

Search for strange matter by Rutherford backscattering

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According to a number of suggestions, stable strange matter could exist in the form of supermassive nuclei (or 'strange nuggets')^{1,2}. In contrast to ordinary nuclei, which contain only 'up' and 'down' quarks, a piece of strange matter should comprise a mixture of 'up', 'down' and 'strange' quarks in roughly equal proportions. Small amounts of strange matter could have survived from the early stages of the Universe¹. Alternatively, strange matter might reach the Earth as a flux of strange nuggets produced in collisions of neutron stars³. Limits to the cosmic flux of strange nuggets with masses in the range from 10^{-4} to 250 g have been obtained in a search for light produced by the nuggets in the upper atmosphere⁴. Here we report the results of a search for supermassive nuclei by using Rutherford backscattering of heavy ions. The method is sensitive to a broad range of masses extending to those that exceed the projectile mass by several orders of magnitude. Upper limits for the abundance of strange nuggets with masses $A \approx 4 \times 10^2$ to 10^7 AMU relative to the number of nucleons were found to be in the range 10^{-10} to 10^{-14} .

To set a useful sensitivity limit for experiments designed to search for strange matter, De Rújula and Glashow estimated the maximum concentration of strange nuggets in the Earth's crust³. They assume a value of $\sim 10^{-24}$ g cm⁻³ for the local dark matter density of our Galaxy. Assuming that the whole of dark matter consists of strange nuggets, this flux corresponds to an annual Earth infall of strange matter of $\sim 10^9$ g. Over the Earth's 4.6-Gyr history this results in a maximum crustal concentration of 10^{-7} by mass. For the mass range considered in our experiment, $A \approx 4 \times 10^2$ to 10^7 , this limit extends from 3×10^{-10} down to 10^{-14} nuggets relative to the number of nucleons. Because nuggets with these masses are already stopped in the Earth's atmosphere³ they should not be distributed equally over all of the crust but should be concentrated in its upper layer, in which region the local abundance of nuggets may therefore be higher by two to three orders of magnitude.

In our experiments natural samples were irradiated with beams of ^{238}U and ^{208}Pb nuclei provided by the heavy-ion accelerator UNILAC in Darmstadt. The bombarding energy was 1.4 MeV per nucleon; this is far below the Coulomb barrier of nuclei, so that the cross-section for nuclear reactions is negligible⁵, and the interaction of nuclei is dominated by elastic scattering. In this case the angle and the velocity of the scattered projectile nucleus are determined by the mass of the target nucleus. In a single scattering event a projectile can be scattered into the backward hemisphere only by a heavier nucleus. Therefore, scattering of ^{238}U or ^{208}Pb through angles of 90° - 180° would indicate the presence of more massive and possibly strange nuclei.

Scattered nuclei were detected by a system of twelve low-pressure multi-wire proportional counters⁶ (Fig. 1) divided into four identical modules, each of which consisted of one start- and two stop-detectors. The ranges of scattering angles covered by this system are 92° - 120° and 127° - 170° , with a total solid angle of 1.15 sr.

The identification of detected nuclei is based on the following

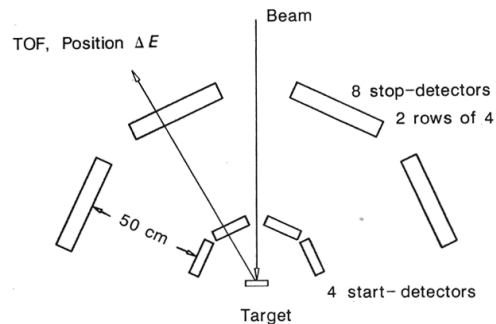


Fig. 1 Schematic diagram of the detection system. Four modules of multi-wire proportional counters are installed symmetrically around the beam axis (top view). Each detector module consists of a single start- and two stop-detectors, placed one above the other.

quantities. The time-of-flight (TOF), or equivalently the velocity, of each scattered nucleus is calculated from the time signals of start- and stop-detectors. The specific ionization (ΔE), which depends on the atomic number Z and the velocity v of the nuclei according to $\Delta E \propto (Z/v)^2 \ln(v^2)$, is measured by the stop-detectors, and, by calibrating ΔE against TOF, ΔE therefore characterizes the atomic number of each nucleus (Fig. 2). The trajectory and, in turn, the scattering angle is obtained from the position measurements in the start- and stop-detectors.

A target of ~ 1 - 2 mm thickness, prepared from an iron meteorite (Sam's Valley meteorite, Medford, Oregon, 1894), was irradiated with 1.7×10^{14} particles of ^{238}U . Figure 2a and b shows the two-dimensional spectra, in terms of ΔE as a function of TOF, of particles in the angular regions 92° - 120° and 127° - 170° , respectively. No data were recorded below $\Delta E \approx 110$ (in relative units) because of an electronic cutoff.

The solid curves in Fig. 2a, b represent the 2σ range (95.4% probability) of ΔE -TOF values for ^{238}U scattered from a thin uranium target in a calibration experiment. No scattered uranium nuclei were recorded for a TOF below 90 ns. Some uranium nuclei with a TOF greater than 90 ns are seen at 92° - 120° (Fig. 2a), but no uranium nuclei were recorded at angles exceeding 127° (Fig. 2b). This strong decrease in the number of scattered nuclei with angle is typical of multiple scattering, and for this reason the events with TOF > 90 ns were excluded from the analysis. The absence of events between TOF ≈ 30 ns, which corresponds to the initial velocity of uranium nuclei, and 90 ns can be used to estimate limits for the abundance of supermassive nuclei in a certain mass range. The lower limit of this mass range is determined by TOF = 90 ns, which corresponds to backscattering of uranium from nuclei with mass $A \approx 400$ located at the target surface.

A group of scattered nuclei with TOF centred around 70-80 ns, with specific ionization much lower than that for uranium ions of the same velocity, was observed at angles of 92° - 120° (Fig. 2a). From comparison with the calibration curves, this group was identified as comprising nuclei with $Z \approx 30$, which we thus attribute to iron nuclei. The dashed curve in Fig. 2a shows the loci of iron nuclei as calculated from tabulated energy-loss values⁷. As iron is the main component of the meteorite, an observation of scattered iron nuclei is not surprising. Such events can result from rescattering of iron recoil nuclei produced in primary uranium-iron collisions. We emphasize here that the identification of nuclei does not require any knowledge of the underlying scattering process (single or multiple), but is based entirely on the experimental calibration curves of ΔE against TOF.

To calculate upper limits for the abundance of supermassive nuclei with mass A , the Rutherford-scattering cross-section and

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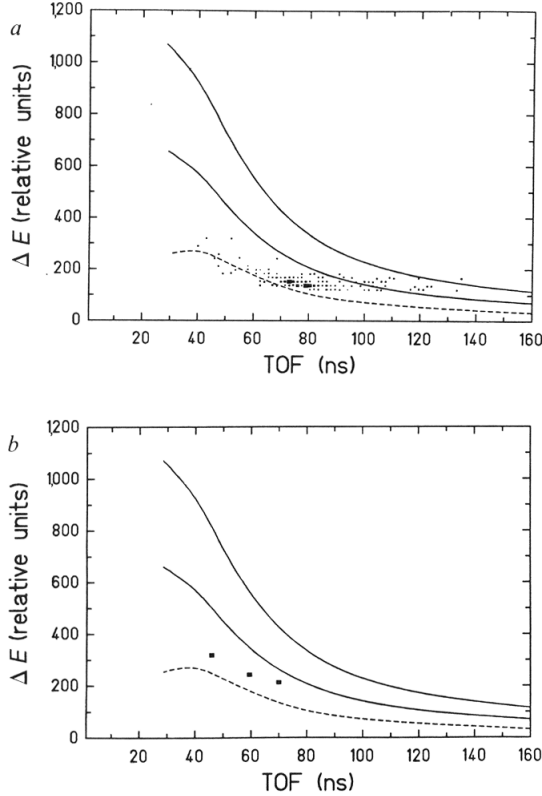


Fig. 2 Two-dimensional spectrum of specific ionization (ΔE) against time-of-flight (TOF) in the angular regions 92° - 120° (a) and 127° - 170° (b). The points represent the loci of a total of 245 (a) and 3 (b) detected particles. No data were recorded below $\Delta E \approx 110$. The initial projectile velocity corresponds to a TOF of 30 ns. The dashed line indicates the calculated locus of ^{56}Fe nuclei and solid lines span the 2σ range for scattered ^{238}U from a calibration experiment.

the effective target thickness must be known. The latter depends on the scattering angle and the mass A . The charge Z , as a function of A , of the supermassive nucleus determining the Rutherford cross-section was taken from the calculation in ref. 2 (with parameter values $E/A = 899$ MeV and $\alpha_c = 0.6$). With other values of these parameters, the upper limits decrease by up to a factor of 20, so that our estimate is model dependent. The Rutherford cross-section was calculated assuming point-like colliding nuclei, which is a good approximation for masses of (strange) nuclei up to 10^4 because the minimal distance between the nuclei is several times their size. For larger masses the minimal distance from the surface of the strange nucleus to the projectile becomes comparable with the size of the strange nucleus, which could necessitate corrections to the Rutherford formula. At present, our knowledge of strange nuclei is insufficient to enable such corrections to be calculated. The upper limits are shown by the solid line in Fig. 3 as a function of the mass number A of the supermassive nucleus. There is increasing sensitivity with increasing mass because of the corresponding increase in the Rutherford cross-section.

The screening of the nuclear charge by electrons inside a large strange nugget could be important, making an estimate of the effective charge difficult. As Farhi and Jaffe explain⁸, no appreciable screening occurs up to $A \approx 10^7$. We did not extend the

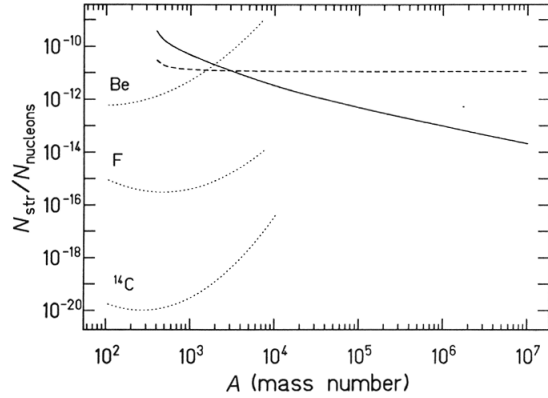


Fig. 3 Upper limits for the abundance of strange nuclei and supermassive relic particles (N_{str}) relative to the number of nucleons (N_{nucleons}) as a function of the respective mass A . The solid line represents the upper limit for the abundance of strange nuclei from Rutherford backscattering of ^{238}U in an iron meteorite, and the dashed line shows the upper limit for the abundance of supermassive relic particles from Rutherford backscattering of ^{238}U in a lanthanide sample. Dotted lines show upper limits for the abundance of supermassive relic particles from a search for heavy isotopes of light chemical elements⁹.

estimated limits beyond $A \geq 10^7$ because above this, no reliable information on the screening was available. It is also important to note that the Coulomb barriers of strange nuggets are high enough⁸ (except for nuggets of low atomic number) that elastic scattering is dominant at energies of 1.4 MeV per nucleon.

In addition to the iron meteorite, several terrestrial samples were studied using ^{238}U and ^{208}Pb beams: garnets, manganese nodules and the group of lanthanide elements extracted from the minerals apatite, monazite and bastnesite. The combined upper limits, not shown, are two times lower than those for the iron meteorite.

The dotted lines in Fig. 3 show results of a search for supermassive isotopes of light chemical elements, using an electrostatic spectrometer⁹. These isotopes were expected to be ordinary nuclei containing supermassive particles that are relics of the Big Bang¹⁰⁻¹². The upper limits obtained for the abundance of supermassive isotopes with masses between 10^2 and 10^4 were rather low; we can consider these limits to be those for strange matter as well.

Our results, on the other hand, can be interpreted as giving upper limits for the abundance of supermassive relic particles that are bound to nuclei by hadronic interactions so that they cannot be detached in a collision process. Such limits are shown by the dashed line in Fig. 3 for relic particles attached to lanthanide elements. These limits can be considered as complementary to the previously published results (ref. 9 and references therein) because they cover a range of masses ($> 10^4$ AMU) which was not investigated in ref. 9.

From our present knowledge of strange matter² we do not expect its properties and abundance to fluctuate from one atomic number to the next. Thus, a further improvement in sensitivity can be achieved with chemically enriched targets, particularly by using chemical separations¹² of elements which do not occur naturally, such as technetium¹³, plutonium¹⁴ or promethium. Strange matter with atomic numbers of these elements should be as stable and as abundant as that of neighbouring atomic numbers. Thus, by chemically separating these elements from bulk material it is possible to obtain targets enriched in strange matter by several orders of magnitude. A similar reasoning applies to supermassive relic particles¹².

Our limits for the abundance of strange matter are close to the instructive estimates of De Rújula and Glashow³. At present we do not consider it useful to put constraints on these theoretical considerations, because, for the samples investigated here, we cannot exclude the possibility of appreciable fluctuations in the concentration of supermassive nuclei caused by fractionations during chemical processes in the early Universe. Further studies of primitive meteorites, which have not been subjected to gravitational effects and whose composition reflects the primordial abundance of nuclei, may provide appropriate data from which to extract such constraints.

We thank E. Jäger, E. Schimpf, D. Gembalies-Datz, J. Asher, Y. Gil and M. Klin for their help in preparing the experiment. Advice and assistance from H. J. Beeskow, H. Daues and H. Stelzer is acknowledged. We are indebted to V. Dangendorf, D. Morrissey and Th. Wilpert for help and discussions. Financial

support was provided by the Minerva Foundation (M.B., K.L., M.O.) and the Bundesministerium für Forschung und Technologie.

Received 2 August; accepted 12 December 1988.

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