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A New Method for Searching for Massive, Stable, Charged Elementary Particles*

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Abstract

I describe a new method of searching for electrically charged and stable elementary particles with masses larger than about 10^{13} GeV/c^2. This method is based on measuring the terminal velocity of uniform radius liquid drops falling in air. The range of this search method and concomitant imponderables are discussed.

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I. INTRODUCTION

In this paper I describe a new method of searching for electrically charged and stable elementary particles with masses larger than about 10^{13} GeV/c^2. Such particles would have to have been created during the early history of the universe and would have to be sufficiently abundant so that there was of order one such particle in 0.01 to 0.1 grams of certain bulk materials. The search method consists of measuring the terminal velocity of liquid drops falling in air, the drops having been produced with uniform radius and containing the materials being investigated. The method occurred to me because of the current searches for particles with fractional electric charge[1,2] being carried out by my colleagues, Valerie Halyo, Eric Lee, Irwin Lee, Dinesh Loomba, and myself at the Stanford Linear Accelerator Center.

The motivation for this method of searching for massive particles is that accelerators, either under construction or projected, limit produced elementary particle masses and hence searches to below about 5×10^3 GeV/c^2 mass. Even search experiments at a 100 TeV proton-proton collider would be limited to below 5×10^4 GeV/c^2 mass. On the other hand we do not know the equations that set the masses of most of the known particles and we do not know if there is any upper limit on the mass that a particle may possess. Therefore even with the limitations of this new method, particularly the requirement that the particle be stable, it is worthwhile to search for particles with masses far beyond the reach of current or projected accelerators.

II. SEARCH METHOD

The principle of the search method is simple. Consider a spherical liquid drop of radius r, density ρ, mass m, falling under the influence of gravity through a gas, usually air, of viscosity η. According to Stoke's law the *terminal* velocity v is given by

$$v = \frac{mg}{6\pi\eta r} \quad . \tag{1}$$

The measurement of the terminal velocity v and the relation $m = 4\pi\rho r^3/3$ gives m and r. In this search method we produce a very large number of liquid drops of uniform radius r, hence uniform mass m, and hence uniform terminal velocity v. I denote this velocity by $v(m)$.

Next suppose that a few of the drops of radius r contain an elementary particle of mass M, then the terminal velocity for those drops would be

$$v(m+M) = \frac{(m+M)g}{6\pi\eta r} \quad . \tag{2}$$

Figure 1, an illustrative plot of number of drops N versus v, shows what we hope to see: a very large peak in N at $v(m)$, and a relatively very small peak at $v(m+M)$. Note the search method does not directly make use of the massive particle's electric charge; as explained at the end of this paper, charge is required for the particle to be bound in the drop.

I will show that when M is the same magnitude as m or larger, we will be able to clearly distinguish $v(m+M)$ from $v(m)$, and hence give evidence for the existence of a particle of mass M. The method depends upon producing drops of uniform r, called r_{normal}, and of being able to demonstrate that the rare $v(m+M)$ signal is not caused by rare drops with anomalously large r and hence anomalously large m. The sensitivity of the method depends upon the tails of the $v(m)$ not overwhelming the $v(m+M)$ peak. Before taking up these points I will briefly describe the apparatus.

The measurement of v will be obtained using the apparatus shown schematically in Fig. 2, an apparatus similar to the ones we use in our fractional electric charge searches.[1,2] Liquid drops are produced using an annular piezoelectric transducer disk to squeeze a cylinder containing the liquid, ejecting the drop through a small hole in an aperture plate as described in Refs. 1 and 2. The radius r of the drop is set by the radius of the hole in the aperture plate and by the amplitude and shape of the voltage pulse applied to the piezoelectric transducer. We have made drops with r as small as 3 μm and as large as 25 μm by using different hole radii and different amplitude and shape voltage pulses. Other methods of producing liquid drops of such small radii may also be used.

The measurement of the terminal velocity v is made using the apparatus in Fig. 2. A light source flashing every Δt s, either a stroboscopic lamp or an array of LED's, produces a periodic image through a lens onto the faceplate of a CCD camera with discreet picture elements. These periodic images of the falling drop are processed through a video frame grabber in a desktop computer, the centroid of the drop being determined. If two successive images give the drop centroid at vertical positions z_n and z_{n+1}, then $v_n=(z_n - z_{n+1})/\Delta t$. Four or more measurements are made of v_n as the drop falls and their average gives v for that drop.

The liquid drops to be used in these searches will consist of a silicone oil base carrying finely powdered minerals or metals as colloids or sediments. I believe the best materials for the search are those that have not undergone geochemical changes or refining processes: meteorites, the insides of old rocks, perhaps samples from the moon's surface. If the particle has fractional electric charges the arguments of Lackner and Zweig[3] reinforce this belief.

The amount of material examined in a search is given by $mxfT$ where x is the fraction of m constituting the material of interest, meteorite for example, f is the drop production frequency in Hz, and T is the search time period in s. As an example consider a drop with 5 μm radius and x=.3; and suppose 0.1 gram of the material is to be studied. Using 0.9 for the specific gravity of silicone oil, this requires $fT\approx 10^9$ drops. As the experimental technique progresses we expect to attain $f\approx 100$ Hz, hence $T\approx 10^7$ s would be sufficient. The use of larger drops, a 10 μm radius for example, substantially increases the amount of material studied per unit time. However as discussed in Sec. IV, the size of the drop affects the lower limit of the M search range.

III. SENSITIVITY OF SEARCH METHOD

I now turn to the questions of (a) the uniformity of $v(m)$ of the drops produced by the described apparatus, and (b) the shape of the distribution of $v(m)$, particularly the behavior of the tails of the distribution. In our first fractional electric charge search experiment[1] we studied about 6×10^6 drops with an average r of about 3.5 μm and a $v(m)$ of about 0.14 cm/s. We found that the distribution of $v(m)$ was gaussian with a root mean square $\sigma_v \approx 0.01\ v(m)$, once we had properly set the amplitude and shape of the voltage pulse on the piezoelectric transducer and some other parameters of the drop generator. In particular the tails of the distribution were gaussian.

In the proposed massive particle search experiments we expect to study at least $N=10^8$ drops and perhaps as much as $N=10^{10}$ drops. If all the drops contain only ordinary matter we will see only the large peak in Fig. 1. Consider a $v(m)$ peak with 10^9 drop peak centered on $v(m)_{\text{average}}$. If the tails are still gaussian then there will be on the average only 1 normal radius and mass drop with $v > 1.07\ v(m)_{\text{average}}$. Of course we do not know if the distribution of $v(m)$ will continue to be gaussian at the tails when the numbers of drops exceeds 10^7. That is something we have to find out by experiment. Assuming such gaussian tails we would certainly notice the $v(m+M)$ peak if $v(m+M)$ were larger than about 1.1 $v(m)$. This inequality means that M would have to larger than 0.1 m.

But what about the possibility that the drop generator occasionally produces an anomalous drop of some other radius $r_{anom} > r_{normal}$. Since

$$v = \frac{2g\rho r^2}{9\eta}$$

we would measure a larger v. Then if we assumed that $r = r_{normal}$, we would be led to an indication that these drops contained a massive particle. This false signal would be very dangerous if drops with r_{anom} all had almost equal r_{anom} 's.

Therefore we must use an independent measurement of the drop radius. This second measurement, called r_i , is obtained using the size of image of the drop on the CCD camera. The measurement precision of r_i depends upon the size of the CCD picture elements, the method used to calculate r_i from the picture element signals, and the electronic noise. I calculate that with proper design of the imaging system the measurement of r_i has a *maximum* upper limit of 1.2 r_{normal}. If an anomalously large drop has more than twice the mass of a standard drop, r_i will be larger than 1.26 r_{normal} . Therefore as long as the search is restricted to $M+m > 2m$ the search is not compromised by the production of anomalously large drops.

The rate at which drops with different values of r_{anom} are produced sets the lower limit on the sensitivity of this search method in terms of massive particles per gram of examined matter. If the uniformity of drop radii obtained in our earlier experiment[1] is maintained with larger numbers of drops, I believe a $\nu(m+M)$ peak containing 10 or more drops would warrant further investigation. Hence if we study 0.01 grams or 0.1 grams or 1 gram of a particular material, the respective sensitivities are 1000 or 100 or 10 massive particles per gram.

IV. RANGE OF SEARCH METHOD AND CONCOMITANT IMPONDERABLES

This requirement $M > m$ and the present technical lower limit on r_{normal} fix the lower limit on M. At present the smallest drops we ordinarily use have r_{normal} = 3 μm. The maximum specific gravity of the drops will be about 1.4, hence these drops have a mass of 1.6×10^{-13} kg, in elementary particle units 0.9×10^{14} GeV/c^2. We can probably reliably produce drops with r_{normal} = 2 μm, giving a lower limit on M of about 10^{13} GeV/c^2. I do not see how to extend this method to yet smaller drops: it may be difficult to make such drops reliably, it will be difficult to get reliable measurements of r_i, and it will be difficult to search through large amounts of material.

The upper limit on M comes from necessity in this search method of the massive particle remaining bound in ordinary matter while in the earth's gravitational field. There must exist a binding force, F_b, between the particle and the drop's ordinary matter so that F_b is larger than the gravitational force on the particle Mg. The straightforward binding mechanism is electric charge. To estimate F_b, I suppose (a) the massive particle has an electric charge e, where e is the electron charge, (b) the binding energy to the ordinary matter is about 1 eV, and (c) F_b extends over about 10^{-10} m. Then F_b is about 1.6×10^{-9} nt, and M must be less than $F_b/g \approx 1.6 \times 10^{-10}$ kg $\approx 10^{17}$ GeV/c^2.

Hence this proposed search for massive stable particles with electric charge could extend from 10^{13} to 10^{17} GeV/c^2. There is certainly some optimism in the calculation of these limits. The lower limit might not be quite so low if it proves to be difficult to use drops of less than 3 μm radius. The upper limit might not be quite so high if the particle has fractional electric charge or I have been too generous in estimating the strength of F_b.

I don't see a way to apply this method to a neutral massive particle unless it is a magnetic monopole, the magnetic force producing F_b , or unless the particle carries a new type of force producing F_b. With respect to the existence of a magnetic monopole the search method of this paper would be less sensitive than completed searches.[4] With respect to a new type of force, I have learned in forty years of experiments that hoping for one miracle, such as a new massive particle, adds spice to the research. But hoping for two miracles, a new particle and a new force, is not wise.

There are obvious imponderables in this search method: the existence of massive stable charged particles in the mass range of 10^{13} to 10^{17} GeV/c^2; the uncertainty as to whether such particles exist in sufficient concentration in the materials that are accessible to examination; and the upper limit on the mass range discussed in the previous section. In view of the first two imponderables the reader may ask why my colleagues and I are pursuing this research, what is our motivation?.

Our motivation is twofold. First, in spite of elaborate and beautiful hypotheses about the mass spectrum of the elementary particles, supersymmetric particle theory and some variants of string theory for example, we have no experimental proof of the reality of these proposals, hence they remain hypotheses however beautiful they may be. Experimenters, driven by their curiosity, and by their responsibilities, have no choice but to search for more massive particles either by conventional means using accelerators or by unconventional means such as this search method.

The second motivation is well known to experimenters but has only occasionally been described in print. It is the intellectual pleasure of the experimental technique itself.[5,6] In this search method we have the pleasure of learning about, inventing, and using techniques and technology involving particle physics, fluid mechanics, microfabrication, machine vision, high rate data acquisition and manipulation, colloid chemistry, and even the arcane field of grinding and pulverizing.

V. ACKNOWLEDGMENTS

I am greatly indebted to my companion in research, Eric Lee, who has invented, designed and developed much of the experimental equipment we use in our searches for particles with fractional electric charge, that equipment forming the basis for the massive particle searches proposed in this paper. I am grateful to Dinesh Loomba for reading this manuscript and for numerous very helpful discussions. I also thank Valerie Halyo, Irwin Lee, and Gordon Shaw for stimulating discussions.

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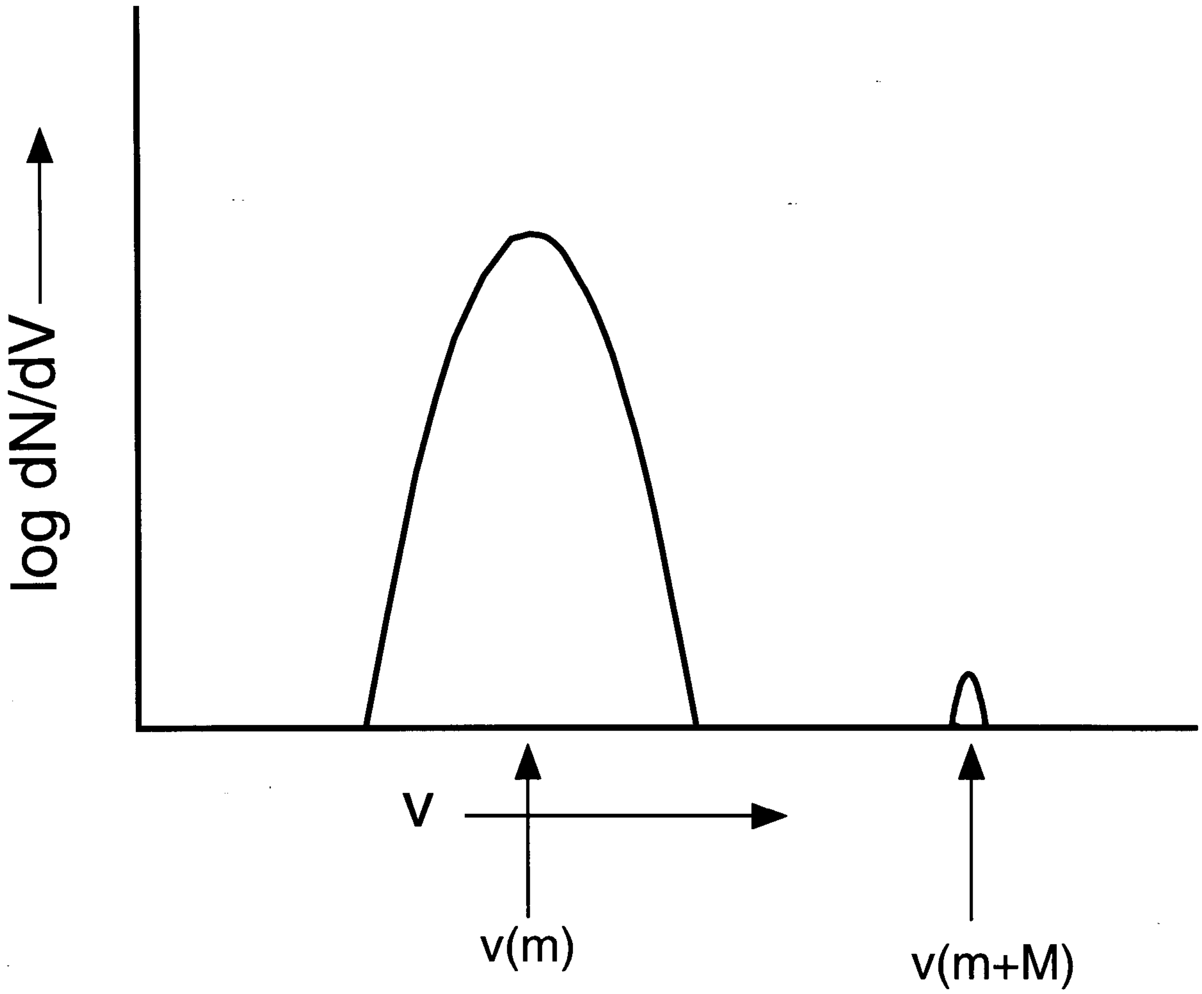

Fig. 1. Illustrative plot of number of drops N versus v, the terminal velocity, shows what we hope to see if some drops contain a massive particle of mass M : a very large peak at $v(m)$, and a relatively very small peak at $v(m+M)$. The mass of the drop is m.

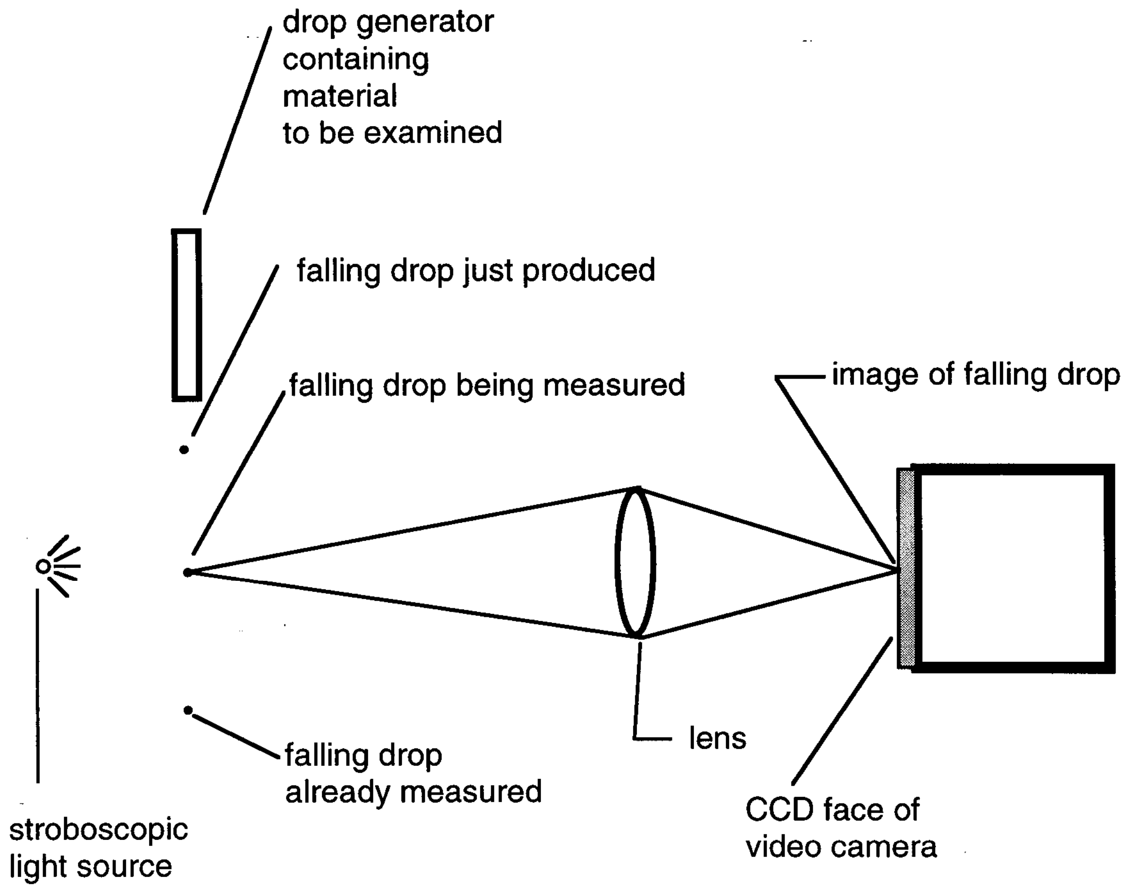

Fig. 2. Schematic of the apparatus. Liquid drops containing the material being examined for the presence of massive elementary particles are produced with uniform radii using a piezoelectric drop generator. The drop radius can be controlled to be as small as 3 μm and as large as 25 μm. The terminal velocities of the drops falling through air are measured using a periodically flashing light source that produces an image through a lens onto the faceplate of a CCD camera. These periodic images of the falling drop are processed through a video frame grabber in a desktop computer, the vertical position of the drop being determined as a function of time. Multiple measurements are made of the terminal velocity as the drop falls.