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Dedicated to Professor Iwo Białynicki-Birula on His 90th Birthday

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Thinking BIG

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Here we develop an informal speculation, which is focused on the existence of fundamental scales for measures of physical interest. In the present case, the scale of interest is the one for energy density, or pressure, for which a fundamental scale is not commonly known. Currently, however, the results being achieved in connection with high, and particularly extremely high, values of energy density are of interest. These speculative remarks are submitted as a contribution to the celebration of a birthday anniversary of Iwo Bialynicki-Birula and address the possibility that a search for the missing energy density scale can conceal and/or reveal something of fundamental interest. This may be particularly true, thinking of a search for such a scale, because a parallel example, a search of historical significance for a new physical scale, can be cited. The present author has enjoyed knowing Professor Iwo Białynicki-Birula, and thanks him for the continuing pleasure of communication and consultation, as well as for a period of random occasions of table tennis warfare, and a close cooperation shared thirty years after that, which is recalled here.

topics: fundamental physical scales, unit of largeness, unit of smallness, serendipity

1. Introduction

The cooperation mentioned in the Abstract was enlivened by shared co-workers, notably including a senior theorist working behind the gates of Livermore National Laboratory in California, mostly closed to Polish scientists at the time, and an enthusiastic Ph.D. student who moved between Warsaw and Rochester. One memorable challenge was to fully understand the role that we guessed would be played by our discovery [1, 2] of Lagrange points for atomic electrons that are irradiated by microwave fields. These fields were originally considered circularly polarized and later linearly polarized, able to trap an atomic electron in very large quantum-atomic orbits with stability previously unsuspected, and conceptually a match for planetary orbits controlled by Lagrange-point force balance.

Later experimental work [3] not only confirmed the theoretical field-created orbits [4, 5], but was able to produce quantum wave packets for electrons in long-time stably transported and non-spreading orbits, engaging principal quantum numbers larger than $n = 600$, thus greatly exceeding previous large-size records for stable non-spreading atomic orbits [6].

With such a dramatically new situation under experimental control, one is attracted to begin *Thinking Big* in a fundamental but natural way. Taking the very large quasi-Rydberg orbits recorded in Houston [3] as a starting example, one could think to ask, how large is LARGE? This question would have a ready answer if a fundamental scale of largeness were known. This introduces our central question, namely what is the *fundamental* scale for large size? Does such a fundamental limit exist to be consulted? What do large physical size scales imply? Do they indirectly suggest, or even define, an entire domain of ultimate “largeness” in physics?

We will consider the possibility of ultimate largeness. We believe that search for an answer could begin with commonly understood facts such as the following. Within the most recent half century, cosmology has provided an unsuspected frontier for physics, and cosmological largeness may be a prominent characteristic. One knows that blackbody radiation is a phenomenon that is truly cosmic in scope, and relatively new. Since its discovery it has been carefully observed and analyzed. Much more recently than the discovery of cosmic blackbody radiation, both dark matter and dark energy have been accepted as newly-emerging phenomena with cosmological scope. They are still without universally agreed details of origin or ultimate consequence. Approaches to understanding them have been proposed and are being explored in a variety of ways. There is no fundamental scale yet associated with them. Here we speculate that a scale associated with their poorly defined large extent is attractive to consider. This could even be paired with direct attention to largeness in a domain where largeness itself can be recognized as under the current study. This is widely understood as the so-named high energy density and pressure (HEDP) domain of exceptionally high energy density and/or pressure. There is already wide international cooperation engaged in aggressive attack on examples of HEDP physics [7].

On elementary dimensional grounds, pressure is the same as energy density and is well-suited as an experimental measure. Large values of pressure have been obtained in several ways. One way has become sufficiently developed to be recognized with the award of the Physics Nobel Prize. Gerard Mourou and Donna Strickland won the Nobel Prize for physics in 2018 with the invention of CPA lasing (chirped-pulse amplification of lasing) in the Laboratory for Laser Energetics (LLE) at the University of Rochester. This now allows laboratory delivery of high values of tightly focused electromagnetic energy and has created a growing awareness of the HEDP regime. It is now accepted as a regime for experimental entry, by terrestrial laboratories [7], into studies of the highest energy densities and pressures on Earth.

Coincidence should not be overlooked. It is an obvious fact that *large* is the generic opposite to *small* and is understood as a conventional marker term, both scientifically and conversationally, for relative size among any array of physical objects. More intriguing is this question, namely is it possible that wide-ranging HEDP studies, perhaps reaching toward extreme cosmic-scaled largeness, can lead to disruptions of established physics at truly fundamental levels? Consequences of a scale for largeness, for great physical size, suggest attention to the consequences that followed attention to its opposite earlier counterpart, as follows. One knows that there was a centuries-long focus on smallness just in the casual sense, i.e., the term "atom" was widely familiar and used conversationally to mean an object so small that its smallness was incomparable. The modern epoch for the first meaningful use of the word atom was the 1800's, when the atom acquired a specific scientific meaning that accompanied the striking scientific advances occurring in chemistry. This happened by identifying as well as naming different types or kinds of atoms as actual objects. These were thought and taught as unbreakable and so were able to combine in fixed proportions to make different composite compounds (i.e., molecules). For example, salt is a common compound made of sodium and calcium atoms, but the atoms were still objects unquantifiably small. This use of "atom" for smallness did not yet mean that a reliable scale for smallness existed.

A backward look can remind us how a scale emerges. Measurement comes first. Fundamental scales recognize measurable quantities having limits. These scales serve to compare the values that are obtained as a result of measurement. The speed of light c is the fundamental value against which all other speeds can be judged by comparison, and the Compton wavelength provides the fundamental quantum value for particles by which its observed quantum momentum can be judged. No scale of fundamental origin is commonly accepted now as associated with energy density or pressure, especially high pressure. In regard to this, there might be some relevance in the way science did obtain a smallness measure. By inventing the "history" of quantitative smallness one can examine the question of whether we are presently entering a zone of experimentation that could unexpectedly, serendipitously quantify "fundamental largeness" for the first time. It is fair to say that HEDP work is now within an experimental regime that is "scalelessly high". This recognizes a goal to be approached, and concedes that no naturally "fundamental" scale presently exists against which to compare high HEDP pressures.

Discoveries of natural scales usually occur accidentally, i.e., without deliberate intent. As mentioned, questions that in retrospect engaged the nature of "fundamental smallness" were being asked over many years (centuries) up to about 1890. In those times, not every alchemist or chemist or physicist was completely convinced that an "atom" was an actual thing that existed even to be detected. Thus "atom" served as a natural but not precisely defined limit for the obvious concept of "smallness". There was no fundamental size that could be identified as the characteristic size or "typical' size for an atom, although different chemical elements were gradually and widely conceded to be made of different atoms and to have different small sizes. An interesting early example of an approach to the measurement of atomic (or molecular) size was a reported observation of the size of molecules at Clapham Pond in London in the 1750's by the perennially curious and carefully observant Benjamin Franklin — the first American scientist. This is a topic, which Franklin is known to have speculated on, because he noted and reported the amazingly large area over which a small quantity of oil could spread freely and very thinly on the surface of the pond water and still remain an intact film. Later, Lord Rayleigh improved Franklin's observation. Quantitative estimates based on knowledge of oil volume and pond area then led Rayleigh to a value consistent with an oil-molecule size of about 1 nanometer — 100 thousand times smaller than a human hair is wide. This set an amazing new record-low value for direct measurement of any small physical size. But this gave rise to no fundamental scale for comparison, but the story was continuing in England.

Soon afterward an astonishingly smaller value of particle size was not directly measured but was convincingly implied by the use of an entirely different kind of observation. This was reported in 1913 by the doctoral students Johannes Geiger and Ernest Marsden working for Ernest Rutherford in Manchester. Their laboratory experiments revealed the existence of a relatively and enormously very massive and tiny nucleus (so-named by Rutherford) in an empty space within gold atoms. It was about 5 additional orders of magnitude smaller than Franklin's and Rayleigh's work could provide, but still not accompanied by a fundamental scale unit.

What happened next? Actually not next, but what had happened a bit earlier? In the half-century before Rayleigh's simple pond-side experiment and 100 years after Franklin's observations, systematic measurements of another type with an entirely different motivation in mind, having nothing to do with particle sizes, were being carefully made by large numbers of scientists working worldwide. They were rapidly developing the new field of atomic spectroscopy, making innovations and then reporting results that we associate with such names as Fraunhofer, Bunsen, Kirchhoff, Ritz, Rydberg, Angstrom, Balmer and others. Values for different frequencies of light emitted by atoms were steadily accumulated, with mostly unsuccessful attempts to correlate them. A combination of squares of small integers extracted from the frequencies and published by Balmer in 1885 was just one of many inexplicable correlations of frequency data. It paid for all that experimental effort about 3 decades later in 1913. As every physicist knows, Balmer's numerical formula from 1885 provided the amazingly accurate numerical confirmation of Niels Bohr's new theory of hydrogen in 1913, which was based on Rutherford's "planetary" view of atomic electrons but included angular momentum quantization. From Bohr's theory, a fundamental measure of atomic smallness finally emerged as the "Bohr radius" $a_0 = \hbar^2/(e^2 m)$. It serendipitously found both the explanation for the vast array of previously uncorrelated wavelengths collected by spectroscopists, as well as a new use for Max Plank's constant h. Thus, Bohr identified in fundamental terms what "atomic size" really means for smallness. This was a clear breakthrough. After that, atoms could be seen as just well-coordinated assemblies of electrons, all attracted by Coulomb's law to Rutherford's central nucleus. However, the real mystery of atoms took 15 more years for it to be fully resolved. Entirely unexpectedly, the final resolution for atoms was not about atoms, but it used atoms to explore the first consequences of a completely new and very unexpected wave, which turned out to be in complete control of the electrons. That new wave is currently taught to physics students and called quantum mechanics.

Now we can reflect again on the HEDP physics. A natural question is whether its scale can be extracted and comprehended in a similar way. Maybe so, with the right orientation. It also has a key missing factor needed for describing poorly understood and emerging physical phenomena. The factor that is missing is the unrecognized fact that cosmologic distance is practically and fundamentally scale-less today. Currently, it has an out-of-scale largeness that is (inversely) similar to the out-of-scale smallness of atoms in 1900.

It is intriguing to push even further than the existing facts justify. One can imagine, without yet having the necessary ideas in their proper order, that LLE in Rochester and its cooperating partner laboratories in the world [7] are already taking data that will be serendipitously relevant to a Balmer-type first correlation of data, possibly to be made in 2030–2060 (recall the 3 decades from 1885 to 1913) and predict a new phenomenon of fundamental importance. Pushing harder, can one imagine that the central 2060 phenomenon underlying the newly scaled largeness will be "dark energy", playing a role similar to "atom" as the key phenomenon that led toward the a_0 smallness scale in 1915? Some similarities suggest a positive answer. Many physicists (weren't then — aren't now), finally and fully convinced that existence of atoms (then) and dark energy (now) is being treated appropriately and fully accepted. Can HEDP experiments turn out to be an opening wedge of innovative studies of dark matter, and use the results to reveal the existence of a fundamentally based "largeness" scale for dark matter? While wildly speculative, this would be an analog of previous worldwide cooperative atomic spectroscopy and the Rutherford invention of an atomic nucleus. The experiment in Rutherford's laboratory gave his visiting scientist Bohr something to go home to Denmark with and think about. Then Bohr theory [8] permanently unified our picture of atoms, showing where the scale of atomic smallness comes from. Who will supply the work, take the data, that sets a fundamental scale for cosmo-galactic largeness?

Acknowledgments

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[7] There are numerous locations where experimental studies associated with high energy density and pressure (HEDP) are currently active and can be found internationally widely distributed. The following list of laboratories and countries with active programs is only suggestive, not complete: China, England, France, Germany, Italy, India, Japan, Korea, Poland, Russia, Spain, and USA. As an example, see High-Energy-Density Physics (HEDP) Theory Group, University of Rochester.

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