Impact ionization of micro-particles at low velocities

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Obviously this is an invariant for all systems $\mathscr{I}$, and the existence of τ is trivial when looked at in this way. It was introduced as above, partly in order to show its operational character, and partly because it is seen to be apparently the nearest thing possible to Stephenson's 'primary time scale'. But it is now seen to be far more arbitrary than Stephenson implies. If we take any different particular event E' as origin, we get a different time τ', and not every event that has a real τ has a real τ', and vice versa.

(*c*) The Machian element is closely bound up with the notion of cosmic time and this we now briefly discuss.

Cosmic time

In the standard development of special relativity there is no explicit mention of any general material contents of the model. If there are such contents, and if their behaviour is not wholly chaotic, and if we still work within the postulates of special relativity, then any event can be taken to be at the origin O of an inertial frame that is related in some special way to the material. For instance, O may be moving with, say, the mean motion of the material in its vicinity; or O may be moving so that, say, the resultant radial motion of remote material is zero. So in some such sense there may be a preferred inertial frame at each event.

A particular case of this is the special relativity, or 'Milne', cosmological model. This is the case where the world-lines of all fundamental observers pass through a unique event E (the 'big-bang') and every observer sees the same picture as every other. In this case, if E is chosen to be the particular event in the definition of the time τ above, then τ is the *cosmic time* of the model. (Kermack and McCrea 1933.)

These considerations are mentioned here in order to show that it is only when we take explicit account of the material present that we may begin to single out a particular preferred primary time scale. It may indeed be natural to do this, and this may be a clue to what Stephenson calls 'Machian' relativity at the end of his paper.

However that may be, so far as the theory of special relativity itself is concerned, Stephenson's work appears to be unfortunately and entirely misleading.

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Impact ionization of micro-particles at low velocities

Abstract. Impact ionization of micrometre-size particles has been observed at velocities down to 60 m s^{-1}, where the empirical law $Q \propto m^{\alpha}v^{\beta}$ is shown to remain valid, the indices having the values $\alpha = 1$ and $\beta = 3{\cdot}4$.

The impact of micrometre-size metallic particles on a molybdenum target has been shown to produce substantial ionization at velocities as low as 60 m s^{-1}, and the law previously established by Friichtenicht (1964), Auer *et al.* (1968) and Auer and Sitte (1968),

$$Q \propto m^{\alpha} v^{\beta} \tag{1}$$

for hypervelocity (1×10^3 to 20×10^3 m s^{-1}) iron and carbon particles impacting on both refractory metal targets such as W and soft targets such as Pb, has been demonstrated to be applicable at these very low velocities (Q is the ionization charge generated, m is the particle mass, v is the particle velocity, α lies between 0·7 and 1·9, β between 2·0 and 3·4). Friichtenicht and Auer *et al.* showed that approximately equal numbers of positive ions and electrons are generated at the impact site, and this is also true to within a factor of 2 at low velocities, permitting the concept of a localized microplasma again to be adopted. Mass spectrometric analysis (Hansen 1968, Auer and Sitte 1968) has shown that the principal ion species are singly charged alkali metals, present as impurities, with some particle material ions, and it is assumed that this will also be the case at low velocities; target material has only been apparent for $v \geqslant 2 \times 10^4$ m s^{-1}.

In the present investigation, approximately spherical carbonyl iron particles having masses in the range 4×10^{-17} to 4×10^{-13} kg (diameters 0·2 to 4·4 μm) were given a positive surface charge of about 10% of the value for field ion emission by interaction with a tungsten point of diameter 70 μm held at a positive potential V_a of 3 to 17 kV, in a dust source similar to that described by Shelton *et al.* (1960), and were electrostatically accelerated through V_a to velocities in the range 60 to 1400 m s^{-1} in a vacuum environment of 2×10^{-5} torr. The velocity and charge, and hence the mass of each particle, were determined from the induced signal on a cylindrical capacitor through which it passed before impacting on an earthed molybdenum target. The target was of venetian blind construction with the slats set at 45° to the particle trajectory, permitting either component of the plasma generated to be extracted from the back of the target by a grid placed 5 mm behind the target and held at a potential of ± 1000 volts, though it was found that the extraction efficiency was constant at least in the range 100 to 2000 volts. The effect of this geometry on extraction efficiency for impacts on various parts of a slat is not known and may account for some of the scatter in the data to be presented, which is for positive ions. The extracted charge was detected by an EMI 9603/2B electron multiplier placed beyond the grid and operated at a gain (for positive ions) of $1{\cdot}8 \times 10^4$ to permit detection of the relatively small quantities of charge generated at low velocities. Interaction between the electron multiplier and photons and ions from corona discharges around the accelerating electrode, though minimized by the absence of a direct optical path between the two, gave a noise background which set the minimum detectable charge at approximately 10^2 positive ions, arriving in a pulse of about 40 μs duration (measured at a velocity of approximately 10^3 m s^{-1}). It is anticipated that improved vacuum conditions and more sophisticated design will permit a lower minimum to be achieved, enabling an ionization velocity threshold to be sought.

Figure 1 shows a graph plotting $\lg(Q/m)$ against $\lg(v)$ for positive ions from iron particles on a molybdenum target; preliminary data over a smaller velocity range for nickel, cobalt, niobium and tungsten particles on molybdenum show similar features, although under the electron microscope these latter particles are open-textured amorphus agglomerates, whilst the iron powder is comprised of compact spheres with occasional small hemispherical protruberances. A least squares fitted line gives the gradient $\beta = 3{\cdot}4$ assuming, realistically, the errors in v to be small compared with those in Q/m; the correlation coefficient is 0·91 and the limits for 95% confidence level are 0·84 and 0·92. A separate plot of m against $Qv^{3\cdot4}$ showed the most likely value of α to be 1, giving

$$Q \propto mv^{3\cdot4}.$$

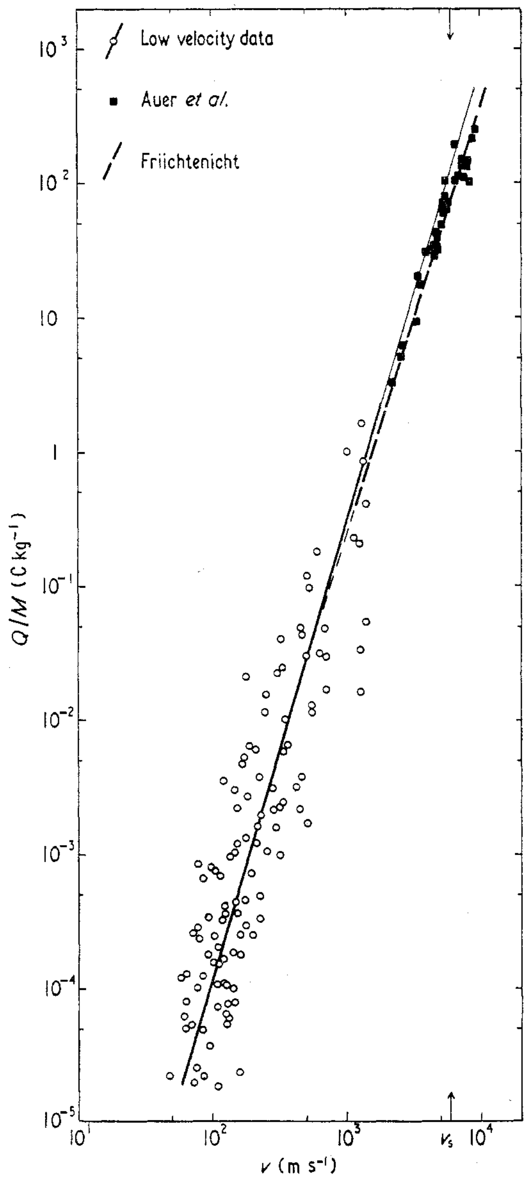

Figure 1. The dependence of Q/m (positive ions) on particle velocity v, for Fe particles on a Mo target. The data of Auer *et al.* and of Friichtenicht for Fe particles on a W target are shown for comparison. (v_s is the velocity of sound in bulk Fe.)

Extrapolation according to this result shows good agreement with the data of Auer *et al.* and Friichtenicht, demonstrating the validity of this law over the considerable range of almost 8 orders of magnitude of Q/m and $2\frac{1}{2}$ of v. It is not known at this stage whether the scatter on our points can be attributed to the statistics of low velocity impacts, or whether it is instrumental (for instance, variable ion extraction efficiency over the target, or failure of the particles to make contact with the accelerating tip so that they are not accelerated through the full value of V_a). The calculated errors in the measurement of Q/m and v of $\pm 75\%$ and $\pm 12\%$ are insufficient to account for the scatter. No correlation could be established between the plasma charge Q and the accelerating charge initially carried by the particle although at low velocities they have comparable magnitudes, and it is evident from the induced signal on the target that the accelerating charge is collected by the target a few microseconds before the impact charge is extracted for detection. The total number of charges generated will be diminished by recombination before the extraction field can penetrate the plasma, and interpretation of equation (1) in terms of projectile–target interaction without regard to the behaviour of the plasma is unlikely to be successful; it is suggested that the observed lack of appreciable variation between widely differing projectile and target materials reflects plasma rather than impact properties.

The kinetic energy of a particle with a velocity of 60 m s^{-1} would increase the particle temperature by less than 4 deg C if dispersed uniformly throughout the particle on impact without loss to the target, so it is evident that the kinetic energy of the particle must be dissipated and the plasma generated in a time very much less than $d/v_s = 5{\cdot}7 \times 10^{-10}$ s, where d is the particle diameter (3 μm) and v_s is the velocity of sound in the particle ($5{\cdot}95 \times 10^3$ m s^{-1} for bulk iron), to obtain a sufficient local energy density for ionization. The absence of any effect when $v \simeq v_s$ (figure 1) also indicates that the impact energy is localized, and the craters with depths of several particle diameters formed in massive targets at hypervelocities (Auer *et al.*) can be attributed to erosion by the plasma rather than mechanical penetration by the particle. For a 3 μm particle at 60 m s^{-1} only about $0{\cdot}2\%$ of the atoms in a particle could be involved geometrically in an impact before appreciable dissipation occurs, whilst only about $5 \times 10^{-9}\%$ are found to be ionized. The vaporization energy from 20 °C is 4·54 eV per atom for Fe and the ionization energy is 7·87 eV, so the available kinetic energy is sufficient to vaporize $3{\cdot}5 \times 10^8$ atoms, compared with 1×10^2 ions extracted from the plasma, which again suggests that the kinetic energy is destroyed almost instantaneously, increasing the potential energy of a very small volume to generate a microplasma ionized to about $3 \times 10^{-5}\%$ (neglecting excited states and recombination losses). These qualitative conclusions remain valid if the ion species are alkali metal impurities with lower ionization potentials than iron.

The interpretation of the law $Q \propto mv^3$ is rendered more difficult by its extension to $v \ll v_s$, but Friichtenicht's suggestion that $mv^2 . v$ reflects the rate of arrival of kinetic energy remains plausible, though the v term might be better interpreted as a measure of the fraction of the particle that can interact with the target before locally generated potential energy is dissipated. We are improving and extending our measurements to gain greater insight into this problem.

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Aperture of counter telescopes for parallel pairs of particles

Abstract. The difference between the aperture of a counter telescope for single particles and for pairs is explained. Expressions are given for both apertures and the significance of the difference for the interpretation of underground data is indicated.

In a study of groups of cosmic ray muons penetrating underground (Barton 1968) it was necessary to calculate the effective aperture of a telescope for parallel pairs of particles. The details of the calculation were omitted from that paper but, since the concept has given rise to some misunderstanding (Castagnoli *et al.* 1969, Bibilashvili private communication), it seems useful to explain it more clearly.

Following the notation of Stern (1960), the aperture of a counter telescope for single particles can be defined as $A_1(\rho)$, so that the counting rate R_1 for a particle intensity $I = I_0 \cos^{\rho}\theta$ is given by $R_1 = A_1(\rho)I_0$.

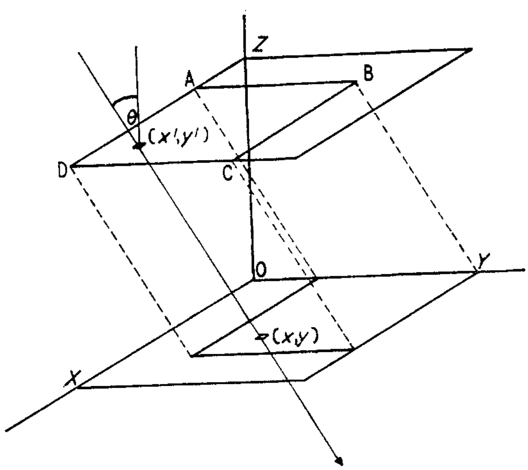

Figure 1. Telescope geometry.