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THE DETECTION OF A SUPER EXPLOSION

by

R. W. Spence
E. C. Anderson

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THE DETECTION OF A SUPER EXPLOSION

I. Basic Assumptions

We shall arbitrarily choose as a basis for discussion a thermonuclear reaction (initiated by a fission reaction) giving about one thousand times as much energy release as the present fission bombs. We shall assume the following D-D reactions to go with equal probabilities:

$$_1H^2 + {}_1H^2 \longrightarrow {}_1H^3 + {}_1H^1 + 4.0 \text{ Mev}$$

$$_1H^2 + {}_1H^2 \longrightarrow {}_2He^3 + {}_0n^1 + 3.3 \text{ Mev}$$

The tritium produced in the first reaction will react with deuterium as follows:

$$_1H^3 + {}_1H^2 \longrightarrow {}_2He^4 + {}_0n^1 + 17.6 \text{ Mev}$$

The overall reaction we shall assume is, therefore:

$$5\ {}_1H^2 \longrightarrow {}_2He^4 + {}_2He^3 + {}_1H^1 + 2\,{}_0n^1 + 25 \text{ Mev}$$

In particular, we shall assume that we start with 2×10^{29} deuterium atoms, and that the reaction goes to completion so that 8×10^{28} neutrons are released. We shall further assume that practically all of these neutrons get slowed down to thermal energy before reacting with the atmosphere.

In this report we will consider the possibility of detecting such a super explosion if it were set off in the atmosphere; we will not discuss the detection problem existing if the explosion occurred under water or under ground.

II. Activities Produced by Reactions of Neutrons with the Atmosphere.

Table I shows the activities produced by neutrons in the atmosphere assuming that all the neutrons are at thermal energies when the reactions occur. Short-lived activities such as 8 sec. N^{16}, 31 sec. O^{19}, 40 sec. Ne^{23}, 75 min. Kr^{87} have been omitted, together with a couple of reactions which give C^{14}, but in insignificant amounts. Atom abundances (second column) are given relative to N^{14}, atom productions (column 6) and initial activities (column 7) are given relative to C^{14}. It can be seen that the chief reaction is $N^{14}(n,p)\ C^{14}$.

Some of the activities are also produced in fission. Thus 9.7 yr Kr^{85} is fed into the atmosphere by reactors to such an extent that the use of this nuclide for detection purposes is out of the question(1). We can assume that any thermonuclear reaction will be initiated by a fission reaction, so some of the activities in Table I will be produced by fission. [redacted] We have omitted 9.7 yr. Kr^{85} because of its pile production, and 4.5 hr. Kr^{85} because we do not know its fission yield; however a half-life of 4.5 hr. is so short that this nuclide does not look very promising for detection purposes. [redacted]

DOE b(3)

DOE b(3)

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(1) Private communication from A. Turkevich.

TABLE I

Stable Nuclide	Relative Atom Abundance	Thermal Cross Section (Barns)	Active Nuclide	Half-life	Relative**** Atom Production	Relative**** Initial Activity	Activity from Super (8×10^{28} neutrons) d/m
N^{14}	1	1.7	C^{14}	5700 yr	1	1	1.8×10^{19}
A^{40}	5.9×10^{-3}	1.24	A^{41}	1.83 hr	4.4×10^{-3}	1.2×10^{5}	2.2×10^{24}
A^{36}	2.0×10^{-5}	6.5***	A^{37}	34.1 d	7.6×10^{-5}	4.6	8.3×10^{19}
Kr^{84}	3.6×10^{-7}	0.096 0.063	Kr^{85}** Kr^{85}**	4.5 hr 9.7 yr	2.0×10^{-8} 1.3×10^{-8}	0.22 7.6×10^{-6}	4.0×10^{18} 1.3×10^{14}
Kr^{78}	2.2×10^{-9}	0.26	Kr^{79}	34 hr	3.4×10^{-10}	5.0×10^{-4}	9.0×10^{15}
Xe^{126}	4.6×10^{-11}	~ 0.6 *	Xe^{127}	34 d	1.6×10^{-11}	1.0×10^{-6}	1.8×10^{13}
Xe^{130}	2.1×10^{-9}	~ 3 *	Xe^{131m} **	12 d	3.8×10^{-9}	6.8×10^{-4}	1.2×10^{16}
Xe^{132}	1.4×10^{-8}	0.2	Xe^{133} **	5.27 d	1.6×10^{-9}	6.3×10^{-4}	1.1×10^{16}
Xe^{134}	5.4×10^{-9}	0.2	Xe^{135} **	9.2 hr	6.4×10^{-10}	3.5×10^{-5}	6.3×10^{16}
Xe^{136}	4.6×10^{-9}	0.15	Cs^{137} **	33 yr	4.0×10^{-10}	6.9×10^{-8}	1.2×10^{12}
He^{3}	$\sim 4 \times 10^{-12}$	5000	(by B-decay) H^{3}	12 yr	1.2×10^{-8}	$\sim 5 \times 10^{-6}$	$\sim 9 \times 10^{13}$

* From ANL, communicated by A. Turkevich
** Also produced in fission
*** McMurtrie and Crawford, Phys. Rev. 77, 840 (1950)
**** Some of these values are a factor of two smaller than those given in LAMS 983 because of an error in the latter report.

Atom abundances were calculated from elemental abundances given in The Atmospheres of the Earth and Planets, p. 1 by G. P. Kuiper

Cross sections were taken from Trilinear Chart of Nuclear Species by W. H. Sullivan and Tables of Neutron Cross Sections, Mon P-405, by K. Way and G. Haines.

[redacted]

TABLE II

Active Nuclide	[redacted]	Activity from Super giving 8×10^{28} neutrons. d/m
Xe^{131m}		1.2×10^{16}
Xe^{133}		1.1×10^{16}
Xe^{135}		6.3×10^{16}
Cs^{137}		1.2×10^{12}

DOE b(3)

* Assuming 1% of I^{131} decays to Xe^{131m}

[redacted] The comparison is not fair, because undoubtedly much of the fission produced activity is trapped in particles and would not be collected in a xenon fraction. Also, the fission product activities given are incorrect because it was assumed for simplicity that each nuclide has no ancestors, but was formed directly in fission. Actually some of the iodine parents have appreciable half lives, particularly 8 day I^{131}. Nevertheless, the overwhelming ratio of fission product xenon to super product xenon makes these nuclides quite unsuitable for differentiating between a super and an ordinary fission bomb. Kr^{79} and Xe^{127}, while not produced in fission, are obviously eliminated as possible candidates, since the former has to compete with radio krypton from both pile production and fission associated with a super, while the latter is swamped by other xenon activity even after many months.

DOE b(3)

Of the remaining possible nuclides, H^3 is a possible reactant and product of a thermonuclear reaction and will be discussed later in this report; A^{41} has such a short half-life (1.83 hours) that it will decay far too rapidly to allow its use for detection purposes. We are left with C^{14} and A^{37}, and we will now proceed to show that these active nuclides look very promising.

III <u>C^{14} and A^{37} Activities.</u>

We have seen that a super releasing 8×10^{28} neutrons will give rise to 1.8×10^{19} d/m of C^{14} and 8.3×10^{19} d/m of A^{37}. These amounts of activity will suffice for the detection of a super if

a) the amount of each activity already present in the atmosphere (from the reaction of cosmic ray neutrons on N^{14} and A^{36}) is not too great, and

b) if the specific activity of the sample being counted is great enough so that the observed counting rate is sufficiently above the counter background. Clearly, the exact value of the specific activity depends on the extent to which the super induced activities are spread throughout the atmosphere at the time a sample is taken for analysis. We shall make the pessimistic assumption that mixing with the atmosphere is complete.

If we take the mass of the atmosphere as 5.2×10^{21} grams(2) or 1.8×10^{20} moles, and the mole fraction of CO_2 in air as 3×10^{-4} then there are 5.4×10^{16} moles of CO_2 or 6.5×10^{17} grams of C in the entire atmosphere. The specific activity of natural C has been measured,(3) and is 15 d/m/gram. Therefore, the C^{14} activity in the entire atmosphere is 1×10^{19} d/m, or about half the super produced activity.

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(2) Handbook of Chemistry and Physics, 29th Edition, p. 2579; Chemical Rubber Publishing Co., 1935

(3) E. C. Anderson, Thesis, University of Chicago, June 1949. Libby, Anderson and Arnold, <u>Science</u>, <u>109</u>, 227 (1949). The value reported in these papers has since been raised slightly by recalibration of the counters used.

In order to calculate the A^{37} activity already present in the air, we will assume that the total amount of C^{14} and A^{37} in the world is in secular equilibrium with the rate of production from cosmic ray neutrons. The CO_2 in the air is estimated to contain only 1.5% of all the earth's exchangeable carbon[4] so $\frac{6.5 \times 10^{17} \text{ g}}{0.015} \times 15 \text{ d/m/g} = 6.5 \times 10^{20}$ d/m is the C^{14} activity of the whole world, hence is the rate of production of C^{14} atoms from cosmic ray neutrons. (This may be compared with the value 6.2×10^{20} min^{-1} calculated for the slow neutron flux in the atmosphere using the most recent direct measurements with BF_3 counters.) The rate of production of A^{37} is 7.6×10^{-5} of the C^{14} rate (Table I, column 6), hence the total A^{37} activity is 4.9×10^{16} d/m, compared to the 8.3×10^{19} d/m formed by a super reaction.

Table III summarizes the above conclusions, together with some calculations of expected specific activities.

TABLE III

Active Nuclide	Moles Carrier	Activity in Atmosphere from Cosmic Ray neutrons d/m	Activity from Super d/m	Specific Activity from Cosmic Rays d/m/mole	Specific Activity from Super d/m/mole
C^{14}	5.4×10^{16}*	1.0×10^{19}	1.8×10^{19}	180	330
A^{37}	1.7×10^{18}	4.9×10^{16}	8.3×10^{19}	0.03	50

* As CO_2

It can be seen that for A^{37}, the contribution from activity produced by cosmic ray neutrons is negligible, and indeed would not be important even

(4) See Reference No. 3.

if the super induced A^{37} were lowered by a factor of 100.

The same cannot be said for C^{14} if, as assumed, the activity ends up in the CO_2 molecule. A smaller super than we have assumed might still be detected by C^{14}, however, because Table III was based on the assumption that all of the C^{14} produced had mixed with the earth's total atmosphere. Furthermore, there is no evidence that all of the C^{14} will end up as CO_2. The CO content of air is not well known, but probably is very low; if a fair fraction of the super induced C^{14} is present as CO the situation becomes very favorable because practically all of the cosmic-ray induced C^{14} is present as CO_2. Experimental work on this aspect of the C^{14} problem is necessary.

The question still has to be answered of whether or not the samples collected are "hot" enough to count above the counter background. For purposes of discussion let us assume that the gases collected for counting are CO_2 and argon, and that the samples are to be counted in a gas-filled proportional counter at one atmosphere pressure and a volume of 2.24 liters (or 0.1 mole). (Other measuring techniques are also possible; the above is chosen merely as a specific, practical example). We see from Table III that 0.10 mole of CO_2 would have an activity of 33 d/m from super induced C^{14} and 18 d/m from cosmic ray induced C^{14}. The counter background, estimating from past experience with C^{14} counters, would be about 15 c/m. Therefore no trouble should be encountered in using C^{14} for detecting a super giving 8×10^{28} neutrons. Similarly, 0.10 mole of argon would have a super induced activity of 5 d/m, the cosmic ray induced argon activity being negligible. The counter background can only be estimated but the situation is made favorable by the fact that A^{37} decays by K-capture and about 95% of the disintegrations lead to emission of monoenergetic electrons of 2.8 Kev energy (by internal conversion of the Cl K-X radiation) [5] so that pulse analysis techniques should help in reducing the counter background. The background might be reduced to perhaps 5 c/m.[6] Therefore it appears that A^{37} will serve to detect a super giving 8×10^{28} neutrons.

It is difficult to estimate the smallest super that could be detected by analyzing air samples for C^{14} and A^{37}. A factor of ten lower than the super we have been discussing seems fairly easy, because it would be reasonable to expect that air samples would be collected before the bomb products had spread to more than 10% of the entire atmosphere. Perhaps in favorable cases, the bomb products might mix with only 1% of the entire atmosphere, thus gaining another factor of ten, assuming of course that the important 1% could be located and sampled. Better estimates cannot be made until counter backgrounds have been investigated experimentally. In the case of C^{14} the chemical species in which the C^{14} exists in the atmosphere is very important, for under favorable circumstances, the limit of detection might be low enough for the detection of even an ordinary fission bomb.

A word should be said about the feasibility of collecting the samples from the air. Neither CO_2 nor argon presents serious difficulties. One can get 0.10 mole (2.24 l) of argon from 242 liters of air, and 0.10 mole of CO_2 from 7460 liters of air. The collection of other carbon

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(5) McMurtrie and Crawford, Phys. Rev. 77, 840 (1950)
(6) Private communication from C. J. Borkowski of Oak Ridge National Laboratory.

compounds such as CO will have to be investigated, but the problems involved do not look particularly difficult.

IV Detection of Tritium.

In addition to the small amount of tritium formed by an (n,p) reaction on He^3 in the atmosphere, tritium may be produced in two other ways: the reaction of fast neutrons on N^{14}, [two reactions are possible: N^{14} (n,t)C^{12} and N^{14}(n,t) $3He^4$] and the reaction: ${}_1H^2 + {}_1H^2 \longrightarrow {}_1H^3 + {}_0n^1$ which is one of the main D-D reactions involved in the thermonuclear reaction of the super. The amount of tritium produced in these ways is not easy to estimate. We can very crudely estimate the amount of tritium formed from N^{14} as follows. We assume a cross section for (n,t) reactions on N^{14} of 0.01 barn, (7) and a total cross section of 10 barns. Then not more than 0.1% of the neutrons will give tritium (depending on the width of the (n,t) absorption band and the reaction threshold). If practically all the neutrons give 8×10^{28} atoms of C^{14}, then less than 8×10^{25} atoms of tritium will be formed, or an activity of less than 10^{19} d/m.

Of the tritium formed in the D-D reaction of the super, most disappears by a D-T reaction. It has been estimated by Harris Mayer of the Theoretical Division that perhaps 0.5% of the tritium formed might be left at the end of the reaction. Thus, if one started with 2×10^{29} deuterium atoms, one should have formed in the thermonuclear reaction about 4×10^{28} tritium atoms, of which 2×10^{26} atoms might remain, giving rise to an activity of 2×10^{19} d/m. This activity would overshadow any activity

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(7) Cornog and Libby Phys. Rev. 59 1046 (1941), Libby ibid 69 671 (1946)

produced by the action of neutrons on He^3 in the atmosphere. It might be argued that some tritium would be formed by the action of neutrons on He^3 produced in the other D-D reaction. While some tritium might be produced in this manner, the amount will not be large, since the cross section is high only for thermal neutrons, and much of what is formed will further react with deuterium.

Even if the above calculations are correct there still remains the problem in what chemical species the tritium will finally be found. It could be present for example as water, ammonia (which exchanges rapidly with H_2O) or elementary hydrogen. If we assume that the tritium is as water, then we can calculate a specific activity. Of the 1.8×10^{20} moles of air, from 10^{-2} to 10^{-3} is water vapor. Taking 5×10^{-3} as the mean mole fraction, there are 9×10^{17} moles of water vapor in the entire atmosphere. If we assume that the tritium mixes completely with the earth's atmosphere (and that is does not precipitate) then the specific activity of the water will be 3×10^{19} d/m $\div$ 9×10^{17} moles = 33 d/m/mole. About the most that can be said about the use of tritium for detection purposes is that one would not rely on it but might as well look for it.

V Deuterium.

The mole fraction of H_2 in the atmosphere is 5×10^{-7} and of water vapor about 5×10^{-3}. Therefore, of the 1.8×10^{20} moles of air, 9×10^{13} moles are H_2 and 9×10^{17} moles are H_2O. Since the abundance of deuterium in natural hydrogen is 0.02%, we have 1.8×10^{10} moles of deuterium or 2×10^{34} atoms of deuterium present as the element in the entire atmosphere, and 2×10^{38} atoms of deuterium present as water vapor. (We have here assumed that the ratio of hydrogen to deuterium is the same for atmospheric H_2 and H_2O as it is for water on the earth.) The contribution of even 2×10^{29} atoms of deuterium (if the super were unsuccessful) is therefore not great. If deuterium not undergoing the D-D reaction were present as water vapor, only for a very early sample could one detect a change in the natural hydrogen-deuterium ratio. If unburned deuterium were present as the element, it is possible that its presence could be detected, although the observed change in the hydrogen-deuterium ratio would be small (except for an early sample collected before much mixing with the atmosphere had occurred). Suppose, as a concrete example, that after a super reaction involving 2×10^{29} deuterium atoms, that 10% of the deuterium remained as the elementary gas, and had mixed with 1% of the entire atmosphere at the time a sample was collected. We would therefore have 2×10^{28} deuterium atoms added to the $2 \times 10^{34} \times 10^{-2} = 2 \times 10^{32}$ deuterium atoms already there. Thus the deuterium content would increase by one part in 10^4. However, if exchange between H_2 and D_2 is slow, the deuterium from a super could remain as D_2 and the ratio of such D_2 to D_2 already in the atmosphere will be more favorable. If the mole fraction of HD in atmospheric hydrogen is 2×10^{-4}, then the mole fraction of D_2 will be about 4×10^{-8}. Thus, of the 9×10^{13} moles of atmospheric H_2, 3.6×10^6 moles are D_2, giving 4×10^{30} atoms of deuterium as D_2. If 10% of the super deuterium remains unchanged and mixes with 1% of the earth's atmosphere, then 2×10^{28} atoms of deuterium (as D_2) are added to 4×10^{28} atoms of deuterium (as D_2) already present. An unsuccessful super would release 2×10^{29} atoms of deuterium (as D_2). Therefore, the use of deuterium for detecting a super, particularly an unsuccessful super, is not completely out of the question, especially if the HD (and D_2) content of the atmosphere is very constant.

VI. He^3

If a super gave 4×10^{28} He^3 atoms, and atmospheric mixing were complete, these He^3 atoms would be added to $\sim 7 \times 10^{32}$ atoms of He^3 already present. If the mixing were only with 1% of the earth's atmosphere, then one would be adding 4×10^{28} atoms to 7×10^{30} atoms, or the He^3 content would increase by about 6 parts in 10^3. This increase could be detected only if the He^3 to He^4 ratio in atmospheric helium were very constant.

VII. Detection of Preliminary Thermonuclear Experiments.

The foregoing discussion was limited to a full-fledged super. It is quite conceivable, however, that before such a super were tried, preliminary experiments would be done on thermonuclear reactions. In particular, one would want to look for evidence that the ignition of deuterium-tritium mixtures had occurred.

We have seen that the most promising method of detecting a super depends upon looking for radioactive nuclides formed by reactions of the large number of neutrons emitted by a super. Detection methods based on analyses for deuterium, tritium, and He^3 do not look hopeful for a super, and are correspondingly worse for a small thermonuclear reaction (unless, of course, a sample of air could be obtained quickly from the immediate vicinity of the explosion). However, one other possibility exists of

[redacted]

detecting a thermonuclear reaction: If enough fissions are caused by fast neutrons, ratios of fission product activities will change, because symmetrical fission becomes more probable the faster the neutron causing fission. Thus symmetrical fission in U^{235} becomes almost 100 times more probable for fission caused by 14 Mev neutron than for thermal fission. ("Bomb spectrum" neutrons from an ordinary fission bomb give about twice as much symmetrical fission as thermal neutrons). If a few percent of the fissions were caused by 14 Mev neutrons, certain activity ratios would be appreciably changed. Now there is no guarantee that an experiment designed to test thermonuclear reactions would necessarily lead to a considerable amount of fast fission, although certain types of experiments probably would. Abnormally high activities of such fission products as Cd^{115} and Ag^{111} would certainly be good evidence of a thermonuclear reaction, but normal activity ratios would not be evidence of the absence of a thermonuclear reaction. A super would very likely give abnormal activity ratios and it would be hard to distinguish between a super and certain types of thermonuclear experiments (such as the "booster" gadget) just from fission product activity ratios alone; the presence or absence of C^{14} and A^{37} could be used to distinguish the super from the experimental shot.