LIFETIME OF ANTIMATTER METEORS

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Abstract. The lifetime of antimatter fragments which may enter the Earth's atmosphere in the form of meteors is determined in this paper, for cases in which the annihilation may be accompanied by the evaporation process. The antimatter object can be penetrated by the nucleon – antinucleon annihilation products, which can be generated by interactions of atoms of antimatter fragments with the atmospheric molecules. Vaporization of its own antiatoms may be followed, in case of a high rate of annihilation, so that the lifetime of the antimatter object may become shorter, compared with the case of annihilation without vapor production of the meteor. The lifetime of the antimatter fragment is dependent upon the temperature of the object and thus vaporization of such an object would last for as long as $\delta\tau = R\delta/\xi$, where ξ is the intensity of evaporation, δ its density and R its radius.

1. Introduction

There are three possible consequences for the energy that can be absorbed, due to the passing of elementary particles through the interior of an antimatter meteor. Such particles are the products that can be generated by atmospheric molecules in the annihilation process with the antimatter atoms of the meteor. (1) The first case supported by Naunberg and Ruderman (1966), considers the atom-antiatom annihilation cross section to be as large as that of the elastic cross section between them and therefore every atmospheric molecule striking on the surface of the antimatter meteor may undergo annihilation. According to this scenario, there may be no reduction mechanisms of the atom-antiatom annihilation cross section, so that an antimatter meteor to be explosively evaporated at a high altitude (above 300 km). The reason for the above study was to oppose arguments presented by Cowan, Alturi and Libby (1965), who suggested the possibility of an antimatter meteor entrance in the Earth atmosphere. This suggestion was presented as an explanation for the tremendous explosion that took place in Siberia near the Tunguska river in 1908, but the reason of this explosion still remains an enigma. (2) In the second case, the energy deposition is too low, due to a low production of annihilation particles and the antimatter meteor remnant which may survive its infall flight can be cooled, keeping the object at a temperature, where no vapours could be produced. This case is discussed recently (Papaelias, 1984; Papaelias, 1993) and can take place either at high altitudes, in case of a large cross section, or even at the ground level, in the case of a smaller one. (3) A third case, supported also recently (Papaelias, 1984; Papaelias and Apostolakis, 1990), suggests that there may be mechanisms that can interfere in the process of the annihilation of antiatoms by atmospheric atoms or molecules, preventing

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in such a way a complete vaporization of the antimatter object during its infall flight, before its cosmic velocity is being lost.

The aim of the current paper, is to discuss the third possibility. The lifetime of an antimatter remnant is derived here, for the case in which the cosmic velocity of the object is decreased and the object can be heated at temperature values, where antiatom vapours possibly can be produced. This is an intermediate case, where the annihilation cross section may be reduced by the mechanisms mentioned above (Papaelias and Apostolakis, 1990) and the procedure of annihilation of an antimatter meteor may be delayed, compared with the case described by Naunberg and Ruderman (1966).

2. Analysis of the Method

For the simple system of the $\bar{p}p$ annihilation interaction, the duration of the interaction may last for a time period equal to only 10^{-13} s for solids and liquids, (10^{-9} s for air), as derived by Teller and Fermi, during the decade of forties. This value must be taken as the lowest possible limit and the annihilation lifetime may be not always as small as that suggested by Teller and Fermi (1947) for the $\bar{p}p$ interactions, but for cases of annihilation of complex atoms with complex antiatoms it may vary by the atomic number that each of the two annihilating atoms may consist of (Papaelias, 1984; Papaelias and Apostolakis, 1990). Recent experimental results have showed that this is true and the behaviour of antimatter annihilating with ordinary matter is not a simple process, as it was widely accepted by most of the particle physicists in the past. The two mirror matter constituents may annihilate each other by complex procedures that closely reach the arguments presented previously (Papaelias, 1984; Papaelias and Apostolakis, 1990).

At the Low Energy Antiproton Ring (LEAR) of CERN, a Japan–German collaboration (Eades *et al.*, 1993; Eades, Hughes and Zimmerman, 1993; Yamazaki *et al.*, 1993; Widman *et al.*, 1993) have showed that the annihilation lifetime τ of antiprotons interacting with ordinary matter, may greatly vary from the value ($\tau \sim 10^{-13}$ s) for a solid or liquid absorber and 10^{-9} s for air, calculated by Fermi and Teller in 1947. Experimentalists surprisingly observed, that in Helium-3 and Helium-4, antiprotons resist annihilation and the lifetime of annihilation may become as greater as a hundred million times than the value calculated by Fermi and Teller. This result comes close to the arguments presented (Papaelias, 1984; Papaelias and Apostolakis, 1990) in which the time duration of interaction for complex antiatoms with ordinary atoms was proposed ($\tau \sim 10^{-5}$ s) to be a reasonable value, making the antimatter objects comparably stable in the excess of ordinary matter.

The experimental results mentioned above, have triggered researchers at CERN to put forward to examine experimentally (CERN COURIER, June 1992), many questions that have been raised by this experiment. (A) Does the lifetime depend on the physical/chemical state of the stopping substance? (B) Are there potential applications in exotic atom chemistry? Questions of this kind had been proposed in the past, as the philosophical basis for the study of annihilation interactions between antiatoms and atoms made of ordinary matter and consequently for the study of antimatter meteors that may enter the Earth's atmosphere (Papaelias, 1984; Papaelias, 1987; Papaelias and Apostolakis, 1990).

Because complex antiatoms annihilated by complex atmospheric atoms and molecules may cause additional delaying procedures, such as the formation of positronium states (Papaelias, 1984; Papaelias and Apostolakis, 1990), it becomes evident now, that the study of antimatter meteors annihilating with ordinary atoms – such as the atmospheric atoms or molecules – is not as simple as the $\overline{p}p$ annihilation interaction. The article of CERN COURIER mentioned above, fairly characterized such discrepancies between theory and experiment unusual – to say the least – and among the questions to examine, the role of the positronium is also included for future experiments. An antimatter chemistry science probably is arising and possibly, the annihilation lifetime could be found varying with the atomic number of the two mirror atoms that may take place in the process of annihilation.

The annihilation lifetime of an antimatter fragment is determined by the simple relation $\delta\tau = (N_L\delta/A)(R/r)$ (Papaelias, 1993), where N_L is the Loschmidt number, δ the density of the antimatter meteor, A its atomic mass, R the radius of the object before its entrance in the atmosphere and r the rate of annihilation per cm^2 of the surface of the object. When applying this relation with typical values, we found that for a given radius of an antimatter object, e.g. $R = 10^{-4}$ cm, the annihilation lifetime is approximately 97 days at heights, where the annihilation rate per cm^2 is too low ($\sim 10^{12}$ annihilation interactions/cm^2/s), a value which is not adequate to cause evaporation of the object. If the annihilation may take place at higher altitudes, or the reducing mechanisms of the annihilation cross section may keep this rate at low values, vaporization of the object may be prevented, and the antimatter object may last longer. In contrary, if the annihilation can take place at lower altitudes, or the rate of annihilation is higher than in the case discussed earlier (Papaelias, 1984; Papaelias, 1992), then the lifetime of the object could become much shorter.

3. Calculations

The Bethe-Bloch formula and the EGS code (Ford and Nelson, 1978) is used here to calculate the energy deposition of the charged and neutral pions respectively (Papaelias, 1991), for the fraction of the annihilation products (π^+, π^-, $\pi^0 \rightarrow \gamma\gamma$) produced by the annihilation interactions between the antiatoms and the atmospheric molecules, that can penetrate the antimatter fragment. Such a penetration may cause an increase of the temperature T. When moving, the heat balance of the antimatter object, is $4\pi R^2(Q + h\xi) = \pi R^2 E(R) r$, where $E(R)$ is the heat absorbed by the antimatter object, due to the passing through its body of the annihilation products generated by a single atmospheric molecule, that can be annihilated in front of its surface. The function $E(R) = f(R)$ is discussed earlier (Papaelias, 1991) and for the case of an antimatter meteor of radius $R_1 = 0.9$ cm is estimated to be $\sim 2.5 \times 10^{-11}$ cal/molecule N_2 annihilated on its surface, while for radius $R_2 = 0.01$ cm is estimated by extrapolation to be $\sim 8 \times 10^{-13}$ cal/molecule N_2. The terms Q and $h\xi$ are the radiation and evaporation losses, respectively, and $Q + h\xi$ is the total amount of heat expended on radiation and evaporation per unit area and time. A rate r per unit of surface (molecules/cm^2/s) is required to be annihilated on the antimatter fragment's surface, for the case in which there is equilibrium between the heat absorbed in the object and the heat loss from the object, due to thermal radiation and vapor production for a given value of temperature T and for a radius of antimatter object R. For iron micrometeors, the emmissivity $\epsilon(T)$ according to calculations by earlier researchers (Öpik, 1958) can be given by the formula $\bar{\epsilon} = 0.193\ (T/1500)^{0.65}$ and the adopted radiation formula for a smooth iron surface is $Q = 9.64\ 10^{-8}\ T^{4.65}$, which is valid for a smooth iron surface within the range of temperatures between 1500–3000 °K. For a rough surface, $Q = 9.53\ 10^{-8}\ T^{4.65}\ (1000R)^{0.3}$, for $0.1 > R > 1.04\ 10^{-3}$ cm, which is a range of radii discussed in this paper. When by annihilation and vapour production, the radii may become lower to the value of $1.04\ 10^{-3}$ cm, the previous formula for smooth surface can be used. The rate r can be estimated from Table I, where an antimatter fragment having an equivalent radius $R_1 = 0.9$ cm – corresponding to a surface $S = 10$ cm^2 – requires a rate of annihilation r_1 to remain at a constant temperature T. By extrapolation in Figure 1, it is possible to get the rate $r_2 > r_1$ for a fragment of radius $R_2 = 0.01$ cm ($R_2 < R_1$). It is true, that due to the small radius of these objects and the high energy of the annihilation products, a slight fraction of the energy carried by these products can be finally deposed in the interior of the antimatter objects.

In Table I, the intensity of evaporation ξ and the heat loss Q due to the thermal radiation and due to the escape of the antimatter vapours $h\xi$, as a function of the temperature T are given, where by the letter h the heat of ablation is denoted. These are values given by previous researchers (Öpik, 1958) for the case of an iron meteor made of ordinary matter and the same values are expected – as well for any other constant characterizing physical properties – for an antimatter one, that can be made also of iron.

From Table I, it is obvious that when the antimatter fragment starts melting, a large amount of vapours is starting to escape too. The intensity of vaporization for a temperature T, is given by the interpolation formulae (Öpik, 1958) $\log \xi = 5.167 – 15700/T$ for $T > 2200$ °K or $\log \xi = 6.167 – 17900/T$ for $T < 2200$ °K (iron case). The ratio $\xi(3000\ °\mathrm{K})/\xi(1600\ °\mathrm{K})$ is equal to $8.9\ 10^4$, while the corresponding ratio for the heat losses at the same temperature is only $7.5\ 10^2$. Therefore, once the temperature of the antimatter fragment starts increasing, the number of the annihilation interactions starts also to increase, resulting in

TABLE I

The temperature T, the intensity of evaporation ξ, the heat loss $(Q + h\xi)$, and the rates of annihilation interactions per unit of surface r_1 and r_2. The values of rates are those required to keep the temperature of the object at a constant value, for two different cases of antimatter objects of radius $R_1 = 0.9$ cm and $R_2 = 0.01$ cm, corresponding respectively to the rates r_1 and r_2 (iron case).

T °K	ξ g/cm^2/s	$Q + h\xi$ cal/cm^3/s	r_1 Molecules	r_2 N_2/cm^2/s
1600	9.52×10^{-6}	1.82	7.2×10^{10}	2.2×10^{12}
1800	1.67×10^{-4}	3.38	1.4×10^{11}	4.2×10^{12}
2000	1.65×10^{-3}	7.62	3.0×10^{11}	9.5×10^{12}
2200	1.09×10^{-2}	24.72	9.9×10^{11}	3.1×10^{13}
2400	4.21×10^{-2}	76.77	3.1×10^{12}	9.6×10^{13}
2600	1.34×10^{-1}	223.98	9.0×10^{12}	2.8×10^{14}
2800	3.61×10^{-1}	581.04	2.3×10^{13}	7.3×10^{14}
3000	8.50×10^{-1}	1352.73	5.4×10^{13}	1.7×10^{15}

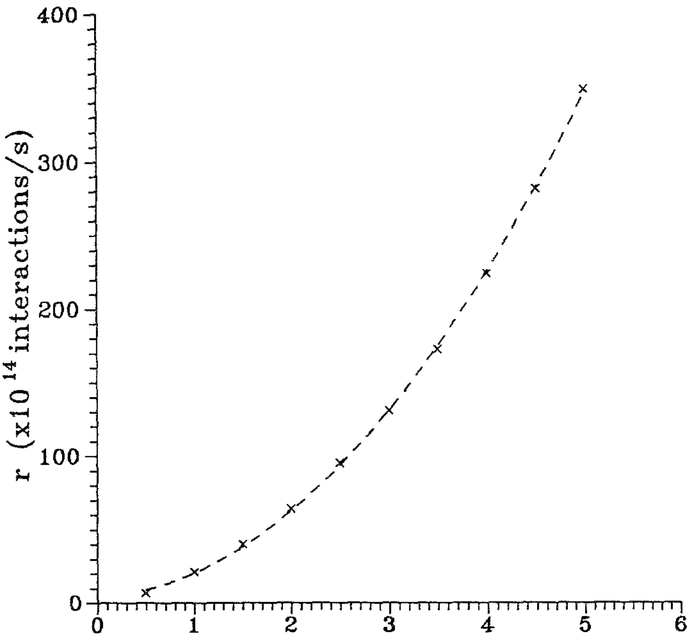

Fig. 1. The number of annihilation interactions per s, between atmospheric molecules required to evaporate the atoms of an antimatter meteor (made of iron) in 1 s, as a function of the radius R of the object. The dashed curve corresponds to a polynomial best fit of 2nd degree.

a greater production of antimatter vapours. Consequently, the life time of the antimatter fragment may become shorter, but as vapours can continually escape from the fragment's surface, the mass and consequently the radius of the antimatter fragment is obviously decreasing. Because of this mass loss, a higher rate of annihilation interactions is required, to keep the temperature of the antimatter fragment at a constant value, for otherwise the temperature of the object may be decreased and consequently the amount of the antimatter vapours may become smaller, or can be completely ceased. In the latter case the antimatter object may continue losing its mass, by the annihilation process only.

The amount of mass $\mathrm{d}m$ which can be lost from the surface of a solid object (made either of ordinary matter or antimatter) by the process of vaporization, can be calculated from the equation $\mathrm{d}m = -4\pi R^2\xi \; \mathrm{d}t$, where $\mathrm{d}t$ is the time duration, required for the mass $\mathrm{d}m$ of the antimatter object to be evaporated. Since, the mass $\mathrm{d}m = 4\pi R^2 \; \mathrm{d}R\delta$, it follows that, $\mathrm{d}t = -\delta \; \mathrm{d}R/\xi$. Hence, an antimatter fragment may be completely evaporated within a time interval, equal to $t = R\delta/\xi$. For $R = 0.01$ cm, at a constant temperature T, e.g. 1600 °K, the time interval required for the antimatter object to be completely evaporated is approximately 2 h and 16 min. Obviously, the lifetime is slightly shorter due to the mass loss by the annihilation process, added to that of the vaporization process.

4. Remarks and Discussion

As shown in Figure 1 for $\tau = 1$ s, the rate for complete evaporation of a cosmic object of radius $R = 0.01$ cm made of antimatter, occurs when $r_0 = 3.3.10^{14}$ cm^{-2} s^{-1}. A similar value was also predicted by less accurate calculations, done by earlier researchers (Naunberg and Ruderman, 1966). This would happen, if the radius of the object could be remained unchanged, but as the radius is decreasing, more and more annihilation interactions are needed to keep the temperature constant. Neglecting the latter and taking circumstances similar to meteors made of ordinary matter, moving with initial velocities of $\sim 10^6$ cm/s, it would normally cause complete evaporation of the antimatter object, at heights above 300 km. A priliminary study about the way that this can be prevented was given in previous papers (Papaelias, 1984; Papaelias, 1987) and the mechanisms reducing the annihilation cross section between antiatoms and ordinary atoms have been discussed too (Papaelias and Apostolakis, 1990). Some of these arguments are already justified by the experimental results, as stated in the above. A further discussion about this problem with more accurate calculations, will be followed (Papaelias, 1994).

5. Summary

The lifetime of an antimatter object annihilated in the Earth's atmosphere has been derived for the following two cases. (1) When the annihilation is the sole mechanism of mass loss (Papaelias, 1993) and (2) in the case in which the annihilation can be accompanied by the vaporization process. In the second case, the lifetime of an antimatter meteor is shorter by several orders of magnitude than in case in which the annihilation process could be the unique mechanism of mass loss, even when the size of the antimatter meteor is greater than in the first case.

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