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The Origin of the Broken Power Law Spectrum for Cosmic Rays

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A long-standing puzzle in cosmic ray physics has been the nature of the spectrum, which is very well modeled by a broken power law with differing exponents, both close to -3, above and below the "knee". We show that a rather simple hadronic evaporation model reproduces the correct non-integer exponents as well as why they are close to 3, in addition to the location of the knee – all without requiring fits or any free parameters. It is also consistent with the observed composition changes with energy. The model is predictive, with some successful predictions already and has broader implications for nuclear physics and particle astrophysics.

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1. Introduction

It is well known that high energy cosmic ray (HECR) energy distributions [1, 2, 3] follow a broken power law spectrum whose theoretical basis is presently not entirely understood[4]. A variety of mechanisms have been proposed: either "top-down", where initially very high energy particles come from decays of heavy remnants from the early universe, or "bottom-up" ones which involve cosmic accelerators of various kinds, including "one-shot" acceleration, perhaps around neutron stars or black holes where large electric fields might be found with relatively small orthogonal magnetic fields which would otherwise produce energy losses due to synchrotron radiation, and diffusive (Fermi) acceleration via collisions of charged particles with moving magnetic fields due to astrophysical shock waves.

The observed differential flux with respect to energy dN/dE is proportional to $E^{-\alpha}$ with an exponent α near 2.7 below the "knee" at about 1 PeV and near 3.1 above the "knee".

There are at least two notable problems with traditional explanations. The first is obtaining the exponents. While Fermi acceleration can at least give rise to a power law spectrum, it is difficult to argue for even one of the correct exponents, let alone two. In first order Fermi acceleration the exponent is 1 plus a source-dependent correction, while second order Fermi acceleration gives an (incorrect) exponent of 2. A short and very readable account of high energy cosmic ray acceleration mechanisms can be found in [5].

Secondly, since multiple sources would contribute to what is measured on earth, one has to explain, in addition to the knee: 1) why the observed spectrum is as smooth as it is (*i.e.* why each source, within observed errors, appears to have the same exponent), and 2) why various sources should be distributed in such a way and with such intensities that there would, even with the same exponents over some range where they operate, be no jumps in the spectrum. One might also ask for an intuitive reason as to why both the exponents are close the value 3, and yet both non-integer.

2. A New Model: Evaporation from Hot Hadronic Matter

The discussion above suggests that a more economical explanation, not requiring such apparent fine-tuning, and, if possible, giving the correct exponents, would be worth considering. We argue below that cosmic rays are well described as hadrons evaporating from hot hadronic matter in astrophysical objects such as neutron stars without any special acceleration mechanism needing to be invoked.

A statistical thermodynamic view of the HECR energy distribution was pioneered employing a non-extensive entropy by Tsallis and collaborators and and later interpreted in terms of temperature fluctuations by Beck and collaborators(see reference [8] for references). For our purposes we apply *entropy computations* in a form originally due to Landau[6] for the Landau-Fermi liquid drop model of a heavy nucleus. The energy distribution of some of the decay products are thought to be evaporating nucleons from the bulk liquid drops excited by a heavy nuclear collision[7]. Although the entropy for this model is computed from non-relativistic quantum mechanics, and the cosmic ray version of evaporation of course requires an ultra-relativistic limit, the basic physics we propose remains the same.

A simple argument, which we present below in section 3, gives the exponent of 2.7 below the knee, was given in [8] assuming evaporation of bosons. In [9] we found, rather remarkably, that the exponent 3.1 comes about naturally via essentially the same argument assuming that fermions are evaporated. This leaves open the question of why one might think that evaporation of bosons or fermions would be favored below or above the knee, and in reference [10] we found that this too, has a natural explanation in terms of known physics via nuclear photo disintegration, and the characteristic energy scale for atomic transitions. This gives, without adjustable parameters or fits, the correct value for the energy of the knee. This is presented in section 5.

In addition to being the first model since Fermi acceleration to give a power law spectrum (it is otherwise generally assumed, with an exponent chosen by hand), but this time with two exponents and an explanation for where the exponents change. We also give a clear physical reason for why the exponents are close to 3.

Furthermore, after references [8, 9, 10] were completed, AMS measurements[11] of the high energy electron spectrum found the same power law as seen above the knee in ultrahigh energy cosmic rays[12]. This would be difficult to understand via any conventional acceleration models, but is natural in the context of evaporation where the exponent is characteristic of fermions, and thus applies equally to the evaporation of electrons. As such, this was a striking confirmation of a prediction of the model. An important issue concerning the nature of energy loss of high energy electrons in cosmic magnetic fields is in [12].

We now give some details of the physics and calculation involved, referring the reader to references [8, 9, 10, 12] for more details and references.

3. Exponents for Evaporation

For compactness of presentation, we calculate, together, the exponents for the power law spectrum of evaporation of bosons, fermions, and classical particles (obeying Boltzmann statistics). To each kind of particle we associate a parameter η defined by $\eta = 1$ Bose, $\eta = 0$ Boltzmann, and $\eta = -1$ Fermi. We work in the extreme relativistic limit, appropriate for high energy cosmic rays, and neglect interaction between the evaporating particles, treating them as an ideal gas.

The density of states per unit energy per unit volume for ultra-relativistic particles is proportional to the square of the energy. The mean energy per particle in an ideal gas is thereby

$$E_\eta = \frac{\int_0^\infty \frac{\varepsilon^3 d\varepsilon}{e^{\varepsilon/k_BT} - \eta}}{\int_0^\infty \frac{\varepsilon^2 d\varepsilon}{e^{\varepsilon/k_BT} - \eta}} = \alpha_\eta k_B T, \tag{3.1}$$

where the integrals are readily calculable (see references [8, 9]) in terms of the Euler gamma function $\Gamma(s)$ and the Riemann zeta function $\zeta(s)$. In terms of the mean energy $E_\eta = \alpha_\eta k_B T$ introduced in equation 3.1, the heat capacity per evaporated boson is

$$c = \alpha k_B = T\frac{ds}{dT} = \frac{dE}{dT} \tag{3.2}$$

where the classical value of α is given by $\alpha_0 = \frac{\Gamma(4)}{\Gamma(3)} = \frac{3!}{2!} = 3$ while

$$\alpha_1 = \frac{\Gamma(4)\zeta(4)}{\Gamma(3)\zeta(3)} \approx 2.701178 \ \ (\text{Bose}),$$

$$\alpha_{-1} = \frac{7\alpha_1}{6} \approx 3.151374 \ \ (\text{Fermi}). \tag{3.3}$$

From equation (3.2), the entropy as a function of energy is given by

$$s(E) = \alpha_\eta k_B \ln\left(\frac{E}{E_0}\right). \tag{3.4}$$

A power law energy distribution then follows from equation 3.4 with probability of a given energy being proportional to the exponential of the corresponding entropy so that

$$\frac{dN}{dE} \propto \left(\frac{E_0}{E}\right)^{\alpha_\eta}, \tag{3.5}$$

again with an exponent which depends on the statistics obeyed by the evaporating particle species, but otherwise completely determined *without* the need for fits to data or any adjustable parameters.

4. Below the Knee

Below the knee, we take the evaporating particles which we take to comprise cosmic rays to be bosons, comprised of clusters of protons and neutrons (bosonic nuclei).

Nuclear matter is a strongly interacting system which is notoriously difficult to treat in any rigorous way from first principles in terms of protons and neutrons (much less the more fundamental gluon and quark degrees of freedom). Nevertheless, models treating nuclear matter as comprised of bosons have been remarkably successful [14] and this is the only assumption we will need.

The quantum hadronic dynamical models of nuclear liquids have been a central theoretical feature of nuclear matter[15, 16, 17]. The theory of quantum hadronic matter is modeled in the main as an effective Bose (collective meson) theory. These models involve condensed scalar and vector mesons in about equal amounts. The scalar field may be thought to describe collective alpha nuclei embedded in the liquid while the vector field may be thought to describe deuteron nuclei embedded in the liquid. The neutron stars are evaporating through the surface from the nuclear matter within the bulk liquid into the "vacuum" or dilute gas. A simple model of neutron stars is to consider them to be gigantic nuclear droplets[18, 19] facing a very dilute gas, *i.e.* the "vacuum". Neutron stars differ from being simply very large nuclei in that most of their binding is gravitational rather than nuclear, but, the droplet model of nuclear model should still offer a good description of nuclear matter near the surface where it can evaporate.

Evaporation of bosonic nuclei (α particles, deuterons, *etc.*) thus explains the exponent of close to 2.7 below the knee naturally and without free parameters. It does depend on the validity of the bosonic description of nuclear matter, and in so doing lends support to interacting boson models of atomic nuclei [14].

5. Above the Knee via a Bose-Fermi Phase Transition in the Sky

In the previous sections we have shown that evaporation of bosonic hadronic matter gives the observed exponent below the knee while fermionic evaporation gives the correct answer above. We now explain why this is to be expected in light of a somewhat more complete description.

Nuclear matter is inevitably accompanied by electrons, which we have neglected so far, and nuclei themselves are subject to photodisintegration. Simple relativistic kinematics given in detail in [10] shows that nuclei coming out with energies of $\sim$ 1 PeV (the knee), will photodissociate on photons arising from the atomic physics energy scale of around 10 eV. This corresponds to photons emitted as electrons are captured (however transiently) by nuclei. This sets the scale for the knee (this is not a sharp feature, so an estimate is appropriate). Above this scale the nuclear matter should be described no longer by bosons, but by their constituent fermions, protons and neutrons. This implies a shift in exponent to the fermionic 3.1 above the.

It is interesting to note that very recently theoretical calculations have suggested a quantum phase transition in nuclear matter between a bosonic and fermionic phase[20].

Note that the closeness of both exponents to 3 has a simple explanation: for evaporation of classical particles the exponent would have been exactly 3, and, intuitively, the bosons "bunch together" to reduce it to 2.7 while the fermions "get away from each other" to push it up to 3.1.

6. Confirmation from Electrons and a Note on their Propagation

As noted in [12], the recent observation[11] by AMS that the high energy electron spectrum (30 GeV to 1 TeV) also follows a power law with the same exponent as that seen for high energy cosmic rays above the knee – an otherwise seeming mystery – is immediately understandable if the electrons are supposed to come from a similar evaporation process from hot matter (for example, white dwarf stars). This follows simply from the fact that electrons, like protons, are fermions. Possible objections that such high energy electrons would suffer large energy losses due to synchrotron radiation in cosmic magnetic fields are answered in [12], noting that the energy loss via radiation damping is not exponential in propagation time or distance.

7. Conclusions and Implications

A simple model based on the evaporation of hadronic matter explains all the main features of the high energy cosmic ray spectrum including: a broken power law energy spectrum (giving not only for the first time since Fermi acceleration, power laws, but also the correct exponents and the correct location of the knee where they change – with no fits or free parameters), with a tendency (observed) towards (bosonic) nuclei at energies below the knee and fermions (protons) above the knee. The extremely smooth nature of the spectrum over many orders of magnitude without steps or kinks (other than the knee) is explained naturally since the same spectral shape is expected for any source, so what it observed here is just a sum. The model also explains the lack of (potentially observable) anisotropy at high energies since there are no special cosmic accelerators assumed which would give preferred directions. The high energy electron spectrum was also predicted successfully to be the same as that for high energy cosmic rays above the knee simply based on their being fermions, like protons.

Further tests lie in further composition studies, though these will require more consideration of propagation effects, but our results are already supported by existing data. Taking this model seriously as giving a reliable background shape opens up the field of high energy particle astronomy by searches for interesting astrophysical sources as ones which do *not* match the evaporation background in energy distribution and/or composition. The implications of boson models (which this work strongly supports) for nuclear matter beyond cosmic ray physics are significant, but space constraints require we leave this for a separate publication.

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