to be zero. $r=0$ is then still a geodesic, but in addition there must be neighboring geodesics with zero geodesic deviation from it—the geodesic must be part of a rigid congruence. This gives an intuitive picture of the internal degrees of freedom responding to the equation for geodesic deviation.

(3) Einstein-Maxwell theory.—In this case the analysis is many times more difficult than in the previous cases and has not been completed. Nevertheless, to lowest order in the approximation, several interesting results and one surprising result are obtained. The Lorentz force law in terms of a unique "background" is obtained, as well as electromagnetic interactions with *I*. The surprising result was the appearance of the radiation reaction term $\frac{2}{3}e^2(\dddot{\xi}^\mu + \ddot{\xi}^\alpha \ddot{\xi}^\alpha \dot{\xi}^\mu)$ in the force law, with no mass renormalization term. This result is preserved under the test-particle limit. It appears to us as if this is a major success of this approach. It supports speculations that a quantized version of general relativity might eliminate some of the self-energy difficulties in quantum electrodynamics.

It seems natural to interpret the singularities in Robinson-Trautman solutions as "elementary" singularities, with no interactions with external sources, while the more general solutions would represent the interaction of these "elementary" singularities with sources or a background field. The same could be said of the charged counterparts.

There appears to be a major drawback in this approach to equations of motion. The acceleration has been formally defined in terms of $\dot{P}_0/P_0$, in analogy with flat space. But no means has been presented by which, even in principle, $\dot{P}_0/P_0$ and hence the acceleration could be measured. The situation is, however, not hopeless—it appears likely that one can place a family of geodesic observers into such motion that by observing the time derivative of the Doppler shift, they would be measuring directly $\dot{P}_0/P_0$. This can be done when the world line $r=0$ is nonsingular. This point will be amplified on in the more complete version of this work.

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# CORRELATION BETWEEN FISSION TRACKS AND FISSION-TYPE XENON FROM AN EXTINCT RADIOACTIVITY*

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Meteoritic whitlockite containing excess fission tracks has a large concentration of excess neutron-rich xenon isotopes which is 25 times that calculated from the track density. The isotopic spectrum is identical to that calculated previously for the Pasamonte achondrite. These results uniquely associate this spectrum with in situ fission. Identification of the fissioning nucleus as $Pu^{244}$ gives $Pu^{244}/U^{238} \approx 1/30$ at the time of xenon retention. Neither "sudden" nor "uniform" nucleosynthetic models give consistent solutions for $Pu^{244}/U^{238}$ and $U^{235}/U^{238}$.

There are two independent lines of evidence for fission products in meteorites: (1) Several meteorites contain distinct enrichments in the isotopic abundance of the neutron-rich Xe isotopes suggestive of fission.[1-3] (2) Studies on minerals from several other meteorites have revealed high densities of charged-particle tracks with properties characteristic of fission tracks rather than tracks of heavy cosmic-ray ions.[4-6]

In all cases studied the concentrations of U appear to be inadequate to account for either the observed track densities or the amounts and isotopic composition of the excess Xe in terms of spontaneous fission or induced fission. The excess fission tracks and excess neutron-rich Xe are usually attributed to the spontaneous fission of $Pu^{244}$

(82 Myr half-life) during the early history of the solar system. Strong evidence already exists for the presence of $I^{129}$ (17 Myr half-life) at the time of formation of many meteorites.[7] Thus, it is reasonable that $Pu^{244}$, with a half-life 5 times greater than $I^{129}$, should also be present. However, while $Pu^{244}$ can only be formed in galactic $r$-process nucleosynthesis,[8] $I^{129}$ could also be formed in local particle irradiations within the solar system following its isolation from the galaxy as a whole.[9]

In the absence of an experimentally established correlation between the excess tracks and Xe there is no direct proof that they represent the same phenomenon. In addition to this basic qualitative question, it is of great importance to establish whether or not the $Pu^{244}/U^{238}$ values obtained by the two methods can be quantitatively compared. Further, for phases with a high concentration of fission tracks, the expected high enrichment of the fission component with respect to other Xe components would allow a precise determination of the fission Xe spectrum.

Detailed track measurements by Cantelaube, Maurette, and Pellas[6] on different phases in the St. Severin chondrite show that the mineral whitlockite [$\beta$-$Ca_3(PO_4)_2$] has a high track density (~$7.4\times10^6/cm^2$) which cannot be due to heavy cosmic-ray ions. Spontaneous fission of $U^{238}$ can account for only 1/7 of the tracks. These authors attribute the excess tracks to the spontaneous fission of $Pu^{244}$.

Through the generous cooperation of Dr. P. Pellas, Dr. F. Kraut, and Dr. J. Orcel of the Museum National d'Histoire Naturelle, France, a sample of St. Severin was provided to us for study (H2402b). A high-purity (~90%) whitlockite sample (30 mg) was prepared and the track density reported by Cantelaube, Maurette, and Pellas[6] confirmed. The rare gases in the whitlockite were extracted by vacuum fusion and measured on a high-sensitivity mass spectrometer. In addition samples of feldspar and total meteorite were similarly analyzed. The analytical techniques, methods of spectral decomposition, and detailed results will be discussed elsewhere.

The conclusions stated here are very insensitive to the assumptions made in the data analysis. The critical results are as follows:

(1) The whitlockite has a high concentration of excess, neutron-rich xenon isotopes (see Fig. 1) as well as a high density of excess fission tracks. The number of excess $Xe^{136}$ atoms is about 25 times greater than expected from the fission-track density.

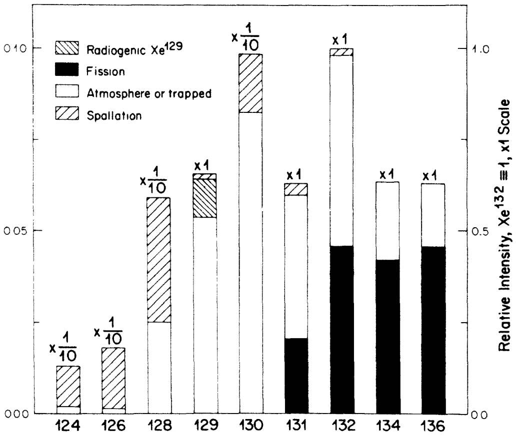

FIG. 1. Histogram of the isotopic ratios for xenon extracted from whitlockite separated from the St. Severin chondrite. Note that the scales on the left and right are different. The fractions of each isotope due to the four components are shown.

(2) The $Xe^{136}$ excess observed in other minerals with a low track density and in the total meteorite is a factor of ~200 less in concentration than in the whitlockite.

(3) A significant excess of $Xe^{129}$ is observed in the whitlockite (see Fig. 1) as well as in the other samples.

(4) The calculated isotopic spectrum of the excess neutron-rich xenon isotopes ($Xe^{131}$ to $Xe^{136}$) is defined with high precision (see Fig. 2 and Table I) and is identical with the previous best estimates of the so-called fission-xenon component of the Pasamonte achondrite.[1,10-12] The fission $Xe^{134}/Xe^{136}$ ratio is compatible with a type of excess heavy Xe found in other achondritic meteorities. This isotopic composition appears to be ubiquitous and uniquely defined.

These results show that there is a strong qualitative correlation between the excess heavy Xe isotopes and excess fission tracks in meteorites. The presence of excess heavy Xe in the same grains as excess tracks establishes that these effects arise from the same process and that this process is nuclear fission.

From the apparent uniqueness of the isotopic spectrum we conclude that the fission products (Xe and tracks) are not a mixture of several components. The high concentrations of fission Xe and fission tracks in the whitlockite as compared to that in other minerals or the total meteorite shows that the Xe excess is most reasonably understood as the result of in situ decay of a single fissionable isotope and not as an inherited or

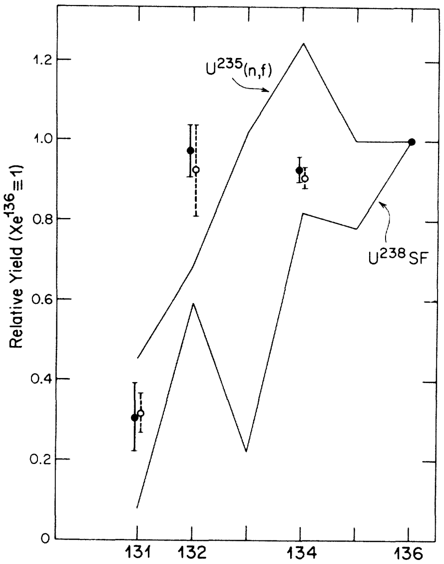

FIG. 2. Neutron-rich excess xenon spectrum normalized to $Xe^{136} = 1$ for the St. Severin whitlockite (closed circles). This spectrum is attributed to fission because of the correlation with fission tracks. The Pasamonte fission spectrum (open circles) (Ref. 11) is shown for comparison. These spectra are identical to within experimental error and differ from the two uranium fission-yield spectra.

trapped fission component. The discrepancy between the track density and the excess $Xe^{136}$ is attributed to annealing. Whitlockite is known to have a low track retention temperature.[6]

Neither the tracks nor the Xe excess can be accounted for by induced fission. Furthermore, the concentration of the fission products in a phase rich in U and, presumably, the rare earths is to be expected from the chemical properties of Pu. These provide the most direct arguments that we are observing the effects of the spontaneous fission of $Pu^{244}$ contained in these meteorites at the time of their formation. If so, then the fission spectrum as reported here is the one to be tentatively associated with $Pu^{244}$. Comparison of a precise meteoritic spectrum with the laboratory $Pu^{244}$ Xe spectrum, when this becomes available will provide an unequivocal test of the $Pu^{244}$ identification. Other examples of "fission-type" xenon,[3,13-17] e.g., as found in carbonaceous chondrites, cannot from our considerations be attributed to $Pu^{244}$ spontaneous fission and must be due to some other process.

Assuming that the U concentration found by Cantelaube, Maurette, and Pellas (Table I) is representative of our samples, we calculate a $Pu^{244}/U^{238}$ ratio of 1/30 at the time when the whitlockite first began to retain fission Xe. If Pu was not enriched with respect to U in the formation of the whitlockite, this is a lower limit to the $Pu^{244}/U^{238}$ ratio at the time of formation of the solar system. Previous reports of high $Pu^{244}/U^{238}$ ratios were based on measurements of excess heavy Xe isotopes having the "carbonaceous-chondrite fission" spectrum[14,15]; however, this spectrum should not be associated with $Pu^{244}$. A report of high Pu/U ratio based on track measurements[18] has since been retracted.[5] In general $Pu^{244}/U^{238}$ ratios calculated from Pasamonte-type fission Xe measurements[12,19] and other track studies[4,5] are much lower than that obtained in this work.

Table I. Calculated fission spectrum of St. Severin whitlockite, $Ca_3(PO_4)_2$, based on $U = 1.0 \times 10^{15}$ atoms/g (Ref. 6), total track density $7.4 \times 10^6$ tracks/cm$^2$ (Ref. 6), measured $Pu^{244}/U^{238} = 0.035$.[a]

| $Xe^{131}/Xe^{136}$ | $Xe^{132}/Xe^{136}$ | $Xe^{134}/Xe^{136}$ | $Xe_f^{136}$ (atoms/g) |
|---|---|---|---|
| 0.31 ±0.08 | 0.97 ±0.08 | 0.93 ±0.01 | $(5.3 \pm 0.8) \times 10^9$ |

[a] For $Pu^{244}$: $\tau_{1/2} = 82$ Myr [P. R. Fields, A. M. Friedman, J. Milsted, J. Lerner, C. M. Stevens, D. Metta, and W. K. Sabine, Nature 212, 131 (1966)], $\lambda_f/\lambda_{total} = 1.25 \times 10^{-3}$, assumed fission yield of $Xe^{136}$ 6 %.

Assuming the separation time of the solar system from the interstellar medium to range from 0 to $1.3 \times 10^8$ yr, the range in $Pu^{244}/U^{238}$ is 1/30 to $\frac{1}{10}$ at the termination of nucleosynthesis. This range of values can also be obtained from the calculations of Fowler[20] assuming continuous uniform nucleosynthesis for durations ranging from $3.3 \times 10^9$ to about $1 \times 10^9$ yr. However, these duration times are incompatible with the values (greater than $5.7 \times 10^9$ yr) necessary to account for the solar system $U^{235}/U^{238}$ ratio on the same model.

An upper limit of 360 Myr for the separation time can be set by assuming that all of the $Pu^{244}$ was synthesized in a sudden event. This upper limit is insensitive to errors in the relative production rates. However, a sudden-synthesis model[20] (even allowing for a wide range in relative production rates) fails to give consistent solutions for $Pu^{244}/U^{238}$ and $U^{235}/U^{238}$. Unless the fissioning nucleus is not $Pu^{244}$ or there is considerable chemical fractionation it appears that the theoretical relative production rates are considerably off or that a more complex model for galactic nucleosynthesis is necessary.

We thank Mr. J. Brown for his competent and meticulous work in obtaining the whitlockite separate and in sample preparation. Frequent discussions with W. A. Fowler have been both stimulating and thought provoking. This experiment was conceived when the authors became aware of the high density of tracks and uranium found in whitlockite by Paul Pellas.[21] We thank O. Eugster for useful comments on the manuscript.

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# EXPERIMENTAL OBSERVATION OF SOMMERFELD AND BRILLOUIN PRECURSORS IN THE MICROWAVE DOMAIN*†

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An experimental investigation of transient electromagnetic wave propagation in the microwave frequency range related to the theoretical investigation of Sommerfeld and Brillouin is reported. Both the Sommerfeld and Brillouin precursors are shown experimentally.

In 1914, Sommerfeld and Brillouin calculated the propagation of a transient signal (specifically a sine wave starting at $t=0$ and terminating at $t=T$) through a dispersive medium. The dispersion relation (Fig. 1) of the medium which they considered was given by $k=(\omega/c)[1+a^2/\omega_0^2-\omega^2)]^{1/2}$ where $\omega_0$ is the characteristic frequency of the electron and $a$ is related to the charge, the mass, and the number of electrons in a unit volume. The response to the above mentioned excitation was calculated in a series of now classic papers which are summarized in a book by Brillouin.[1]

The interesting results of their calculations can be summarized in modern terms as follows: At a given observation point $z$ the main contribu-