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A SEARCH FOR STABLE INTEGRALLY CHARGED MASSIVE PARTICLES (HAN-NAMBU QUARKS)

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ABSTRACT

A search for stable (or long lived) massive ($\geq$ 1.2 GeV) integrally charged particles is proposed. The method exploits the chemical properties of the atoms these particles would form. Positive particles would form hydrogen-like atoms, negative particles would attach themselves to ordinary nuclei and form an atom having one electron less than the original nucleus. Their identification and a rough measurement of their mass would be performed by mass spectroscopy. The method explores a large kinematical region quite different from other searches (already performed or active at NAL). A rough estimate shows that the method may have a sensitivity as low as 10^{-35} cm^2/nucleon. This search is motivated by the suggestion of Han and Nambu that such particles may be the fundamental constituents of hadrons.

MOTIVATION

Most quark searches to date relied on the fractional charge assigned to these particles in the models of Gell-Mann(1) and of Zweig(2). Much less effort has been spent searching for integrally charged quarks (i.e., fundamental hadron constituents). Their existence was conjectured in 1965 by Han and Nambu(3) in an alternate scheme of hadron structure. Recent experimental data actually seem to favor the latter scheme over others(4).

It should be stated at the outset that the case for stability of Han-Nambu quarks is less clear-cut than it is for fractionally charged ones. The Han-Nambu model can accomodate stable and unstable quarks equally well, depending on whether they carry fractional or integral baryon number(3,4). Also, while the Han-Nambu model provides the chief motivation for this proposal, even a conclusive positive result would only establish the charge and (approximately) the mass. Further identification would be needed for proper classification.

Experimental evidence against stable Han-Nambu quarks is presently rather limited. Their presence in common terrestrial (or even meteoritic or lunar) material might have been detected at some level of concentration even without the benefit of a specific search. This evidence is, however, much less conclusive than it is for fractionally charged quarks. For example, Zeldovich et al(5) quote an upper limit of about 10^{13} quark(+1)/gram (from mass spectroscopis analyses of heavy water), whereas fractionally charged particles have not been found at levels of less than .05 quark/gram in seawater(6). Likewise, no uncommon integrally charged particles have been detected in accelerator or cosmic ray experiments. A few NAL experimental searches already performed or presently active, failed to detect their presence. Their relation to the present proposal is discussed below.

It is desirable to search for both +1 and -1 charged quarks since there are possible reasons why one may succeed and the other fail. Unfortunately, the proposed method would not detect neutral quarks.

The proposed experiment can be carried out entirely parasitically, at little cost and with little manpower.

EXPERIMENTAL CONCEPT

I. Search for q^-

When a large target is irradiated by high energy protons and a stable q^- is produced and is subsequently stopped in the target it would become readily attached to a nearby nucleus. The resulting atom would be chemically similar to the element having one e^- less than the target. This has already been argued by Zeldovich et al.$^{(5)}$ in connection with possible formation of such atoms in the atmosphere by q^- produced by energetic cosmic rays.

The choice of target material must reflect:

(a) Mass Spectroscopic Considerations

(i) Ionization Efficiency of the Sample (i.e., the element Z = Z (target) - 1). Alkali metals have nearly 100% ionization efficiency. Gaseous samples also are readily ionized (1 - 10% by magnetron or plasma type ion sources).

(ii) Isotopic Multiplet Structure of the Target. The q^- carrying nuclei would be expected to have the same relative abundances as the target material and their m.s. signature would be similar but shifted by an amount equal to the quark mass less the quark-nucleus binding energy. Observing a distinctive multiplet could aid greatly in discriminating against contaminants or other spurious background.

(iii) Isotopic Multiplet Structure of the Sample. Likewise if the sample material has isotopic multiplet structure certain background lines arising from scattering in the m.s. ("ghosts") become more readily identifiable since they would have the signature of the sample element.

(iv) Mass Difference of Target and Sample Isotopes. The sensitivity of a m.s. analysis can be influenced by the presence of strong lines (because of their finite width) near in mass to the sought species. From this viewpoint the difference in mass between the target isotopes and the stable (or long-lived) sample isotopes should be as large as possible.

(v) Amount and Purity of Sample. It is important that the amount of sample be kept small (μg to mg quantities). Since a large target is favored for maximum q^- retention this means that the target material (kg quantities) has to be very pure with respect to the sample element (at 10^{-9} to 10^{-6} levels of concentration). For some elements the amount of sample element generated during the irradiation may be comparable to that which can be tolerated as impurity. Likewise the sample should be free from contaminants (at 10^{-6} - 10^{-4} levels of concentration) which have masses in the region where the search is to be performed.

(vi) Radioactivity Problems. The sample should not have any radioactive isotopes ($\tau_{1/2} \gtrsim$ 1 week) which would be produced copiously during irradiation. These could become an important source of background in subsequent (other) use of the m.s. and even constitute a health hazard to personnel.

(b) Chemical Considerations

(i) Chemical Composition of the Target. If the target is a compound or mixture, the experiment can be performed on two or more elements simultaneously during a single irradiation.

(ii) Isolation of Sample Element. The isolation of the sample element from the target should be performed essentially "carrier-free". The initial step(s) in the chemical isolation should be amenable to remote handling (until sufficient decontamination is achieved). Many compounds would be easier to handle, in this respect, than elemental targets.

(iii) <u>Purity of Target</u>. The target should be easily pre-purified with respect to the sample element.

(c) <u>Stability of the (q -nucleus) System</u>. The q^- carrying nuclei may be unstable (with relatively short life-time) against β decay or partide emission. For most nuclei, stability is likely from pure Coulomb energy considerations. If other forces between q^- and the nucleons are significant, stability will depend on the detailed nature of these forces. It is plausible however that decay is less likely if the target nuclei are tightly bound.

(d) <u>Radiation Safety Considerations</u>. A large target subjected to a long, intense irradiation will become quite radioactive. Generally, low Z materials will minimize this. Also, the target should be "worry-free" during the irradiation with respect to melting, leakage of gases produced by the radiation, etc.

(e) <u>Practical Considerations</u>. Cost and availabilty of target material, suitable containers, etc.

Based on these considerations suitable (though not ideal) targets are Ca(→K), Na(→Ne) and O(→N). These are not necessarily our final choices (since that is best decided by testing). To briefly defend these choices (some data on the elements involved are given in Table I):

(1) Ca(→K). Excellent m.s. sensitivity. Both target and sample are multi-isotopic (though more equal abundances would be better). Ca^{40} is very stable against β^- decay. The mass (q^- + Ca^{40}) could be close to K^{41}. Except for K^{40}, the longest lived K-isotope is K^{43} ($\tau_{1/2}$ = 22 h). This isotope should not be produced abundantly and can be virtually eliminated by waiting (~ 3-4 weeks) between the end of the irradiation and the final chemical isolation and m.s. analysis. K^{40}, while produced more copiously is extremely long lived ($\tau_{1/2} \simeq 1.3 \times 10^9$y) and should pose no problems in terms of radiation hazards to equipment or personnel.

(2) Na(→Ne). Good m.s. sensitivity. Ne is multi-isotopic, and has no long lived unstable isotopes. However Na is mono-isotopic and only moderately stable against β^- decay. The mass (q^- + Na^{23}) would have excellent separation from Ne^{22} (the heaviest stable Ne isotope).

(3) O(→N). Good m.s. sensitivity. Both are multi-isotopic (but with poor abundance ratios). N has no long-lived unstable isotopes. O^{16} is an extremely stable nucleus. The mass (q^- + O^{16}) would have excellent separation from N^{15}.

II. Search for q^+

Stable q^+ would chemically resemble hydrogen and remain isolated after stopping in a thick target. If a low Z material (such as graphite) is placed in a sealed system the hydrogen fraction could be extracted at the end of the irradiation (e.g., by burning the graphite and isolating the hydrogen fraction as H_2O).

In this experiment the m.s. identification would be more difficult: (1) H^2 and H^3 would also be copiously present and may well interfere with the q^+ signal. (2) H^3 poses the problem of introducing radioactivity into the m.s. (special facilities exist however that could handle this problem, though some sensitivity may be sacrificed in using them). (3) There would be no multiplet structure present. The reasons why both searches are desirable are (a) free (or bound) quarks might readily decay into the lightest quark of the species (at least this would not necessarily violate any known conservation laws), (b) the search for positive q's is free from the assumption about nuclear stability.

RELATION TO OTHER EXPERIMENTS. KINEMATICAL REGION EXPLORED

A few experiments performed or presently active at NAL relate to the present proposal.

Leipuner (E-72)(7) reports no massive particles of either charge ($3 < M < 11$ GeV) at a level of 10^{-5} of the flux of light particles for 300 GeV/c protons incident on W. The experiment used time-of-flight techniques and searched at four different momenta in the range 30-60 GeV/c (10% resolution) and at an angle of 6.5 mrad.

Ritson (E-96)(8) searched for negative particles ($M \lesssim 4$ GeV) using a long Be target and 300 GeV/c incident protons. No unusual particles were observed at a level of one part in 10^8 of the incident beam particles. This search was performed at 80 GeV/c (1% momentum-bite) and at 3 mrad.

Lederman (E-187) reports no integrally charged particles in the 25-100 GeV/c region at a level of 10^{-7} x the flux of light particles using time-of-flight at 0°. Cronin (E-100) and Mann (E-184) search for production at large angles.

As shown below all these experiments explore a rather different kinematical region from the present proposal. They should be regarded as complementary and not directly competitive.

Assuming a long target (~ 1000 g/cm^2 or ~ 10 collision lengths) is used, this corresponds to the range of a q with kinetic energy ~ 2.5-3.5 GeV (for $m_q \simeq 2$-8 GeV) and q's with less energy would be retained. More important, an energetic q can be expected to interact inelastically with target nuclei, perhaps much like an ordinary hadron. If the q loses on the average 40% of its kinetic energy per collision (through particle production and nuclear excitation) a q of 30 GeV kinetic energy could be retained. Of course, the expected energy loss in any number of nuclear encounters is a broad distribution and no sharp cut-off on the q-momentum can be determined. But it follows that this method is more sensitive to q's with relatively small momentum (compared with the incident momentum). This is to be contrasted with the first three searches mentioned above.

Likewise the angular region of the search cannot be precisely stated. It is broadly confined to the forward direction. In addition to the angle at production, deflections due to nuclear interactions are likely to be important. A target 200 cm long and 15cm in lateral extent subtends 37.5 mrad at the exit face (for a narrow beam on axis). This is a considerable angle at these energies. The angular range is even larger at lesser depths.

Since the primary objective is to establish the existence of q's (rather than quantitative information on their production) the sensitivity of the search to a rather broad range of both angle and momentum is rather desirable in that it makes the search less model-dependent. A small disadvantage is that a negative result would be more difficult to quantify.

In p-nucleon collisions there appear two plausible q production modes (1) $q\bar{q}$ production and (2) dissociation of projectile or target nucleon into q + qq (diquark) or into three q's. The proposed method is primarily sensitive to target dissociation. Table II shows expected kinetic energies (in the lab) of a q for some reactions where the center-of-mass (c.m.) final state is indicated in the diagrams:

$$(A)\ \underset{qq}{\overset{q}{\leftleftarrows}}\xrightarrow{N}\quad (B)\ \xleftarrow{q}\underset{N}{\overset{qq}{\rightrightarrows}}\quad (C)\ \xleftarrow{q}\overset{qq}{\cdot}\xrightarrow{N}$$

In (A) q and qq are at rest in the q,qq system, in (B) qq and N are at rest in the qq,N system and in (C) qq is at rest in the c.m. system. All particles are assumed to travel along the incident direction. For convenience the mass of the incident and final nucleon was assumed to be 1 GeV. The quoted values are not too sensitive to the mass of the final nucleon. (Generally, this would be a more complicated state.) The qq mass was assumed to be m_q+0.3GeV(4).

To contrast this with $q\bar{q}$ production Table III shows the (lab) kinetic energies expected for q's having low c.m. momenta(9) (p^c = 1 GeV/c and 2 GeV/c resp., emitted opposite the incident direction). This shows the proposed method to be much less sensitive to this mechanism. The kinetic energies of the q's from projectile dissociation are expected to be large and have a much larger spread (in the lab) than those from target dissociation.

On the basis of these rough arguments it appears that the low q momentum region ($\lesssim$ 30 GeV) is a rather good prospecting territory having little overlap with other searches. This region is also particularly interesting in that the quark mass has recently been conjectured to be as low as 2 GeV(4).

Several other effects bear on the q-momentum sensitivity:

(a) The hadronic cascade development in the thick target. Given a fixed (lab) q momentum or momentum cut-off the number of q's observed may actually be larger for lower incident momentum(9). For this reason the interacting "secondaries" (ranging in momentum up to the incident momemtum) could make an important contribution.

(b) Multiple interactions inside nuclei. This has, perhaps, an effect similar to (a) although less clear-cut. Present understanding of high energy interactions in nuclei is rather sketchy.

(c) Fermi motion of nucleons in the nucleus and (in case of dissociation) of q's in the nucleon. These are likely only important near the production threshold.

As mentioned before, the sensitivity in this experiment may be somewhat difficult to assess. Confining ourselves to those q's produced and stopped in the target, a 1 kg "active" target embedded in a large target (~ 1000g/$_{cm^2}$ in length and measuring about 15x15 cm laterally) would on the average contain 0.005 of all retained q's. Using 10^{17} as the total number of incident protons and 10^5 atoms/sample as the detection limit of the m.s., the q^- production cross section could be established at the level of $\sim 10^{-35}$ cm^2/nucleon. This is considerably below the quoted sensitivity of other searches and it is to be emphasized that this method explores a rather large and quite different kinematical region.

APPARATUS

The target would be, preferably, rather large (2m long x 15cm x 15cm) and would be located directly upstream of a beamdump. The total number of incident protons should be as high as possible consistent with the irradiation running a few months. About 3×10^{17} total protons seems to be a reasonable goal. The design of the target (and also the chemical isolation techniques employed) must incorporate certain safety precautions. This would intimately involve the actual location of the target. The following is presented to roughly indicate our needs. The final versions should be decided in consultation with NAL staff, based on location, available remote handling equipment and a few low intensity test runs.

(1) Target

The target would consist of a series of "modules". Most of the total length of the target would be taken up by passive material, e.g., steel or possibly a heavier material. At various locations "active" modules would be inserted, each containing typically about 1 kg of graphite or a compound of the aforementioned elements: O, Na and Ca. A reasonable choice of compounds is perhaps NaCl and CaO, but this must be decided by tests. The entire target can be enclosed in a larger vessel for water cooling.

(2) Location

A location in front of a beamdump would be desirable. Water cooling may be necessary.

(3) Monitors

An integrating monitor placed in front of the apparatus would be helpful. Foil packages would be placed at the front and throughout the target for more accurate determination at the end of the irradiation.

(4) Remote Handling Equipment

The required equipment will not likely exceed that presently (or in the near future) available at NAL, e.g., manipulators, TV camera, etc.

(5) Mass Spectrometer

The 100" and 2-stage mass spectrometer of Argonne National Laboratory (Chemistry Division) will be available through the association of one of us (C.M.S.).

SCOPE OF THE EXPERIMENT

(1) Irradiation

The entire irradiation would be run parasitically. A location where the beam is reliably dumped over an area (~ 10 cm x 10 cm) would be ideal. The target construction could be made rugged enough to permit occasional (remote) adjustment. No special conditions of beam structure, etc. are required. Emplacement, adjustment and removal can be done entirely at the convenience of the prevailing general schedule. Likewise any remote handling equipment or facility can be scheduled at a convenient time. Some help in "lining up" the target would be needed from NAL or other experimenters. A total of $\gtrsim 10^{17}$ protons incident on the target of the highest energy possible in accordance with schedule, location, etc. is required. A total elapsed time of less than about 3 months is desirable.

(2) Tests

(a) Some parasitic beam may be required to test the behavior of the modules during irradiation. A location where a relatively low intensity beam is reliably dumped would be used to measure temperature rise, pressure build-up, etc. before the large target is irradiated.

(b) NAL may have presently available some materials which have been significantly irradiated in the past. If NAL wishes to make these available, some preliminary "mini-experiments" could be performed on these (with much lower sensitivity, however).

(c) Some m.s. tests on naturally occurring materials will be performed mainly to establish the nature of the background and to check the chemical purification and isolation techniques. Such tests could even conceivably lead to identification (or suspicion) of quarks produced by cosmic rays. For example, (q^- + Na) formed in seawater might be found in Ne samples or (q^- + Ca) in K contamination of Ca. A new search for q^+ in deuterium samples may also be worthwhile.

(3) Cost Estimates

Following approval, one of us (A.V.G.) would apply to the NAL Physics Department for a grant of about 10K$. This would cover: chemicals (1.5K$), target housing (2K$), test equipment (1K$), chemical apparatus (1K$), etc. Some travel expense may be incurred to perform the m.s. analysis of the hydrogen fraction.

(4) Schedule

Following approval of the experiment and the financial grant, tests would commence on target purification, target behavior during irradiation, etc. (2-3 months) followed by construction of the target (1 month), the irradiation (3 months), and analysis of samples (1 month).

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TABLE I

Abundance and Half-lives of Target and Sample Nuclides for Proposed Targets.

Oxygen (Stable Isotopes	Nitrogen (Established Isotopes)	Sodium (Stable Isotopes)	Neon (Established Isotopes)	Calcium (Stable Isotopes)	Potassium (Established Isotopes)
Mass number (Abundance), [Half-life]*		Mass number (Abundance), [Half-life]*		Mass number (Abundance), [Half-life]*	
16(.9976)	12[.011s]	23(1.0)	17[.11s]	40(.9694)	37[1.2s]
17(.0004)	13[10m]		18[1.7s]	42(.0065)	38[7.5m]
18(.0020)	14(.9964)		19[17s]	43(.0014)	39(.933)
	15(.0036)		20(.905)	44(.0208)	40(.00012)
	16[7.1s]		21(.0027)	46(.00003)	$[\sim 10^9 y]$
	17[4.2s]		22(.092)	48(.0019)	41(.067)
			23[38s]		42[12.4h]
			24[3.4m]		43[22h]
					44[22m]
					45[17m]
					46[110s]
					47[18s]

* Abbreviations: s (seconds), m (minutes), h (hours), y (years).

TABLE II

Lab Kinetic Energy of q for Various Modes of Target Dissociation

Reaction, Incident Momentum	Kinetic Energy of q (GeV)			
	M =2 GeV	M =4 GeV	M =6 GeV	M =8 GeV
(A), 200 GeV/c	2.5	13	31	58
(A), 400 GeV/c	2.5	13	31	57
(B), 200 GeV/c	0.5	5.1	16	36
(B), 400 GeV/c	0.5	4.8	14	29
(C), 200 GeV/c	0.7	6.6	21	47
(C), 400 GeV/c	0.6	5.9	17	38

TABLE III

Lab Kinetic Energy for q with Low c.m. Momentum

q (c.m.) Momentum, Incident Momentum	Kinetic Energy of q (GeV)			
	M =2 GeV	M =4 GeV	M =6 GeV	M =8 GeV
1 GeV/c, 200 GeV/c	10	27	45	63
1 GeV/c, 400 GeV/c	16	40	66	96
2 GeV/c, 200 GeV/c	6.4	21	37	55
2 GeV/c, 400 GeV/c	10	31	55	80