Possibility of a Fission Chain Reaction in Supernova Type I*

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The possibility of a fission chain reaction is discussed for the purpose of explaining the discrepancy between the observed light intensity of supernova type I in its decaying stage and the amount of energy available from the spontaneous fission of Cf^{254}. A convergent fission chain reaction would make the energy output many times larger while at the same time would keep the half-life of the light intensity curve the same as that of the spontaneous fission of Cf^{254}. However, the necessary conditions for this mechanism to contribute appreciably to the energy source do not seem to exist in supernova type I; other mechanisms are required to explain the discrepancy.

A SUPERNOVA of type I, after an initial period of about 30 to 100 days following the explosion, exhibits an exponential decrease in its light intensity with a half-life of 55 days.[1] The half-life numerically equals that of the spontaneous fission of Cf^{254} [2]; the spontaneous fission energy of Cf^{254} has been considered as the energy source of the supernova in its decaying stage.[3,4] However, to account for the observed light intensity it is necessary to assume a mass of 6 sun-masses to be blown off during the explosion in order to synthesize enough Cf^{254} by the *r* process,[4] i.e., the neutron capture process on a fast time scale.[5,6] On the other hand, the mass of the Crab Nebula, the present day remnant of the Chinese supernova of 1054 A.D., is estimated to be about 0.1 sun-mass; but due to uncertainties in estimation, a value for this mass of about 1 sun-mass would not be unreasonable.[4] Thus a discrepancy of at least a factor of 6 seems to exist.[7]

In this note we consider a mechanism by means of which fission energy many times more than that available from Cf^{254} may be released at a rate according to a half-life equal to that of Cf^{254}. When a Cf^{254} nucleus undergoes spontaneous fission it releases about four neutrons. These neutrons may induce fission in the fissionable material present in the supernova shell and a chain reaction of fission may result. We are not interested in the divergent chain reaction, for which the reproduction factor k is greater than unity and by which the fission fuel will be used up in a short time. (Possibly such a reaction might take place in some other circumstances.) We shall consider only the convergent chain reaction for which k is less than unity and the multiplication factor m equals $1/(1-k)$. The chain reaction serves the purpose of a fission multiplier—each Cf^{254} nucleus acts as a trigger which sets off a series of m fission events. The total energy release is thus increased about m times from that available from Cf^{254} alone. Since the m fission events follow the fission of the first Cf^{254} almost instantaneously, the time rate of total energy release is the same as that of spontaneous fission of Cf^{254}. Thus the energy output follows a decay curve of 55 days half-life.

The conditions under which this mechanism will work properly are that: (1) there be enough secondary fission to ensure a reproduction factor k close to unity; (2) the reproduction factor k remain constant in time. The fulfillment of these conditions depends on the chemical composition of the supernova shell and the kinematics of the explosion. The neutrons released in fission may be captured by many materials, and may decay spontaneously in addition to inducing secondary fission. The supernova shell is essentially hydrogen mixed with some $4n$-type nuclides. These isotopes do not absorb neutrons but act as a moderator to slow down neutrons. The degraded neutrons will then react, through resonance levels, with the *r*-process products (about 1% of the supernova shell[4]) i.e., the medium-weight nuclides of $80<A<210$ and the heavy-weight nuclides of $230<A<$ about 265, resulting in capture or fission. The chain reaction does not change the chemical composition of the supernova shell appreciably. Therefore it seems reasonable to assume that the reproduction factor k is nearly constant in time (no "poisoning" of this "cosmic reactor"). Because of the resonances it is difficult to estimate the ratio of fission to capture. Cameron[8] pointed

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[1] W. Baade, G. R. Burbidge, F. Hoyle, E. M. Burbidge, R. F. Christy, and W. A. Fowler, Publ. Astron. Soc. Pacific **68**, 296 (1956).

[2] P. R. Fields, M. H. Studier, H. Diamond, J. F. Mech, M. G. Inghram, G. L. Pyle, C. M. Stevens, S. Fried, W. M. Manning, A. Ghiorso, S. G. Thompson, G. H. Higgins, and G. T. Seaborg, Phys. Rev. **102**, 180 (1956); J. R. Huizenga and J. Diamond, Phys. Rev. **107**, 1087 (1957).

[3] G. R. Burbidge, F. Hoyle, E. M. Burbidge, R. F. Christy, and W. A. Fowler, Phys. Rev. **103**, 1145 (1956).

[4] G. R. Burbidge, E. M. Burbidge, W. A. Fowler, and F. Hoyle, Revs. Modern Phys. **29**, 547 (1957).

[5] C. D. Coryell, Annual Report, Laboratory for Nuclear Science, M. I. T., 1956 (unpublished).

[6] Peter Fong, Bull. Am. Phys. Soc. **2**, 15 (1957).

[7] W. A. Fowler has pointed out in a private communication that on the basis of a recent work by Woltjer the discrepancy has become less serious. L. Woltjer, thesis, University of Leiden, 1957 (unpublished). Woltjer shows that only the mass of the visible filaments ~0.1 sun-mass can be determined.

[8] A. G. W. Cameron (private communication).

out that a preliminary value of m of about 8 is too optimistic; based on his values of abundance and cross sections he estimated the value of k to be a small fraction. In order that no neutrons are lost by spontaneous decay it is necessary that the reaction (capture and fission) lifetime of neutron be much shorter than its spontaneous decay lifetime. As the expansion of the supernova shell goes on, its density decreases and the time required for a neutron to react with heavy nuclides increases. Fowler[9] pointed out that after several hundred days the density will be so small that spontaneous decay will take place before any reaction. This situation is not improved even assuming the exploding material to be confined in a shell.[10] It appears that the necessary conditions are not realized in supernova type I and thus other explanations perhaps are necessary.[11] In view of the plausibility of the fission chain reaction and its possible occurrence in other circumstances it was decided to publish these results and point out the difficulties regarding the supernova type I.

Another source of fission contributing to the chain reaction may be mentioned here. The odd A, very heavy nuclides ($A>254$), such as E^{255}, have long half-life against spontaneous fission. After capturing a neutron and converting itself to an even-even nuclide (by β decay if necessary), such a nuclide will become one with extremely short spontaneous fission half-life and therefore will undergo fission "immediately." Thus the neutron capture processes of such very heavy odd-A nuclides also contribute to the fission chain reaction just as does the induced fission. However, the amount due to this source is likely to be small.

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[9] W. A. Fowler (private communication).

[10] J. Greenstein pointed out some difficulties of such an assumption in a private communication although a calculation shows that a shell of a thickness of the sun-radius is stable against thermal diffusion and leak-proof for the neutrons.

[11] E. Anders has now published a paper in Astrophys. J. **129**, 327 (1959) considering Fe^{59}, instead of Cf^{254}, to be responsible for the exponential decline of the supernova light curve.

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Two-Nucleon Stripping Process*

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A new expression is derived for the differential cross section of processes in which two nucleons are captured from an incident alpha particle or similar projectiles. The formula derived is compared with a similar one previously obtained together with some experimental data on the $O^{16}(d,\alpha)N^{14}$ reaction. Fairly good agreement is observed.

It is well known that the theories of the stripping reactions[1] of deuterons were successful in describing the main features of many such reactions, especially the experimentally observed forward peaking. On the other hand, some deuteron stripping reactions showed a backward peaking of the stripped particles distribution, which was explained in terms of the heavy-particle stripping process, as developed by Owen and Madansky.[2]

Quite recently, however, experimental results have accumulated on reactions in which two nucleons are stripped from the projectile and captured by the target nucleus. This is the case for (α,d) and (He^3,p) reactions[3] and data are also available for their inverse. These cases show also the forward and backward peaking characterizing the deuteron stripping process. This may suggest that in the two-nucleon stripping reaction, a mechanism similar to that responsible for deuteron stripping may take place. An expression for the differential cross section of this process, based on the first

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[1] S. T. Butler, Proc. Roy. Soc. (London) **A208**, 559 (1951); A. B. Bhatia, K. Huang, R. Huby, and H. C. Newns, Phil. Mag. **43**, 485 (1952); R. Huby, Proc. Roy. Soc. (London) **A215**, 385 (1952); F. L. Friedman and W. Tobocman, Phys. Rev. **92**, 93 (1953); W. Tobocman, Phys. Rev. **94**, 1655 (1954); R. G. Thomas, Phys. Rev. **100**, 25 (1955).

[2] L. Madansky and G. E. Owen, Phys. Rev. **99**, 1608 (1955); G. E. Owen and L. Madansky, Phys. Rev. **105**, 1766 (1957).

[3] T. S. Green and R. Middleton, Proc. Phys. Soc. (London) **A69**, 28 (1956); D. A. Bromley, E. Almzvist, H. E. Gove, A. E. Litherland, E. B. Paul, and A. J. Ferguson, Phys. Rev. **105**, 957 (1957); R. L. Johnston, H. D. Holmgren, E. A. Wolicki, and E. G. Illsley, Phys. Rev. **109**, 884 (1958); J. B. Marion and G. Weber, Phys. Rev. **102**, 1355 (1956).