site of the fall, agree with one another quite well and place the yield at something in excess of 10^{23} ergs, probably about 10^{24} ergs. If this were the result of a nuclear explosion of some sort, then the yield of neutrons into the atmosphere with the consequent formation of carbon-14 from atmospheric nitrogen should be detectable by analysis of plant material which was growing at that time. It seemed worth while, therefore, to make such an analysis, and the growth rings of a tree were chosen for this purpose.

Phenomena of the Fall

Before reporting the present work it may be of interest to repeat some of the accounts of the effects of the Tunguska meteor. The general area of the fall is composed of taiga with peat bogs and forest and is (fortunately) very sparsely populated. One eye-witness, S. B. Semenov, a farmer at Vanovara some 60 km away, told L. A. Kulik, who investigated the meteor first in 1927 (ref. 2), that he was sitting on the steps outside his house around 8 a.m., facing north, when a fiery explosion occurred which emitted so much heat that he could not stand it: "My shirt was almost burnt on my body". However, the fireball did not last long. He just managed to lower his eyes. When he looked again, the fireball had disappeared. At the same time, an explosion threw him off the steps for several feet, leaving him briefly unconscious. After regaining his senses, a tremendous sound occurred, shaking all the houses, breaking the glass in the windows, and damaging his barn considerably.

Another observer[3], P. P. Kosolopov, a farmer and neighbour of S. B. Semenov, was working on the outside of his house, when suddenly he felt his ears being burnt. He covered them with his hands and ran into his house after asking Semenov if he had seen anything, on which Semenov answered that he too had been burnt. Inside the house, suddenly earth started falling from the ceiling and a piece from his large stove flew out. The windows broke and he heard thunder disappearing to the north. Then he ran outside, but could not see anything.

A Tungus, Liuchetken, told Kulik on April 16, 1927, that his relative, Vassili Ilich, had some 500 reindeer in the area of the fall and many "storage places". With the exception of several dozen tame deer, the rest were grazing in that area. "The fire came by and destroyed the forest, the reindeer and all other animals". Then several Tungus went to investigate and found the burnt remains of several deer; the rest had completely disappeared. Everything was burnt in Vassili Ilich's storage including his clothing. His silverware and samovars (tin?) were molten. Only some large buckets were left intact.

According to Krinov[1] the dazzling fireball moved within a few seconds from the south-east to north-west leaving a trail of dust. Flames and a cloud of smoke were seen over the area of the fall. Visible phenomena were observed from a distance as great as 700 km, and loud explosions were heard after the passage of the fireball at distances up to 1,000 km.

The first inspection of the site was carried out by Kulik in 1927 (ref. 2). Trees were blown down over an area with a radius of 30–40 km. Exposed trees were uprooted with their roots pointing toward the centre of the explosion in a radial manner. Additional expeditions by the Academy of Sciences of the U.S.S.R. were sent in 1928 and 1929–30. The centre of the explosion area was found to have been ravaged by fire and searing could be traced to a radius of 15–18 km from the centre of the explosion. Numerous holes with a diameter from several to several tens of metres had been found in the first expedition of 1927; however, subsequent work including excavations up to 34 m depth did not yield any meteoric material. These holes were explained later by Kulik as natural formations[4]. During 1938–39, an aerial survey was conducted over the devastated area to assess more completely the extent of the destruction.

The fall of the meteor resulted in a seismic wave recorded on the Zöllner–Repsold pendulums of the Irkutsk Magnetic and Meteorological Observatory[1]. Subsequent analyses for the epicentre of the earthquake coincide with the location of the fall and also established the accurate time of the event.

In addition, several observatories in Russia and Europe recorded the barometric waves caused in the atmosphere by the meteor. The seismic and barometric effects have been discussed in detail by Krinov[1], Fesenkov[5], and Whipple[6]. The Tunguska meteor also caused a definite disturbance of the Earth's magnetic field as registered at the Irkutsk Observatory and others around the world. The disturbances were similar to those recorded following nuclear explosions in the atmosphere.

After the fall of the meteor, the nights were exceptionally bright everywhere in Europe and Western Siberia. As far south as the Caucasus, newspapers could be read at midnight without artificial light. The brightness slowly diminished and disappeared after a duration of two months[7].

In comparison, if the fall had occurred in the United States over, say, Chicago, visible phenomena would have been noticed as far away as Pittsburgh, Pennsylvania, Nashville, Tennessee, and Kansas City, Missouri. The thunder would have been heard in Washington, D.C., Atlanta, Georgia, Tulsa, Oklahoma, and in North Dakota.

The Meteorite Hypothesis

The results of the first investigations of the Tunguska site led to the belief that a meteorite of very large initial mass penetrated the Earth's atmosphere and hit the surface, destroying itself in a violent explosion[6]. This explanation sought to account for the absence of meteoritic debris in the fall area. Since a crater was never found, it was assumed that one might have been formed in a layer of permanently frozen soil which lost its form rapidly and could no longer be distinguished after the first summer.

In the analysis of Fesenkov[5] all evidence points to a retrograde orbit around the Sun with considerable inclination of its orbit to the ecliptic. This is atypical for meteorites derived from asteroidal disintegration. Another interpretation of the motion of the meteor is that it moved parallel to the Earth at much lower speed, in which case its relative speed had to be very low. In view of the great energy released, the explanation of a retrograde orbit associated with high relative speed is to be preferred over a slow relative speed which is difficult to reconcile with the effects of the meteor, such as burning the area, etc.

The Cometary Hypothesis

This hypothesis was proposed by A. S. Astapovich and independently by F. J. W. Whipple in 1930 (ref. 6). The evidence in favour of a cometary nature of the meteor is the motion of the meteorite opposite to that of the Earth and the resulting high velocity of an estimated 60 km/sec[5] which yielded on impact the calculated 10^{23} ergs. Since F. L. Whipple's comet model[8] consists of a conglomerate of frozen ices such as methane, water and ammonia interspersed with solid mineral matter, the meteor or small comet appears likely to have exploded above the Earth's surface without leaving significant traces of matter on the ground. Based on the observations of the Potsdam Geodetical Institute which permit the velocity determination of the shock wave propagated through the atmosphere, the speed of 318 m/sec measured corresponds to an atmospheric height of 5–6 km, which is the altitude of the main explosions of the meteor[5,6].

Further evidence favouring a small comet is the unusual luminescence of the night sky immediately after the fall over Siberia, Russia, and Western Europe, but not the United States or in the southern hemisphere[5]. Evidently the dust tail was directed away from the Sun, as expected for comets, and extended in a north-westerly direction at the moment the main body hit. The dissipation of this tail resulted in the night sky being brighter initially by about 50–100 times the normal value, but 10^4 times less than daylight.

Abbot in California found that approximately from the middle of July, or 2 weeks after the explosion, until the second half of August 1908, the coefficient of transparency of the atmosphere was noticeably depressed[9]. Fesenkov suggested that this was caused by the loss of vast amounts of material from the meteor during its flight through the atmosphere, possibly of the order of several million tons of matter[10].

It appears unusual, however, that such a comet was not observed on its collision course with the Earth, as it should have been seen unless it approached from a direction with very small angular distance from the Sun. Fesenkov estimated the size of the cometary nucleus as about several hundred metres[5], which is perhaps only one order of magnitude below that of well-known comets seen at great distances.

The Nuclear Reaction Hypothesis

In an article by F. Y. Zigel discussing the results of A. V. Zolotov's expeditions of the past three years, the events of the Tunguska fall have been re-examined[11]. The velocity of the meteor has always been required to be large in order to account for the release of 10^{23} ergs on impact. This can be determined from the ratio between the amplitudes of the ballistic wave caused by the velocity of the body in the atmosphere and the blast wave caused by the explosion of the body itself.

Zolotov selected trees which had remained standing and on which traces of the effects of both waves remained. Apparently, the ballistic wave arrived from the west and broke only very slender branches, whereas the blast wave from the north broke large tree branches. From these results he calculated that the ballistic wave before the main explosion was, in fact, of minor size as compared with the blast wave. Eye-witnesses of the Tunguska fall recalled that the flight of the meteor was dimmer than the Sun, corresponding to a velocity in the atmosphere of less than 4 km/sec. If the velocity was more than an order of magnitude lower than this, then the explosion could not have possessed the required energy for the explosion.

These considerations led to the question whether or not a massive chemical or nuclear release of energy occurred at the final break-up of the meteor. The nature of an explosion can be determined by the distribution of the energy released, one factor being the amount of radiant energy emitted.

At 17–18 km from the epicentre, Zolotov found trees which had been subjected to a thermal flash and had started to burn. A natural forest fire was ruled out for the area. In order to start a fire in a living tree, about 60–100 cal/cm² of incident thermal radiation is required. By calculation the radiant energy of the explosion was found to be $1{\cdot}5 \times 10^{23}$ ergs. Other energy-yield estimates for different locations placed the thermal energy of the explosion between $1{\cdot}1$ and $2{\cdot}8 \times 10^{23}$ ergs.

Since the estimated yield of thermal energy is so close to the estimate of the total explosive energy, Zolotov favours a nuclear rather than a chemical explosion.

The Chemical Radical Reaction Hypothesis

In an examination of the records of the fall, the radiation flash stands out among the others discussed by different authors during the past decades. Specifically, the remarks by Semenov and Kosolopov of experiencing burning sensations, and the melting of Vassili Ilich's metal ware, appear to confirm the emission of considerable amounts of thermal radiation by the explosion.

Very large chemical high-energy explosions can create sufficiently intense shock-waves in air which, in turn, will radiate thermal energy, perhaps sufficient to account for the fire-setting in the taiga. From the examination of nuclear explosions, the phenomena accompanying the release of large amounts of energy in air are well known[12]. In the case of a nuclear explosion and a fraction of a second after the detonation, a high-pressure, intensely hot and luminous shock front forms and moves outwards from the fireball.

While the dissipation of kinetic energy in the Tunguska explosion probably accounts for the major portion of energy released, the reaction with air of vast amounts of chemical high-energy species such as the radicals observed on comets can be an additional source of energy. For high meteor velocities, the relative contribution of chemical energy to the final explosive break-up will be small, but for a low-velocity body it may be significant. Theoretical considerations place the output of energy of a system using the recombination energy of chemical radicals midway between that of conventional chemical propellants and nuclear reactions in energy released/unit mass.

A very large chemical radical explosion of the meteor would account for many of the observed phenomena. Our very limited knowledge of the actual concentration of radicals on comets, their exact nature and the mechanism of radical reactions make a quantitative calculation of the release of energy by such a model very difficult, especially in context with the uncertainties of the exact orbit of the Tunguska meteor[13].

The Anti-matter Hypothesis

Discounting any but purely natural phenomena, it becomes difficult to construct a model for either a fission or fusion chain-reaction which would produce the effects observed. For the former, an almost-critical mass of fissionable material might be conceived which became tamped on entering the atmosphere. The tamping would have to be such, however, as to take the material far beyond criticality in a very short time to prevent its disassembly with low yield. The multi-megaton yield observed, however, coupled with the very low efficiency known for the best of such devices, would require a large initial mass—well above the critical mass of normal density uranium or plutonium. Thus, super-criticality obtained by tamping alone could scarcely be credited as the mechanism. On the other hand, to obtain it by increasing the density of a sub-critical mass by compression seems equally unlikely, for this must be a result of the mechanical forces generated by penetration into the atmosphere.

To obtain the effects from a fusion reaction, a sufficient amount of deuterium, and possibly tritium, must be contained in a compressed state and heated to several million deg. C. It must then be maintained in that state so that self-heating can carry the reaction to the explosion stage. Again, it is difficult to conceive of a model for such a mechanism which is attained merely by entry into the atmosphere of the Earth.

In searching for other natural means by which a large nuclear energy yield might be obtained, we are unable to find one other than the annihilation of charge-conjugate ('anti-') matter with the gases of the atmosphere. Several objections immediately arise to this hypothesis, all different from those raised above. No mechanical extremes are required of the model, however.

The first objection is that no evidence is known for the existence of anti-matter in the gross state. Other than as anti-particles produced by high-energy interactions of ordinary matter with itself or with electromagnetic radiation, no anti-matter has been observed. This is understandable in the environment of the Earth, and so one must look to astronomy for such evidence. The complete symmetry between the two charge-conjugate states of matter, however, makes an astronomical test of an isolated, distant object difficult.

The second problem arises in considering the flight of an 'anti-rock' through the atmosphere. If the rock is approximately spherical with diameter d cm and of density ρ g/cm^3, then it might penetrate a distance of $d\rho$ g/cm^2 into an absorbing medium before being consumed. The minimum distance through the atmosphere is about 10^3 g/cm^2. Thus, if the density is of the order 10 g/cm^3, then the diameter of the rock is of the order 100 cm. The number of nucleons in such an object is approximately $\frac{1}{2}Ad^3\rho$, or about 3×10^{30}, and the yield of energy would be of the order 10^{27} ergs, rather than 10^{23} as observed. The fact that the bolide did not reach the surface of the Earth is ignored in this estimate, and is off-set by the additional distance due to the inclined trajectory of the object. The discrepancy factor is, nevertheless, quite large. In addition, the flight of the bolide would have exhibited its largest yield somewhere toward the middle of its path, rather than towards its end—it would have thinned-down and died out.

A second look at the process tempers these conclusions, however. The exceedingly strong radiation shock accompanied by heating of the air ahead of the bolide, in addition to the pressure of electrons and other particles ejected in the forward direction by the annihilation reaction of complex nuclei with other, different complex nuclei, would rarefy the atmosphere ahead and greatly increase the range. A carefully calculated model for such a process may be in order. It could be that only a small fraction of the bolide could annihilate in flight, but that it remains essentially solid until it reaches a point where it is travelling slowly deep in the atmosphere. Here, continued annihilation might heat it to the gaseous stage and dissemble it explosively, resulting in a final annihilation as the gases mixed with atmospheric gases. In any event, the process seems far too complex to dismiss on the basis of a rapid estimate.

Of the three models for a nuclear explosion, we choose the annihilation model as a basis for an estimate of the amount of carbon-14 produced. We must first estimate the number of neutrons produced/nucleon annihilated.

Annihilation of Anti-rock in the Atmosphere

We have, of course, no information concerning the state or the chemical composition of the supposed anti-matter comprising the bolide. Assuming it to be molecular compounds similar to those of ordinary meteorites, we ignore annihilation of the electrons, for these would produce a small fraction of the yield and would form no neutrons in the process.

The simplest case of nucleon annihilation is that of $p\bar{p}$. Even in this instance, the annihilation is not limited to S states, and the process becomes complex due to the various possible angular momentum states in the initial system and various charge states in the final system. The final system may contain pairs of kaons and various numbers of positive, negative and neutral pions. A measure of the number of charged particles emitted in the annihilation of $p\bar{p}$ is given by Horwitz *et al.*[14] as an experimentally obtained histogram extending from zero to seven prongs/event, with a flat maximum in the region of 3–4 prongs. The high average multiplicity greatly complicates the situation because of the many possible quantum numbers in the final state. Refinements[15] in an estimate by taking into account $p\bar{n}$, $n\bar{n}$ and $n\bar{p}$ are obviated by the realization that we may be dealing here with reactions between complex nuclei and between fragments of such nuclei as they become broken by partial annihilation. Let us take four charged pions, on the average, as the basis for proceeding, two positive and two negative/nucleon pair annihilated.

The positive pions will decay in the atmosphere, but the negative ones will, in general, be captured by oxygen, nitrogen and carbon nuclei. In view of the overall uncertainty in this estimate, we will assume that all of the negative pions are absorbed at rest by nuclei. A simplified picture of the process, obtained from the measurement of prongs produced in stars in nuclear emulsions from negative pion absorption, is that of the 140 MeV rest energy of the pion gained by the nucleus, 40 MeV is lost by fast neutron emission at the time of absorption and 100 MeV is then lost by boiling-off of neutrons and charged particles in an evaporative process. Taking the mean energy[16] of the prompt neutrons as 12 MeV and their binding energy as 8 MeV, the mean number of prompt neutrons is 2. Assuming that the probability for then boiling off a neutron is the same as that for a proton, and weighting the probabilities obtained from prong counts accordingly, we find that two more neutrons are produced from light nuclei. Thus, four neutrons are produced per pion absorbed, or eight neutrons per nucleon pair annihilated. In view of the great uncertainties in this estimate, we take the number to be 8 ± 4. Thus, for a total energy yield of 10^{24} ergs by nucleon-antinucleon annihilation and a yield of about 3×10^{-3} ergs/nucleon pair, about $(2{\cdot}7 \pm 1{\cdot}4) \times 10^{27}$ neutrons would be released to the atmosphere.

Effect on Atmospheric Radiocarbon Content

We may make some estimates of the effects of releasing neutrons in amounts such as this in the following way:

Assume that every neutron produced is absorbed in the reaction $^{14}N(n,p)^{14}C$, and that the radiocarbon so produced is rapidly oxidized to carbon dioxide in the atmosphere. Thus $(2\cdot7 \pm 1\cdot4) \times 10^{27}$ molecules of radio-CO_2 mix with the atmospheric gases. Taking the total mass of the atmosphere as $5\cdot3 \times 10^{21}$ g, and the mean carbon dioxide content of the air as 0·030 volume per cent (though this varies geographically and seasonally), we readily calculate the atmospheric carbon dioxide to contain $6\cdot6 \times 10^{17}$ g carbon as carbon dioxide. Taking the decay constant of carbon-14 as $2\cdot3 \times 10^{-10}m^{-1}$, our new radiocarbon should exhibit $9\cdot4 \times 10^{-1}$ d m^{-1} g^{-1} of atmospheric carbon. As the specific activity of atmospheric carbon is $13\cdot56 \pm$ d m^{-1} g^{-1}, this represents an increase of some 7 per cent in the radiocarbon activity[17].

In making this estimate, we have taken the radiocarbon to be uniformly distributed in the atmosphere after both vertical mixing and mixing between the northern and southern hemispheres, and have neglected absorption in the ocean and biosphere. Thus the result is approximate.

An alternative basis for an estimate of the yield of radiocarbon by an anti-matter Tunguska explosion is provided by the data on the yield of this isotope by the testing of nuclear explosives in the atmosphere. By September 1961, the equivalent of 70 MT (1 MT, megaton TNT equivalent is 4×10^{22} ergs) of fission and fusion nuclear explosive was released in air bursts and about 100 MT in surface tests[18]. The specific radiocarbon-level taken up by plants at that time[19] was about 25 per cent above the natural cosmic-ray level of radiocarbon. We may estimate an upper limit to the anti-matter in the Tunguska meteor in the following way:

Taking the full 70 MT of air bursts and one-half of the 100 MT of surface bursts as effective for producing radiocarbon, we have $\frac{70 + 50}{25}$ or 5 MT of fission or fusion fired in the atmosphere producing a 1 per cent rise in radiocarbon activity.

If, now, the known damage parameters of the Tunguska explosion are used as input data for the Nuclear Bomb Effects Computer, a value of about 30 MT (10^{24} ergs) energy yield is obtained (supplement to publication cited as ref. 12), which at 2 BeV (3×10^{-3} ergs) per nucleon pair consumed and 8 ± 4 neutrons yield gives a total neutron yield as shown above, of $(2\cdot7 \pm 1\cdot4) \times 10^{27}$ neutrons. Since the meteor disintegrated in the atmosphere, this would be expected to give $(2\cdot7 \pm 1\cdot4) \times 10^{24}$ carbon-14 atoms. Therefore, if the Tunguska explosion had been due to anti-matter, it should have behaved like 35 MT of fission or fusion fired at the same latitude (say the U.S.S.R. test site at Novaya Zemlya, 74° N, 150° E) and, using our experience with bomb test carbon-14 as a basis of comparison, we can estimate the possible anti-matter content of the 1908 Siberian meteorite.

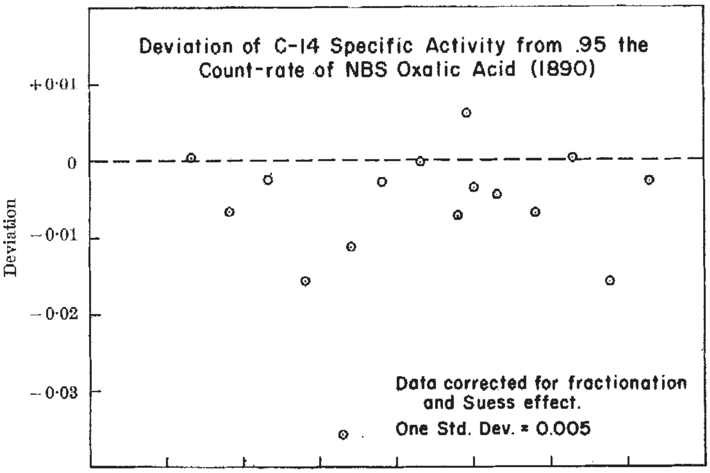

Fig. 2

Radiocarbon Analysis

A section of a 300-year-old Douglas fir (*Pseudotsuga taxifolia*), the 'Hitchcock' tree, which fell in the winter of 1951 in an unsurveyed area (35° 15′ N, 111° 45′ W) of the Santa Catalina Mountains about 30 miles from Tucson, Arizona, was provided by the Laboratory for Tree-Ring Research of the University of Arizona, Tucson. About 20 g of wood was stripped from each ring for the interval of 1870–1936, and the radiocarbon contents of the rings of each fifth year were measured, excepting for the years around 1908. Table 1 contains the results expressed as percentage deviations from the international standard reference level of 1890 (0·95 of the count-rate of the National Bureau of Standards oxalic acid). Column IV contains carbon-13 mass spectrometric corrections in per mil deviation from the Chicago PDB standard. (The mass spectrometric analyses were provided with the help of R. McIver and W. Sackett of the Jersey Production Research Co., Tulsa, Oklahoma.) The percentage deviations in carbon-14, corrected by these figures for isotopic fractionation[20], are contained in column V, according to $\left(\frac{1 + \delta^{14}C}{1 + 2\delta^{13}C} - 1\right) \times 100$. Finally, the last column contains the results corrected again for the effects of dilution of atmospheric carbon dioxide by the burning of industrial fossil fuels[20]. We have used Fergusson's[21] values for this correction (the Suess effect).

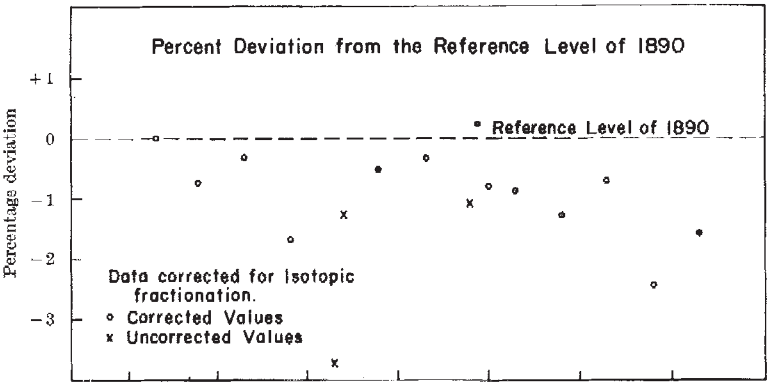

Fig. 1

Additional tree-ring samples were measured from an oak tree (samples provided by L. Wood, Inst. Geophysics, Univ. Calif., Los Angeles) cut in 1964 near Los Angeles (in the Simi Valley, 34° 12′ N, 118° 48′ W). They are given as UCLA-776, 778, 779.

The results of columns V and VI are plotted in Figs. 1 and 2, respectively.

As some 90,000 counts were taken on each sample, the standard deviation in each value is of the order 0·005 of that value. Experience has shown that the equipment is sufficiently stable, so the statistical uncertainty is the principal one.

Discussion

Inspection of Table 1 yields some interesting points: of all the numbers in columns III and V, only those values for the year 1909 exceed the reference-level. In column V,

Table 1. Radiocarbon Content of Tree-rings around 1908[22]

I Sample No.	II Year	III % $\delta^{14}C$ uncorrected	IV Per mil $\delta^{13}C$	V % $\delta^{14}C$ corrected for isotopic fractionation	VI % $\delta^{14}C$ corrected for Suess effect
UCLA-769	1873	0	−22·3	0	+0·05
UCLA-768	1878	−0·72	−23·0	−0·75	−0·67
UCLA-767	1883	−0·31	−22·9	−0·32	−0·22
UCLA-766	1888	−1·64	−22·2	−1·69	−1·59
UCLA-765	1893	−3·75	—	—	−3·60
UCLA-782	1894	−1·26	—	—	−1·11
UCLA-763	1898	−0·48	−22·9	−0·50	−0·30
UCLA-760	1903	−0·28	−23·1	−0·29	−0·02
UCLA-761	1908	−1·07	—	—	−0·72
UCLA-778	1908	−0·96	—	—	−0·61
UCLA-774	1909	+0·26	−22·6	+0·25	+0·60
UCLA-776	1909	+0·17	−24·8	+0·16	+0·51
UCLA-780	1910	−0·70	−22·2	−0·73	−0·38
UCLA-779	1910	−1·50	−24·5	−1·55	−1·20
UCLA-762	1913	−0·81	−22·6	−0·84	−0·45
UCLA-764	1918	−1·20	−22·4	−1·24	−0·69
UCLA-770	1923	−0·63	−23·0	−0·66	+0·04
UCLA-771	1928	−2·40	−22·4	−2·45	−1·58
UCLA-772	1933	−1·50	—22·0	−1·55	−0·27

two others also exceed the standard, but by relatively small amounts. When a mean value is calculated for the points in a forty-year span around 1909, the latter exceeds this value by about 1 per cent.

A second point to be noticed is the presence of strong fluctuations in the years around 1893 and 1928, as well as the presence of other, lesser ones at other times. These fluctuations are typical and appear to be real[23–26], though they rarely exceed 2 per cent, as reported in the literature. In the results presented here, they are all negative with respect to the reference-level, though this is due to the arbitrary choice of the standard level. They are, evidently, due to variations in the carbon-14 burden of the local atmosphere. Such fluctuations tend to obscure the small effect searched for here and make its value the more uncertain.

At least three other instances are known in which strong positive deviations appear to occur[24]. They are A.D. 1687 (+2·65 per cent), 1297 B.C. (+2·23 per cent), and 1925 B.C. (+2·34 per cent), where the deviations are taken with respect to the average values obtained from 39 oak samples ranging in age from 110 to 203 years prior to 1960. When compared with the deviation of the oxalic acid standard, however, which was +4·99 ± 1·06 per cent with respect to the oak average, these deviations are also negative.

Although there are uncertainties in both the estimate of the expected radiocarbon yield on the basis of the anti-matter hypothesis for the Tunguska meteor and in any extra radiocarbon burden of the atmosphere in the years following 1908 as reflected in this work, the data do yield a positive result. They appear to set an upper limit of 1/7 for the fraction of the meteorite's energy which could have been due to anti-matter.

We thank Rainer Berger, Mrs. Gera Freeman, Bette Davis and Emilio Cueto for their advice and assistance.

This work was supported in part by U.S. National Science Foundation grant *GP*–1893 to one of us (W. F. L.) and by the Walter F. Joyce Foundation to another (C. L. C.).

[1] Krinov, E. L., *The Solar System*, edit. by Middlehurst, B. M., and Kuiper, G. P., **4**, 208 (Univ. Chicago Press, 1963).

[2] Kulik, L. A., *Akademiia Nauk S.S.S.R., Co. R. (Doklady)*, No. 23, 399 (1927).

[3] Told to Kulik, L. A., on March 30, 1927. See ref. 2.

[4] Kulik, L. A., *Trans. Lomonosov Inst. Akad. Sci.* (U.S.S.R.), **2**, 73 (1932).

[5] Fesenkov, V. G., *Astronomicheskii Zhurnal*, **38**, No. 4, 577 (1961).

[6] Whipple, F. J. W., *Quart. J. Roy. Meteorol. Soc.*, **56**, 287 (1930); Astapovich is credited for putting forward this suggestion first by Krinov, E. L., in his *Principles of Meteoritics* (Pergamon Press).

[7] Shenrock, A. M., *Monthly Bull. Nikolaev Main Phys. Obs.*, No. 6 (1908). Rudnev, D. D., *St. Petersburg Univ. Student Sci. Trans.*, **1**, 69 (1909). Aposlolov, L., *Mirovedenie*, No. 3, 281 (1926). Whipple, F. J. W., ref. 6.

[8] Whipple, F. L., *Astrophys. J.*, **111**, 375 (1950).

[9] Fesenkov, V. G., *Meteoritika*, **6** (1949).

[10] Fesenkov, V. G., *Meteoritika*, **6**, 8 (1949).

[11] Zigel, F. Y., *Znaniye-Sila*, No. 12, 24 (1961).

[12] Glasstone, S. (edit.), *The Effect of Nuclear Weapons*, prepared by the U.S. Dept. Defense and published by the U.S. Atomic Energy Comm., Washington (1962). McMillan, W. G. (personal communication).

[13] Berger, R. (personal communication).

[14] Horwitz, N., Miller, D., Murray, J., and Tripp, R., *Phys. Rev.*, **115**, 474 (1959).

[15] See, for example, *Nuclear Interactions*, by DeBenedetti, S. (Wiley and Sons, New York, 1964).

[16] Thorndike, A. M., *Handbook of Physics*, edit. by Condon and Odishaw (McGraw-Hill, New York, 1958).

[17] Karlen, I., Olsson, I., and Karlberg, P., *Arkiv Geofysik*, **4**, 465 (1964).

[18] Libby, W. F., *Proc. U.S. Nat. Acad. Sci.*, **45**, 959 (1959).

[19] Fergusson, G. J., *J. Geophys. Res.*, **68**, 3933 (1963).

[20] Suess, H. E., *Science*, **122**, 416 (1955).

[21] Fergusson, G. J., *Proc. Roy. Soc.*, A, **243**, 561 (1958).

[22] Berger, R., Fergusson, G. J., and Libby, W. F., *Radiocarbon*, **7**, 1975 (in the press).

[23] Whitaker, W. W., Valastro, jun., S., and Williams, M., *J. Geophys. Res.*, **64**, 1023 (1959).

[24] Suess, H. E., *Science*, **122**, 415 (1955).

[25] Ralph, E. K., and Stuckenrath, R., *Nature*, **188**, 185 (1960).

[26] Damon, P. E., Long, A., and Sigalove, J., *Radiocarbon*, **5**, 283 (1963).

ARMS CONTROL IN THE ARCTIC

By Dr. TERENCE ARMSTRONG

Scott Polar Research Institute, Cambridge

A RECENT proposal by Alexander Rich and Aleksandr P. Vinogradov (*Bull. Atomic Scientists*, 22, November 1964) has revived interest in the possibility of using the Arctic to further the cause of arms control. The proposal they make may be put briefly thus. The Antarctic is at present the only sizable part of the world where international treaty forbids militarization and provides for inspection. In order to promote the growth of mutual trust between the United States and the U.S.S.R., and specifically to gain more experience of inspection procedures, it is suggested that the Arctic might be a useful area to consider next.

The Arctic is chosen because it has less military value than most other regions, and need not involve many countries—at first only the United States and U.S.S.R., the nearest point of contact of which is, of course, in the Arctic. The territory to be included in the agreement may be increased by stages. First, it is suggested that Alaska and an equivalent area of north-east Siberia, possibly including all, or part of, Kamchatka, should be subject to inspection. Secondly, Greenland might be added, by agreement with Denmark, together with a further equivalent area of Siberia on the Soviet side. Finally, the rest of the Arctic zone might be brought in, involving the participation of Canada, Norway and Sweden. (The authors do not define their "Arctic zone", probably deliberately, but it is likely that Finland would also be involved.)

The stipulation is made that inspection should verify the absence of nuclear weapons and delivery systems only, and should not be concerned with radar installations or military bases as such. In other words, the proposal is primarily for a "nuclear-free zone".

This proposal bears a close resemblance to one put forward to the United Nations in 1957 and 1958. In 1957, the western powers proposed to the Disarmament Commission a measure to safeguard against the possibility of surprise attack. This measure was an inspection system to cover the whole of the United States, the U.S.S.R. and Canada; but if this were unacceptable, an Arctic area, closely similar to that in Rich and Vinogradov's stage