Mass dependence of searches for fractional charge in matter using ion-beam techniques

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If free quarks or other fractionally charged particles can exist, they should be present as a low primordial or cosmic-ray-produced concentration in terrestrial matter. The most sensitive searches have been dependent on the detection of anomalous ions by silicon-barrier or electron-multiplier detection systems, in which the dependence of energy transfer on ion velocity results in a decrease of detection efficiency with increasing mass, leading to a cutoff in observable particle mass for a given accelerating voltage. The factors governing this mass dependence are discussed, with illustrative calculations for a number of typical experiments. It is shown that the reported concentration limits are valid up to typically 10—100 proton masses for anomalous particles either in the free state or attached to low-Z atoms, but with lower sensitivity and reduced mass limits if bound to heavier atoms. The prospects for improving mass limits in future fractional charge searches are discussed. It is concluded that the detectable mass range could in principle be extended by several orders of magnitude in this type of experiment, and that in the case of positive ions of sufficiently high electron affinity the "potential mechanism" of electron ejection might provide a basis for fully mass-independent detection (although at the expense of a direct fractional-charge signature). The problem of pre-enrichment of the sample material is also considered, and a general method of estimating the mass dependence of electrical extraction techniques is given.

I. INTRODUCTION

The success of the quark model of hadrons continues to focus attention on the problem of fractional electric charge. The failure to produce free quarks at current accelerator energies has led to the conjecture that they may exist only in the confined state, in combinations of integral total charge. Nevertheless, since the bound quark charges are in units of $e/3$, it remains possible that at some level of substructure or energy it may be possible to create new types of free particles (e.g., isolated quarks, quark matter, quark or lepton subconstituents, etc.) which possess fractional electric-charge values.

Searches for fractionally charged particles in terrestrial matter are based on the fact that at least one of any such particles would be absolutely stable, and may therefore exist (probably in combination with electrons or atomic nuclei) as a natural abundance of one or both of the following types:[1–7] (a) a small primordial or cosmic-ray-produced concentration in at least one of the common terrestrial materials (water, air, rocks); (b) a geochemically concentrated abundance associated with specific elements having a chemical or crystallographic similarity with, or affinity for, the anomalous atoms.

The most sensitive matter searches so far reported have been based on the extraction of any anomalous ions from the material under investigation and their subsequent acceleration on to silicon-barrier or electron-multiplier detection systems. In these, the detection efficiency decreases with increasing particle mass (decreasing particle velocity), the signal eventually falling below background to give an effective cutoff in observable mass at typically $10—10^2$ proton masses. However, it is now apparent that the mass scales associated with new particles may be very much higher than this—up to even the "grand unification" mass level[8] $\sim 10^{15}$ GeV—and that new-particle searches must thus attempt to cover a much wider mass range. The purpose of this paper is to discuss the factors which limit the detectable mass in ion-beam experiments for different types of fractionally charged ion (including the effect of attachment to high-Z nuclei) with illustrative calculations for the most sensitive published experiments, and to assess the possibilities for future improvements in the mass range of this type of experiment.

General principles leading to approximate mass limits for electron release in a detector are discussed in Sec. II, together with a summary of the principal fractional-charge searches using ion beams. In Sec. III, the mass dependence of experiments based on detection with an electron multiplier is discussed in more detail. There are two principal mechanisms for electron release: "kinetic" ejection (which is mass dependent) and "potential" ejection (which is mass independent). With the aid of values of electron affinity for fractionally charged atoms estimated by Lackner and Zweig[6] we show that the latter mechanism, although not applicable to previous experiments, could make possible mass-independent detection of a significant proportion of possible fractionally charged atoms. In Sec. IV, the mass dependence of experiments based on silicon-barrier detectors is considered. For these, two types of mass limits are calculated: an ultimate limit set by the detector noise, and the reduced-mass range achieved by restricting the search specifically to the energy region appropriate to $\frac{1}{3}$ or $\frac{2}{3}$ the accelerating voltage (as a signature for fractional charge).

Our illustrative calculations show that past searches for fractional charge in ion beams have, in general, been sensitive to anomalous-particle masses up to $10—10^2$ GeV, sometimes extending to 10^3 GeV at reduced sensitivity. However, there is a significant dependence on the type of ion assumed, and in some cases fractionally charged particles attached to high-Z nuclei would not have been observed. We show that experiments designed to operate down to the detector noise limits could reach masses in the region 10^4 GeV for an accelerating voltage $V=10^6$ V (increasing essentially linearly with V), but it would be difficult to improve significantly on this except in the case of ions with an electron affinity high enough for the potential electron ejection mechanism to be applicable.

The investigation of low-concentration levels in this type of experiment may require also the collection of ions from a large volume of source material, and their concentration on to a small test sample (e.g., an ion-source filament). In Sec. V this process is analyzed by means of a simple model which enables general estimates to be made of the dependence of collection efficiency on particle mass and processing rate, assuming the use of extraction methods based entirely on the interaction of electric fields with the hypothetical fractional charge. An additional factor, the probability of release of the anomalous ions from the source filament, is not discussed in this paper.

The principal alternative method of detecting fractionally charged particles, based on the direct measurement of residual electric charge on small isolated (e.g., levitated) samples of bulk matter, is independent of particle mass, but so far relatively small quantities of material have been investigated in this way—of order 10^{-6} to 10^{-3} g for water,[7,9] oil,[4] mercury,[10] carbon,[11] iron,[11,12] and niobium.[13,14] These are thus relevant to abundances of type (b) above, but have not yet explored the quantities necessary to test for abundances of type (a), i.e., typically 1—10 g or more, assuming the upper limit for anomalous particle production in cosmic rays,[15] with the resulting ions accumulated in the sea during the lifetime of the earth. However, in combination with electrical concentration procedures it may be possible to apply the levitation technique to reach these much lower concentration levels, and, in view of the mass limitations of ion-beam searches discussed in this paper, this would appear to be a more satisfactory strategy for future searches for fractionally charged particles.

II. GENERAL PRINCIPLES AND APPROXIMATE MASS LIMITS

The experimental searches which we consider are those based on the detection of rare charged particles by concentration and capture on to a small filament, followed by heating of the filament and acceleration of the emitted ions by a voltage V on to either an electron-multiplier or silicon-barrier detector. For convenience, we refer to the fractionally charged particles, either free or combined with electrons or atoms, as Q-ions, the total ion mass being denoted by M_Q.

For illustration, the techniques used in the most sensitive searches of this type are summarized in Table I, the first two[5,16] being searches in common terrestrial (and lunar) materials, the second two[17,18] being specific searches in niobium and other metals, stimulated by the apparent positive result reported by the Stanford group.[13]

One type of experiment (A in Table I) used an electron multiplier as a detector, which provides a high sensitivity through the observation of single electrons released from a detecting surface, but gives no direct information regarding the charge of the incident ion. The other group of experiments (B in Table I) used silicon-barrier detectors, requiring the excitation of several thousand electrons and therefore of lower inherent sensitivity, but having the advantage that they register the energy deposited and would thus provide an identifying signal $\frac{1}{3}Ve$ or $\frac{2}{3}Ve$ for fractionally charged ions.

In both cases, increasing M_Q—and hence decreasing velocity for a given V—decreases the energy transfer to the electrons, leading to an eventual cutoff mass above which the Q-ion would not be registered by the detector. The approximate mass ranges for which this would hap-

TABLE I. Summary of detection techniques used in ion beam Q-ion searches.

	Authors	Accelerating voltage V (kV)	Detector	Technique	Material	C_0 Q-ions/g
A	Chupka *et al.* (Ref. 5)	+15	Electron multiplier	Preconcentration on to filament. Search for abnormal negative-ion emission from heated filament	Sea water Air Meteorites Sediment Lunar rock	1 10^{-6} 10^7 10^3 10^2
B1	Cook *et al.* (Ref. 16)	+50	Silicon barrier	Preconcentration on to filament. Search for negative ions of anomalous Ve from heated filament.	Sea water Rocks	1 10
B2	Schiffer *et al.* (Ref. 17)	−1000	Silicon barrier	Direct heating of sample. Search for positive ions of energy $\frac{1}{3}Ve$	Niobium Tungsten Iron	10^3
B3	Kutschera *et al.* (Ref. 18)	−700	Silicon barrier	Direct heating of sample Search for positive ions of energy $\frac{1}{3}Ve$ or $\frac{2}{3}Ve$	Niobium	10^2

pen will be calculated in Secs. III and IV for each class of experiment and for various possible types of Q-ion. Note that, in the case of the silicon detectors, there may be a substantial difference between the limiting mass which results from a restriction of the search to kinetic energies in the vicinity of $\frac{1}{3}Ve$ or $\frac{2}{3}Ve$, and the higher limiting masses which would be observable if the charge signature were sacrificed and anomalous signals investigated at all energies down to the typical 10-keV detector noise level.

Both detection techniques depend on the observation of electrons promoted across an energy gap by energy transfer from the accelerated ions, and a general indication of mass limits can be obtained from simple kinematic considerations: if we suppose the target electrons to be free, and the Q-ion mass $M_Q \gg m_e$ (electron mass), then the maximum energy transfer in a (nonrelativistic) quark-electron collision is

$$\hat{E} \simeq 2m_e v_Q(v_Q+v_e) , \tag{1}$$

where v_Q, v_e are the velocities of the quark ion and the electron.

For v_Q below some threshold velocity v_0, $\hat{E} < E_g$ (the gap energy) and excitation cannot occur. From (1) we would have

$$\begin{aligned} v_0 &\simeq \tfrac{1}{2}[(v_e{}^2+2E_g/m_e)^{1/2}-v_e] \\ &\simeq [(E_e+E_g)^{1/2}-E_e{}^{1/2}]/(2m_e)^{1/2} . \end{aligned} \tag{2}$$

For typical ranges of Fermi kinetic energy (5—10 eV) and work function or energy gap (1—4 eV), (2) suggests values of v_0 in the region $(\frac{1}{2}-2)\times 10^7$ cm s^{-1}. Thus for quark ions of charge q, accelerated by a voltage V to a velocity $v_Q=(2qV/M_Q)^{1/2}$, the requirement $v_Q \ge v_0$ gives a detectable mass limit

$$M_Q \le M_L \simeq L(q/e)V , \tag{3}$$

where M_Q, M_L are in GeV, V is in kV, and L is a constant in the approximate range

$$5 < L < 50 . \tag{4}$$

III. MASS DEPENDENCE OF ELECTRON-MULTIPLIER DETECTORS

A more detailed assessment of the effect of ion mass on detection efficiency can be based on the results of a number of theoretical and experimental studies of secondary electron emission as a function of incident ion velocity.[19–21] These indicate two distinct mechanisms for electron ejection: kinetic ejection, where the required energy is provided by the kinetic energy of the incident ion, as assumed in Sec. II; and potential ejection, where the required energy is obtained from the electron affinity of the incident ion—and is, therefore, independent of its velocity and mass.

Parilis and Kishinevskii[20] proposed a model in which kinetic ejection is dominated by Auger processes involving bound electrons rather than the direct ejection of quasifree electrons. More recently, however, Baragiola *et al.*[21] have obtained better agreement with experiment using essentially the simple model of Sec. II. Both models agree on three main features which are broadly confirmed by experimental results: the existence (and approximate magnitude) of a threshold velocity v_0; a linear increase of electron yield with ion energy near this threshold; and a linear increase in yield with velocity well above threshold.

Experimentally determined threshold velocities range from about 3×10^6 cm s^{-1} to $> 10^7$ cm s^{-1}, which correspond to mass limits given by (3) with (for various ion/target combinations)

$$10 < L < 200 . \tag{5}$$

This rather wide range arises partly from experimental uncertainties and partly from the dependence of v_0 on incident and target nuclear charges Z_1 and Z_2. Parilis and Kishinevskii obtain an approximately constant value for v_0 [$(6–7)\times 10^6$ cm s^{-1}] for $\frac{1}{4} \le Z_1/Z_2 \le 4$; as Z_1 and Z_2 figure symmetrically in their model, one would expect any Z dependence of v_0 at more extreme values of Z_1/Z_2 to be essentially symmetrical about $Z_1/Z_2=1$, though for Z_1 or Z_2 small the underlying Thomas-Fermi statistical assumptions break down. Baragiola *et al.* expect v_0 to decrease with increasing Z_1. The majority of experimental data is for $Z_1/Z_2 < 1$, with the lower values of v_0 (larger L) obtained for $Z_1 \sim Z_2$, and higher values of v_0 (smaller L) for dissimilar Z, consistent with either of the above models. We use this approximate trend to indicate in Table II the resulting mass limits for low-Z Q-ions (bare Q or $Q+e$) and for typical ($Q+$ atom) ions.

M_L is, of course, the mass at which the detection probability becomes zero; for masses below M_L the detection probability is essentially the same as the electron yield γ (for $\gamma < 1$). From experimental data summarized in Ref.

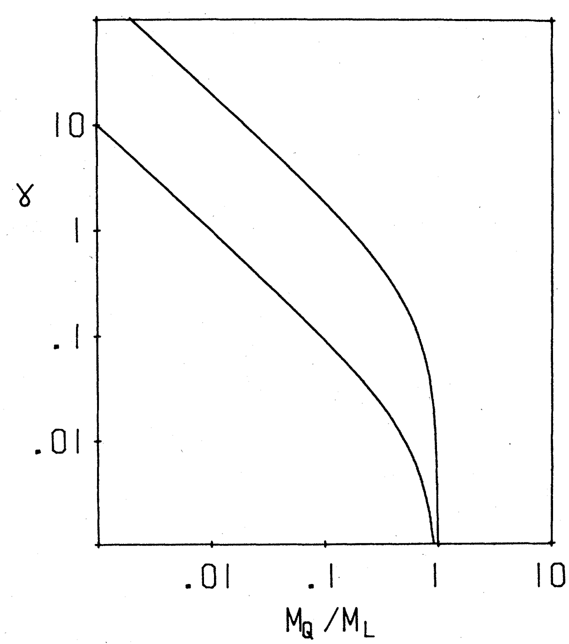

FIG. 1. Expected dependence of electron yield γ on total ion mass for kinetic ejection. The approximate lower and upper limits are based on experimental data for a range of normal ions on various surface materials.

TABLE II. Variation of detection sensitivity with anomalous particle mass for experiment type A of Table I (electron-multiplier detection). Q denotes fractionally charged particle, $Q+e\equiv$positive $Q+$ bound electron, $Q+A\equiv$atomic ion containing positive or negative Q bound to nucleus of charge Ze.

Accelerating voltage (kv)	Type of anomalous ion		Total Q-ion mass (nucleon masses) for relative detection efficiency γ and total (negative-ion) charge $-q$. $\gamma\simeq1$	$\gamma\simeq0.1$	$\gamma=0$ (cutoff)
$+15$	Negative ions	Q or $Q+e$	$(10-40)q$	$(60-240)q$	$(300-1200)q$
		$Q+A$	$(20-80)q$	$(120-480)q$	$(600-2400)q$

19 together with the theoretical energy dependence of γ we find, approximately,

$$\gamma=C_\gamma(M_L/M_Q-1)/\cos\alpha\ , \tag{6}$$

where α is the angle of incidence of the ion trajectory, and C_γ is a constant which depends on the incident ions and surface material.

Observed values for C_γ are in the range 0.01—0.2, and the resulting variation of γ with M_Q/M_L, given by (6), is shown in Fig. 1 (for $\cos\alpha=1$). Since there appears to be no consistent dependence of C_γ on Z_1 and Z_2, we use the mean of the experimental range to arrive at the likely variation of sensitivity with mass shown in Table II.

In contrast to the kinetic mechanism, the potential mechanism for electron ejection results from a distortion of the atomic potential as the ion approaches the surface. It is thus effective even at low incident velocities, and hence independent of M_Q, but does require that $E_a-2\phi\gtrsim0$, where E_a is the electron affinity of the incident ion and ϕ is the work function of the target surface. This condition immediately rules out the potential mechanism for the negatively charged Q-ions sought in experiment A of Table I, since these will, in general, have negative values of E_a.[6]

More generally, the prospects for the mass-independent detection of heavy positive ions can be assessed from the discussions of potential ejection by Kishinevskii[22] and Baragiola *et al.*,[21] who find that the yield dependence on E_a can be fitted by expressions of the form $\gamma\propto(0.8E_a-2\phi)$. Thus useful detection efficiencies might be achieved for $E_a>2.5\phi$; for selected materials, ϕ could be as low as 2—2.5 eV, so that electron affinities greater than about 5—6 eV are needed. The significance of this is shown in Table III, where we summarize the calculations of E_a by Lackner and Zweig[6] for elements with fractional charge added to the nucleus. The four cases tabulated correspond to atoms with modified nuclear charges $Z\pm\frac{1}{3}$, $Z\pm\frac{2}{3}$, together with an appropriate number of atomic electrons to give an overall positive charge $+\frac{1}{3}$ or $+\frac{2}{3}$. We see that for the case of an overall charge $+\frac{1}{3}$ only a few elements would have a sufficiently large E_a, but for overall charge $+\frac{2}{3}$ about 30—40% of the periodic table would be expected to have $E_a>5$—6 eV, including many of the more common elements such as carbon, nitrogen, and oxygen. Thus this mechanism may justify further study as a possible means of detecting some of the likely fractional-charge combinations in a mass-independent way. Of course, in all cases there is the option of increasing E_a by multiple ionization, but the need to discriminate against the increased background of normal ions then becomes a significant (although not insoluble) problem.

IV. MASS DEPENDENCE OF SILICON-BARRIER DETECTORS

We consider now experiments of the type B in Table I, which were based on the use of solid-state (silicon-barrier) detectors. In this case E_g is the energy gap between

TABLE III. Distribution of electron affinities in the periodic table, for fractionally charged atoms or ions of overall charge $+\frac{1}{3}$ or $+\frac{2}{3}$. The figures are taken from the tables of Lackner and Zweig (Ref. 6), using their interpolated value of electron affinity E_a or ionization potential E_i as indicated.

Charge: Nucleus	Atomic electrons	Total	Electron affinity obtained from	Number of elements with electron affinity (eV) exceeding: 1	2	3	4	5	6	7	8	9	10
$Z+\frac{1}{3}$	$-Z$	$+\frac{1}{3}$	E_a for $Z+\frac{1}{3}$	85	73	27	14	8	3	2	1		
$Z-\frac{2}{3}$	$-(Z-1)$	$+\frac{1}{3}$	E_i for $Z-\frac{2}{3}$										
$Z+\frac{2}{3}$	$-Z$	$+\frac{2}{3}$	E_a for $Z+\frac{2}{3}$	92	92	85	68	36	23	13	9	6	4
$Z-\frac{1}{3}$	$-(Z-1)$	$+\frac{2}{3}$	E_i for $Z-\frac{1}{3}$										

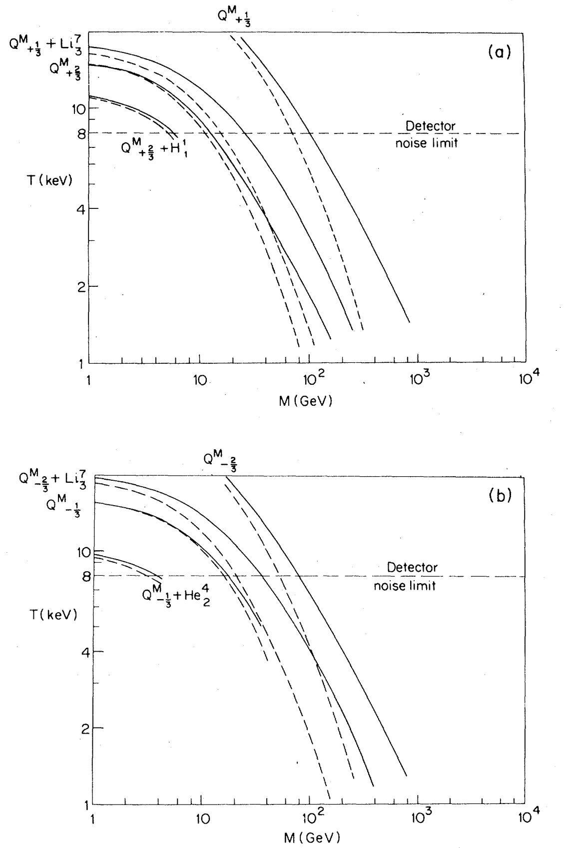

FIG. 2. Energy loss to electrons in Si detector as a function of anomalous mass M for experiment B1 of Table I [Cook *et al.* (Ref. 16); negative ions; accelerating potential + 50 kV] for (a) positively charged and (b) negatively charged Q-ions. (Incident ion denoted by $Q_q^M + E_Z^A$, where E_Z^A is the host atom and q is the fractional charge of Q.)

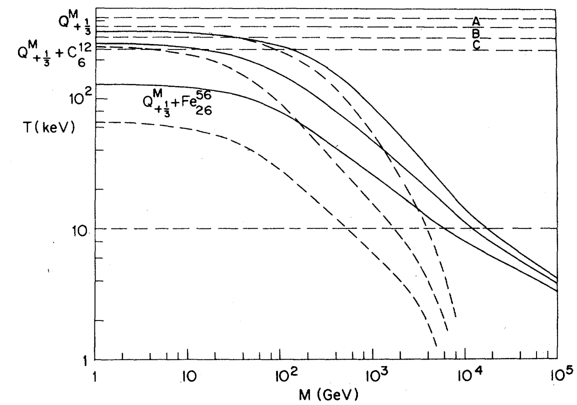

FIG. 3. Energy loss to electrons in Si detector as a function of mass M for experiment B2 of Table I [Schiffer *et al.* (Ref. 17); positive ions; accelerating potential + 1 MV]. Notation as Fig. 2. The three energy intervals for which count values are recorded in Ref. 17 (0.36—0.42, 0.30—0.36, and 0.24—0.30 MeV) are indicated by A, B, and C. Also shown is a hypothetical 10-keV noise limit.

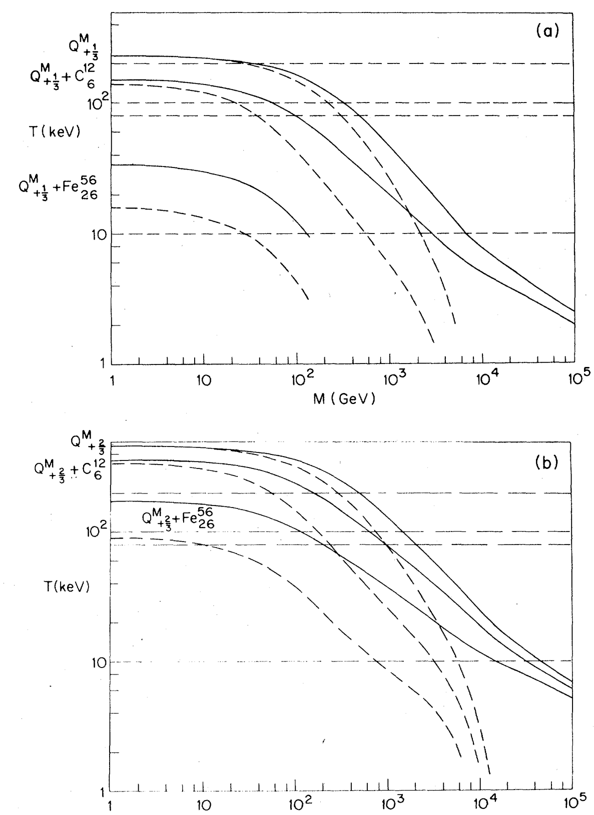

FIG. 4. Energy loss to electrons in Si detector as a function of mass M for experiment B3 of Table I [Kutschera *et al.* (Ref. 18); positive ions; accelerating potential + 700 kV] for Q charge (a) $+\frac{1}{3}$; (b) $+\frac{2}{3}$. Notation as Fig. 2. The horizontal lines at 200, 100, and 80 keV (experimental cut-off) indicate the assumed energies corresponding to $\gamma = 1$, 0.1, and 0 in Table IV. Also shown is a hypothetical 10-keV noise limit.

valence and conduction bands (1.1 eV for silicon) so that the threshold velocity v_0 might be expected to be rather lower (and hence M_L rather higher) than in the previous case. However, whereas an electron multiplier can detect the emission of a single electron (with the background problem essentially that of discriminating against normal ions) the solid-state detectors require the excitation of several thousand electrons to produce a voltage pulse (proportional to the total excitation energy) above their background electrical noise. Moreover, two of the experiments (B2 and B3) looked specifically for particles whose energy deposition was in the region of $\frac{1}{3}$ or $\frac{2}{3}$ of the energy of singly charged ions. This further restricts the detectable mass range since, as the particle velocity decreases, an increasing proportion of the energy is lost by elastic recoil of the target nuclei rather than by electron excitation. We use the standard theory of energy loss by slow ions[23] to estimate the observed energy deposition (i.e., that fraction of the energy lost in electron excitation) as a function of M ($= M_Q - A$, the extra mass of the atom). Details are given in the Appendix, and the results are summarized in Figs. 2—4, taking as examples each of the accelerating voltages used in the silicon detector experiments listed in Table I.

For each accelerating voltage, the measured electron excitation energy E_m has been estimated in two alternative ways: (a) a lower limit obtained by calculating the total energy lost in electron-electron collisions for which the energy transfer exceeds the 1.1-eV energy gap; and (b) an upper limit obtained by adding to (a) energy transfers >1.1 eV to electrons by recoil Si nuclei (assumed quasi-free).

These two energy limits are computed as a function of M for several types of possible Q-ion (bare Q, $Q+$ electron, $Q+$ atom) and used to obtain the limiting mass ranges listed in Table IV. Two types of mass limit are shown: (1) the mass M_f for which the excitation-energy E_m is within about 10% of the expected fractional-charge value E_f, i.e., $\frac{1}{3}$ or $\frac{2}{3}$ of the full energy Ve for singly-charged ions; and (2) an ultimate limiting mass M_n for which E_m would fall below the inherent noise level E_n of the detector (of order 10 keV).

Mass limit (2) is, in general, more difficult to achieve since it involves the identification and exclusion of all anomalous signals in the range $E_n < E_m < E_f$. Of the experiments in Table IV, limit (2) applies to the lower-energy experiment B1, while limit (1) applies to the higher-energy experiments B2 and B3 which investigated principally the energy region around E_f. These experiments would also have observed anomalous signals of sufficiently high counting rate in part of the range $E_m < E_f$, extending their mass range at reduced sensitivity as indicated in Table IV.

The results are consistent with the estimated mass limits ~ 10 GeV for the specific case of Q- or $(Q+e)$-ions $(q=-\frac{1}{3})$ in B1 (Ref. 5) and $\sim 10^2$ GeV for Q-ions $(q=+\frac{1}{3})$ in B3 (Ref. 18); no estimates were previously made for the remaining cases in Table IV, in particular for the sensitivity to $Q+A$ ions.

Note that the Z dependence of mass limit (2) for ($Q+$atom) combinations arises principally from the 200-Å gold layer which is added in order to make electrical connection to the detector surface, and which we have included in the computations. If this could be substantially reduced in thickness (e.g., by a factor of 10), the figures given for mass limit (2) in the case of the $Q+A$ ions would rise to the same order as those calculated for the Q- or $(Q+e)$-ions.

Experiments using higher accelerating voltages (e.g., 3–10 MV) are proposed,[24] and to illustrate the typical increase in detectable mass range for such experiments we show in Fig. 5 the computed mass dependence of the electron excitation energy for various Q-ion energies E_Q. It is evident that for accelerating voltages above about 1 MV the curves scale linearly with E_Q:

$$E_m(nE_Q, nM) \simeq nE_m(E_Q, M) . \tag{7}$$

It is also clear that the detector response drops to zero in accordance with (3) ($M_L \simeq LE_Q$) with, approximately,

$$50 < L < 200 . \tag{8}$$

TABLE IV. Variation of detection sensitivity with anomalous particle mass for type B experiments of Table I (silicon-barrier detection). Ion types Q, $Q+e$, $Q+A$, as for Table II. Column $\gamma=1$ gives approximate mass limit for maximum detection sensitivity. The two limiting mass levels under $\gamma=0$ correspond to (1) observations at $\frac{1}{3}Ve$ or $\frac{2}{3}Ve$ or (2) observations down to detector noise limit, as discussed in text. NS indicates no signal at this efficiency level.

	V (kv)	Type of anomalous ion (total charge qe)		Anomalous mass (nucleon-masses)=total mass-atomic mass for relative detection efficiency γ: $\gamma=1$	$\gamma=0.1$	$\gamma=0$ (cutoff mass): Mass limit (1): searches at $\frac{1}{3}Ve$ or $\frac{2}{3}Ve$	Mass limit (2): Noise limit
B1	$+50$	$q=-\frac{1}{3}$	Q	~ 10			~ 16
			$Q+e$	~ 7			~ 12
			$Q+A$ $(Z=1)$	~ 3			~ 6
			$Q+A$ $(Z>2)$	NS			NS
		$q=-\frac{2}{3}$	Q	40–60			50–80
			$Q+e$	50–80			70–100
			$Q+A$ $(Z=3)$	10–30			20–40
			$Q+A$ $(Z>5)$	NS			NS
B2	-1000	$q=+\frac{1}{3}$	Q	20–40	90–120	100–150	4×10^3–2×10^4
			$Q+A$ $(Z=6)$	NS	4–10	10–20	2×10^3–1×10^4
			$Q+A$ $(Z=26)$	NS	NS	NS	5×10^2–6×10^3
B3	-700	$q=+\frac{1}{3}$	Q	20–50	200–400	300–600	2×10^3–1×10^4
			$Q+A$ $(Z=6)$	NS	20–50	40–100	5×10^2–3×10^3
			$Q+A$ $(Z=26)$	NS	NS	NS	30–130
		$q=+\frac{2}{3}$	Q	300–500	800–1500	1000–2000	6×10^3–5×10^4
			$Q+A$ $(Z=6)$	50–150	200–600	300–900	3×10^3–3×10^4
			$Q+A$ $(Z=26)$	NS	0–100	10–200	1×10^3–2×10^4

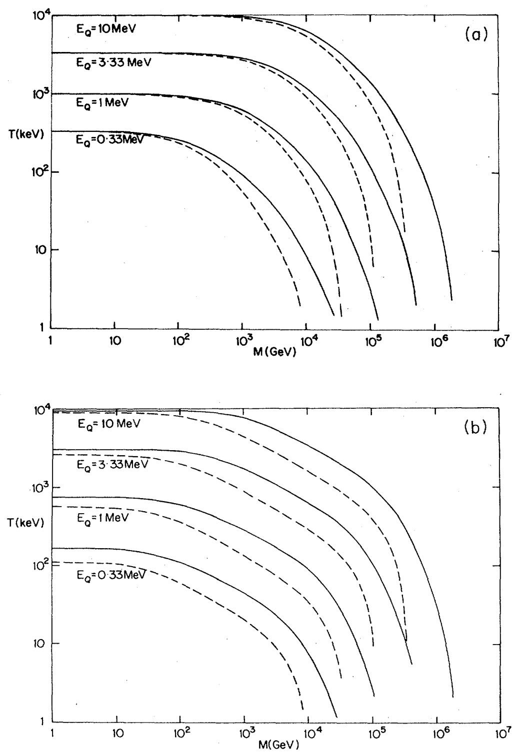

FIG. 5. Energy loss to electrons in Si detector as a function of mass M and Q-ion energy E_Q for "nuclear" charge (a) $\frac{1}{3}$; (b) $26+\frac{1}{3}$.

Consequently the mass limits of either type (1) or type (2) above increase linearly with E_Q.

Figures 5(a) and (b) also show that the Z dependence of the mass limits decreases as E_Q increases, becoming negligible above a few MeV—this reflects the decreasing relative energy loss in the gold layer.

V. ENRICHMENT EFFICIENCY; CONCLUSIONS

We have given a general analysis of the factors governing the mass dependence of fractional-charge searches based on direct detection of anomalous particles in ion beams, illustrating the theory with some specific experiments of this type. These examples show that quoted concentration limits apply to anomalous masses up to typically 10—100 proton masses, the limit depending on the type of Q-ion assumed. In the case of ($Q+$ atom) combinations, the limit, for silicon-barrier detectors, decreases with increasing Z, and Q-ions formed with heavier atoms would not have been detectable. We have also found that ion-beam searches could in principle be designed to reach masses in the region $10\,V$ (kV) proton masses, but that fully mass-independent detection (via the "potential ejection" mechanism) would be possible only in the case of positively charged Q-ions of sufficiently high electron affinity—and with the loss of the direct-energy signature for fractional charge. With increasing theoretical interest in the possibility of very high particle-mass levels, therefore, the further development of ion-beam search techniques appears less appropriate for future experiments than improvements in sensitivity of direct-charge measurement by levitation or free-fall techniques.

In either case it is necessary to consider the general question of the efficiency and mass dependence of any initial concentration or extraction processes, which may be included in these experiments both to increase sensitivity and to transfer the Q-ions to a more suitable ion source material (e.g., a metal filament). Experiments of type B2 and B3 of Table I require no such processes, since the samples under investigation are heated directly in the ion source. The concentration limits in experiments of type A and B1 however, are calculated on the assumption of essentially complete (e.g., 80—90%) extraction of Q-ions from a relatively large initial volume of sample material.

The extraction of hypothetical particles was carried out in A by ion exchange and other chemical processes, and in B1 by various arrangements of electric fields. In each case we can assume an ion extraction rate dn/dt proportional to the instantaneous ion concentration c:

$$dn/dt = R_p c \ , \tag{9}$$

where R_p is a processing constant equivalent to the volume per second from which ions at the initial concentration c_0 could be fully removed by the extraction process. Then, if the material is passed through the system at a throughput R_t ($\mathrm{cm^3\,s^{-1}}$), the equilibrium extraction efficiency f_e will be given by

$$f_e = 1 - c/c_0 = R_p/(R_p + R_t) \ . \tag{10}$$

Thus for high efficiency it is necessary to maintain the condition $R_t \ll R_p$ throughout the mass range covered by the detection system.

As a specific illustration of this, we can make some approximate estimates of R_p and its mass dependence for the electric-field extraction schemes used in experiments of type B1. Corresponding calculations have not been attempted for the ion-exchange process adopted in A, but the principles should be somewhat similar. In general, the electric-extraction techniques used by Chupka *et al.*[5] involved passing a carrier gas containing the hypothetical ions through a region of electric field created around a collection electrode. Details vary with the type of sample: in the case of solids (rocks, sediment, etc.), the heated sample was flushed with argon gas which then flowed through the electric field and past the collecting filament; water samples were first vaporized, diluted with argon gas, and then treated similarly, any solid residue being heated strongly and flushed with argon; air was first passed through a large volume electric field, the collection electrodes then being heated and flushed with argon for transfer to a small collecting filament as before.

In each case the volume extraction rate R_p for $M_Q \to 0$ will be governed simply by the ion velocity v_i (given by the product of ionic mobility μ and electric field E) at the collecting surface of area S:

$$R_p = v_i S = \mu E S \ . \tag{11}$$

For simple collision processes, mobility would be proportional to charge, whereas in the presence of polarization and/or clustering effects ionic mobilities in gases become essentially independent of ion charge.[25] Thus in either case one would expect mobilities of fractionally charged ions to be of the same order as those for normal ions ($\mu \gtrsim 1$ cm^2 s^{-1} V^{-1}) giving an ion velocity $\gtrsim 10^3$ cm s^{-1} for a typical electric field of 10^3 V cm^{-1} (Ref. 26). Hence (assuming a collecting area $S \sim 0.01$ to 0.1 cm^2) typical values of R_p are in the range 10—10^2 cm^3 s^{-1}. Thus provided the gas flow rates are kept much lower than this the criterion $R_t \ll R_p$ for high-extraction efficiency will be satisfied, at least for low M_Q.

To estimate the dependence of R_p on M_Q, we note first that the ionic mobility itself depends principally on atomic or molecular size, and the principal effect of an anomalously high mass would be to increase the time constant for the attainment of the limiting ion velocity. From the equation of motion,

$$(M_Q/e)\ddot{x}+(1/\mu)\dot{x}=E \ , \tag{12}$$

the time constant τ is given by

$$\begin{aligned}\tau=\mu M_Q/e &\simeq 10^{-12}\mu(M_Q/M_p)\\ &\simeq 10^{-12}(M_Q/M_p) \text{ s} \quad \text{for } \mu \sim 1 \text{ cm}^2\text{s}^{-1}\text{V}^{-1}\end{aligned} \tag{13}$$

(where M_p is the proton mass).

The extraction efficiency (10) is modified by (12) to

$$f_e/(1-f_e)=(R_p/R_t)[1-r+r\exp(-1/r)] \tag{14}$$

with

$$r=(R_t/R_p)(\tau/t_e)\equiv\tau/t_r \ , \tag{15}$$

where

$$\begin{aligned}&\text{the "extraction time" } t_e=w/\mu E \ ,\\ &\text{the "residence time" } t_r=wS/R_t \ ,\end{aligned} \tag{16}$$

and w is the typical dimension (parallel to E) of the ion-extraction region. For example, with $w \sim 1$ cm and the above values for μ and E, t_e will be of order 10^{-4}—10^{-3} s.

The quantity r then provides an indication of the mass dependence of the extraction process. For $r \ll 1$, (14) is equivalent to (10) and the efficiency is essentially mass independent. For $R_t \ll R_p$, this requires $\tau < 10^{-5}$ s which, from (13), will be the case up to about 10^7 proton masses. Above about 10^8 proton masses, τ/t_e could become $\gtrsim 1$, making it necessary to reduce R_t sufficiently to maintain $r \ll 1$ throughout the required mass range. Thus if enrichment processes are contemplated in conjunction with fully mass-independent particle searches, it will be necessary to take account of this effect and to assess in greater detail the dependence of f_e on particle mass and extraction geometry. It is, however, clear from the above that electrical enrichment procedures can be designed to reach very high mass levels, so that levitation (or free-fall) measurements with highly enriched samples offer an experimental strategy which appears preferable to the inherently mass-limited ion-beam experiment for future high-sensitivity fractional-charge searches.

APPENDIX

The illustrative curves of Figs. 2—4 were computed using a range-energy program[27] based on the theory of Lindhard *et al.*[23] The total energy lost to electrons is accumulated through the range, with the fraction of this loss which occurs in collisions transferring more than E_g estimated as follows: the energy transfer in a (nonrelativistic) collision between a Q-ion of mass M_Q, kinetic energy E_Q, and a (free) electron (m_e,E_e) with angle θ between their initial trajectories is, for $M_Q \gg m_e$, $E_Q \gg E_e$

$$T \simeq \frac{4m_e}{M_Q}\cdot E_Q\left[1-\left[\frac{M_QE_e}{m_eE_Q}\right]^{1/2}\cos\theta\right] , \tag{A1}$$

i.e., with $m_e=0.5$ MeV and taking $E_e \sim 5$ eV,

$$T\ (\text{eV}) \simeq 2x\,(x-10^{1/2}\cos\theta) \ , \tag{A2}$$

where

$$x=[E_Q\,(\text{keV})/M_Q\,(\text{GeV})]^{1/2} \ .$$

Hence $T>0$ for $\theta_0 \le \theta \le \pi-\theta_0$, where

$$\theta_0 \simeq \arccos(x/10^{1/2}) \tag{A3}$$

and $T>E_g$ eV for $\theta_1 \le \theta \le \pi-\theta_1$, where

$$\theta_1 \simeq \arccos\left[\frac{x-E_g/2x}{10^{1/2}}\right] , \tag{A4}$$

with, of course, the provisos $\theta_0=0$ if $x>10^{1/2}$; $\theta_1=0$ if $(x-E_g/2x)>10^{1/2}$; and $\theta_1=\pi$ if $(x-E_g/2x)<-10^{1/2}$.

We then assume that the fraction of energy loss to electrons in which more than E_g is transferred to the electron is

$$\begin{aligned}f_1 &\simeq \int_{\theta_1}^{\pi-\theta_1} T\,d\theta \Big/ \int_{\theta_0}^{\pi-\theta_0} T\,d\theta\\ &\simeq \frac{\pi-\theta_1+10^{1/2}\sin\theta_1/x}{\pi-\theta_0+10^{1/2}\sin\theta_0/x} \ .\end{aligned} \tag{A5}$$

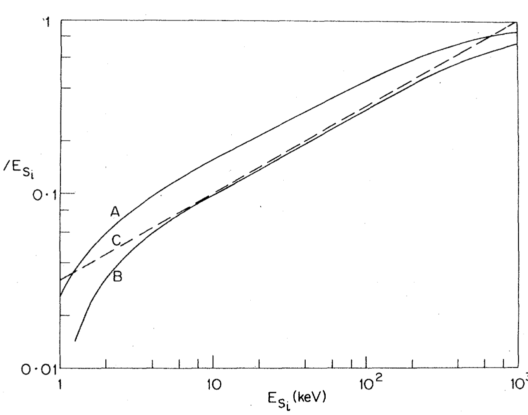

FIG. 6. Energy loss to electrons by Si ions in Si. Curve A, total energy loss; curve B, energy loss in collisions with energy transfer >1.1 eV; curve C, approximation to B used in computations [Eq. (A6)].

Taking $E_g = 1.1$ eV, we than obtain the curves (a) in Figs. 2—5. Though the cutoff masses (above which no collisions result in $T > E_g$) depend strongly on the values taken for E_e and E_g, through most of the mass range f_1 is close to unity for any reasonable assumptions.

To estimate the additional energy lost to electrons by recoil Si nuclei, we first repeat the above computations for Si ions in a Si target (Fig. 6), finding that, in the energy regime of interest, the energy lost to electrons by a Si nucleus of kinetic energy E_{Si} is

$$T_e\ (\text{keV}) \simeq [E_{\text{Si}}\ (\text{keV})/10]^{3/2}\ , \tag{A6}$$

cutting off at $E_{\text{Si}} \sim 0.5$ keV.

The energy transferred to a (free) Si nucleus of mass $M_{\text{Si}}(\simeq 26\ \text{GeV})$ and initially at thermal energy (i.e., essentially at rest) by a Q-ion M_Q, E_Q is

$$E_{\text{Si}} \simeq \frac{4M_Q M_{\text{Si}}}{(M_Q + M_{\text{Si}})^2} E_Q\ , \tag{A7}$$

and thus the fraction of the nuclear recoil energy loss which is then transferred to electrons is

$$f_2 \simeq \frac{T_e}{E_{\text{Si}}} \simeq 0.1 \left[\frac{E_{\text{Si}}\ (\text{keV})}{10} \right]^{1/2} \simeq 0.1 \left[\frac{10.4[M_Q\ (\text{GeV})][E_Q\ (\text{keV})]}{(M_Q + 26)^2} \right]^{1/2} \tag{A8}$$

(with $f_2 = 0$ for $E_{\text{Si}} < 0.5$ keV), from which we obtain curves (b) of Figs. 2—5.

Various refinements have been proposed[28] to the original Lindhard energy-loss model, but since the latter is consistent with typical experimental data for a range of ions[29] to better than a factor of 2, it is therefore adequate for the estimation of approximate mass limits. Any modifications which might result from differences in charge screening for fractionally charged particles should also be unimportant at the level of accuracy required here.

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