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Search for Ultradense Nuclei in Relativistic Collisions of Ar on Pb

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In 2.5×10^8 interactions of 1.1- to 1.6-GeV/nucleon ^{40}Ar ions with a Pb target we saw no tracks of products with $Z>20$ ejected in the beam direction, using a Lexan detector stack. The upper limit on the formation cross section is about 50 nb for products with $26 \lesssim Z \lesssim 40$ and increases with Z to about 1.5 μb for $Z=100$.

Several authors[1-3] have discussed the possibility that stable, abnormally dense nuclei may exist in nature or may be created in high-energy heavy-ion collisions. In the theories of Migdal[2] and of Lee and Wick,[3] the extra energy of compression is more than compensated for by the energy reduction due to meson condensation.

In a specific version of the latter model, Lee[4] considers a scalar meson field coupled to a nucleon field of strength such that the effective mass of a nucleon is reduced to approximately zero near the Fermi surface, and the volume contribution to the binding energy is increased from its normal value, ~16 MeV/nucleon, to ~130 MeV/nucleon. Because its asymmetry energy is also increased whereas its Coulomb energy is unchanged, $Z\approx N$ for an abnormal nucleus and it is stable against fission for values of Z up to $\sim10^4$. (Note, however, that at values of $Z\gtrsim170$ both normal and abnormal nuclei will be unstable in vacuum, spontaneously emitting enough positrons that those electronic levels with energies less than $-m_0c^2$ become filled with electrons.[5,6])

Lee suggests trying to make abnormal nuclei with a large volume-to-surface ratio ($A^{1/3}\gg1$) by bombarding very heavy nuclei with very heavy nuclei at an energy of ~1 GeV/nucleon in the center of mass. In a head-on collision the density would temporarily increase by at least a factor 2, and perhaps by a much larger factor if a nuclear shock wave were to be initiated. The condition $A^{1/3}\gg1$ is to ensure that the increased surface energy does not dominate over the increased volume binding energy.

Our experiment was motivated by numerous, mixed reactions of both theorists and experimentalists to the Lee-Wick model, together with the temporary availability of a beam of relativistic Ar ions at the Bevalac. Because it may be several years before suitable beams of ions with $Z>18$ can be accelerated at the Bevalac, we decided to interpret Lee's condition that $A^{1/3}\gg1$ to include possible reactions

$$\text{Ar}+\text{Pb}\rightarrow\text{abnormal nucleus.}$$

With only a weak beam available, we used a single 5-cm-thick lead brick as a target and looked for inelastic collisions in which an Ar nucleus carried forward with it all or part of the nucleons in a Pb nucleus, leading to high-Z products emitted from the Pb brick in the beam direction. Our detector consisted of 1000 sheets of 250-μm-thick Lexan plastic track detector, placed directly downstream from the Pb target. Of the 5×10^8 Ar ions of initial energy 1.62 GeV/nucleon that entered the target, we estimate that ~50% of them emerged from the target without a nuclear interaction and with an energy of 1.11 GeV/nucleon, and that ~12% of these penetrated the 25-cm Lexan stack without an interaction and emerged with an energy of 0.65 GeV/nucleon.

Lexan has the virtue, characteristic of all dielectric track-recording solids, that it is sensitive only to extraordinarily highly ionizing particles—just the kind we were looking for. The threshold ionization rate for producing a track that can be made visible in Lexan is that corresponding to a minimum-ionizing nucleus of charge ~55.[7] An Ar ion would leave a detectable track only in its last 1 to 2 mm of range, so that in our experiment the Ar beam passed through the Lexan stack without being detected. Tracks of highly ionizing particles were made visible by etching the Lexan in a strong solution of sodium hydroxide for 50 h at 40°C. Each track shows up as a pair of etch pits at opposite sides of a sheet. The length of an etch pit per unit etch time is roughly proportional to the square of the ionization rate. From a series of microscope measurements of etch-pit lengths one can determine the charge of the particle to within one unit of Z.

The above etching conditions were chosen so that events with $Z=18$ had a probability $\lesssim 10^{-2}$ of forming connected etch pits in the shape of a constricted cylinder in the last sheet through which they passed. With increasing Z the probability of a connection rapidly increases, reaching ~80% for $Z=26$ and 100% for $Z>26$. These holes are easily detected by passing ammonia gas through the holes onto blue-print paper. Each event found in this way was inspected in a low-power stereomicroscope, and cones in several preceding sheets were measured if the event appeared to have $Z>18$.

With the ammonia method we could thus quickly locate any nuclei (either normal or abnormal!) with Z significantly greater than 18 that were formed in interactions of ~2.5×10^8 Ar ions at depths in the Pb such that they entered the Lexan stack. Some of these high-Z products would undergo a nuclear interaction before coming to rest and would thus be undetected. The velocity, range, and interaction probability decrease rapidly with increasing Z as can be seen in Table I. Assuming a completely inelastic transfer of the appropriate number of nucleons from a Pb nucleus to an Ar projectile, column 2 gives the range in Lexan of a product Z of an interaction at the downstream side of the Pb target, and column 3 gives the fraction of high-Z products that enter the Lexan, assuming equal interaction probability at all depths in the Pb. The ranges apply to nuclei with "normal" Z/N ratio; for abnormal nuclei with $Z\approx N$ the ranges should scale as M(abnormal)/M(normal) for the same charge and velocity and will not differ drastically from the estimates in column 2. Column 4 gives the efficiency for detecting the stopping nucleus with the ammonia method. Column 5 gives the fractions that come to rest without a nuclear interaction. Column 6 gives our negative results, which we will now discuss.

In our Lexan stack, of thickness such that surviving Ar projectiles would emerge with relatively high energy (~0.65 GeV/nucleon), we expected to see practically no background of Ar or pro-

TABLE I. Limits on production of high-Z nuclear states (with $\tau \gtrsim 10^{-10}$ sec at 1.1 $\lesssim E_{\rm lab} \lesssim 1.6$ GeV/nucleon).

Z	Maximum range in Lexan (cm)	Fraction stopping in Lexan	Detection efficiency (by ammonia)	Fraction surviving interactions	Upper limit on formation cross section
18	43	~0.01	$\ll 0.01$	~0.06	...
26	13	0.8	~0.5	~0.4	50 nb
32	6.4	0.5	1	~0.6	40 nb
36	4.1	0.36	1	~0.7	45 nb
52	0.17	0.07	1	0.96	180 nb
100	0.07	0.008	1	1	1.5 μb

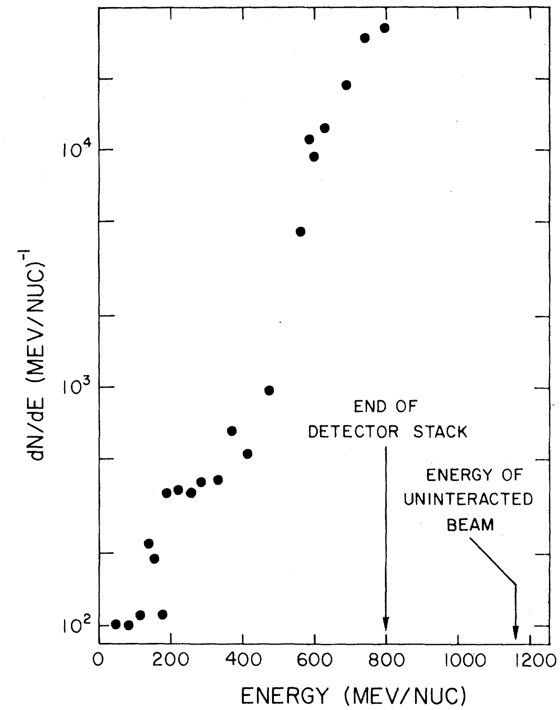

FIG. 1. Energy spectrum of reaction products with $14 \leq Z \leq 18$ as they emerge from the Pb target. These nuclei have momenta within $\sim 5°$ of the beam direction. The arrow at ~ 800 MeV/nucleon indicates the maximum energy of nuclei with $Z \simeq 18$ to which the detector is sensitive. The arrow at ~ 1160 MeV/nucleon indicates the energy of beam nuclei that have not undergone nuclear interactions.

ducts of its nuclear reactions. In their heavy-ion studies at the Bevatron, Heckman *et al.*[8] showed that more than 99% of the products of nuclear reactions of projectiles such as C and O had approximately Gaussian momentum distributions with a standard deviation of $\sim 10^2$ MeV/c and a most probable value close to zero in the projectile frame. To our surprise we saw $\sim 6 \times 10^6$ tracks of particles with $14 \lesssim Z \lesssim 18$ that came to rest throughout the Lexan stack at $\sim 0°$ to the beam, showing that there is a strong non-Gaussian tail extending to large momentum losses. Figure 1 shows the distribution of their energies as they left the target. The curve was calculated by applying an Ar range-energy relation to our microscope measurements of their range distribution. Particles with $Z \lesssim 14$ were undoubtedly also present but, because of the high recording threshold of Lexan, were not efficiently detected. With the ammonia process we were able to sieve out tracks of ~ 3600 nuclei with $Z \gtrsim 18$. The vast majority of these turned out to be Ar ions that had suffered a large momentum loss, perhaps also having lost one or more neutrons. We found fewer than then nuclei with $Z = 19$ or 20 and none with $Z \gtrsim 21$.

Thus, at laboratory energies between 1.1 and 1.6 GeV/nucleon, we find that the cross section for producing long-lived (i.e., surviving a flight path of several centimeters) normal or abnormal nuclei with Z between ~ 26 and ~ 40 in an Ar + Pb collision must be less than ~ 50 nb. Our upper limit on the cross section for production of still heavier nuclei increases with Z to about 1.5 μb for $Z = 18 + 82 = 100$. Except for the heaviest possible products, our limits are far below the 1 μb Lee[4] had estimated for creation of abnormal nuclei in very-heavy-ion collisions.

With a fluence of 2×10^{10} Ar ions and a stack of alternating thin Pb and thin Lexan, the search could be extended down to the 1 nb level. It would also be worthwhile to use lab energies below ~ 600 MeV/nucleon, in order to decrease the longitudinal momentum decay length inside the target nucleus and to increase the probability of initiating a nuclear shock wave that would lead to a large increase in nuclear density.[9] It may even be possible to use the Lexan detectors to search for abnormal nuclei in reactions such as Kr + U, using the weak Kr beam that is expected at the Bevalac in the spring of 1975.

We believe that a positive result of a simple experiment such as we have just described is a necessary (but perhaps not sufficient) prerequisite to a more complex experiment that would measure the mass defect of putative abnormal nuclei by determining their time of flight, magnetic rigidity, charge, and range.

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Nonlinear Gravitational Effects and Magnetic Monopoles*

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The Einstein-Maxwell equations for systems of particles possessing electric and magnetic charge are considered. The consequences of the linear and nonlinear theories are contrasted, by considering a known class of exact solutions. In particular, for these systems of dually charged particles, angular momentum quantization leads to charge quantization only in the linear theory. Furthermore, if "strut" singularities are excluded, then isolated magnetic monopoles are forbidden in these solutions by nonlinear gravitational effects.

The Einstein-Maxwell equations for a system possessing magnetic as well as electric charge are[1]

$$\nabla_\mu F^{\nu\mu} = 4\pi J_e{}^\nu, \quad \nabla_\mu \tilde{F}^{\nu\mu} = 4\pi J_m{}^\nu, \tag{1}$$

$$G_{\mu\nu} = -8\pi G T_{\mu\nu}, \tag{2}$$

where

$$\tilde{F}^{\alpha\beta} = \tfrac{1}{2}|g|^{-1/2}\epsilon^{\alpha\beta\gamma\delta}F_{\gamma\delta}, \tag{3}$$

$$4\pi T^{\mu\nu} = F^\mu{}_\lambda F^{\nu\lambda} - \tfrac{1}{4}g^{\mu\nu}F_{\lambda\sigma}F^{\lambda\sigma}. \tag{4}$$

This energy-momentum tensor, and hence the Einstein equation (2), is invariant under the duality "rotation"

$$F^{\alpha\beta\prime} = F^{\alpha\beta}\cos\theta + \tilde{F}^{\alpha\beta}\sin\theta. \tag{5}$$

The Maxwell equations (1) are form invariant under the transformation (5), with θ constant, and with

$$J_e{}^{\alpha\prime} = J_e{}^\alpha \cos\theta + J_m{}^\alpha \sin\theta, \tag{6}$$

$$J_m{}^{\alpha\prime} = J_m{}^\alpha \cos\theta - J_e{}^\alpha \sin\theta. \tag{7}$$

The dynamical development of two systems of charged particles related by a duality rotation [Eqs. (5)–(7)] will be identical. By means of a duality rotation one can always make the total magnetic charge of the system vanish. The operational meaning of the statement that a particle (or group of particles) has nonvanishing total magnetic charge is clarified by considering an isolated system S consisting of two particles (or subsystems of particles) P and P'. The electric and magnetic monopole moments of P and P' can be determined by observing the electromagnetic field. We are free to define the charge of P to be purely electrical, since we can make its magnetic charge vanish through a duality rotation of S. It then has physical meaning to ask whether P' has nonvanishing total magnetic charge q_m. The linearized theory, which is discussed first, allows q_m to be nonzero. In contrast, for the class of exact solutions of the full nonlinear equations to be considered below, one finds that q_m must vanish if certain regularity requirements are imposed on the metric. Even in the absence of regularity, the quantization of angular momentum does not lead to the standard charge quantization, as it does in the linear theory.

Linearized theory of two dually charged particles.—For simplicity, consider a system of two dually charged particles fixed at positions $\vec{x}_1$ and $\vec{x}_2$. In the linearized theory, the lowest-order Maxwell equations are the same as in special relativity, with $J_e{}^i = J_m{}^i = 0$, and

$$J_e{}^0 = q_{e1}\delta(\vec{x}-\vec{x}_1) + q_{e2}\delta(\vec{x}-\vec{x}_2), \tag{8}$$

$$J_m{}^0 = q_{m1}\delta(\vec{x}-\vec{x}_1) + q_{m2}\delta(\vec{x}-\vec{x}_2). \tag{9}$$

The solution of the linearized Einstein equation in harmonic coordinates is

$$h_{\mu\nu}(\vec{x}) = 4G\int d^3x' \,|\vec{x}-\vec{x}'|^{-1}S_{\mu\nu}(\vec{x}'), \tag{10}$$