Fields in Laser Ablated Plasmas Generalized to Degenerate Electrons and to Fermi Energy in Nuclei with Change to Quark-Gluon Plasma

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ABSTRACT

The studies of laser ablation have lead to a new theory of nuclei, endothermic nuclei generation and quark-gluon plasmas. The surface of ablated plasma expanding into vacuum after high power laser irradiation of targets, contains an electric double layer having the thickness of the Debye length. This led to the discovery of surface tension of plasmas and to the internal dynamic electric fields in all inhomogeneous plasmas. The surface causes stabilization by short length surface waves smoothing the expanding plasma plume. Generalizing this to the degenerate electrons in a metal with the Fermi energy instead of the temperature, resulted in the surface tension of metals in agreement with measurements. Taking then the Fermi energy in the Debye length for nucleons results in a theory of nuclei with stable confinement of protons and neutrons just at the well known nuclear density, and in the Debye length equal to Hofstadter's decay of the nuclear surface. Increasing the nuclear density by a factor of 6 leads to the change of the Fermi energy into its relativistic branch where no surface energy is possible and the particle mass is not defined, permitting the quark-gluon plasma. Expansion of this higher density at the big bang or in a supernova results in nucleation and element generation. The Boltzmann equilibrium permits the synthesis of nuclei even in the endothermic range limited to about uranium.

Keywords: Laser produced plasmas, Ablation, Debye length, Degenerate electrons, Metal surface tension, Fermi energy, Theory of nuclei and nucleation, Endothermic element synthesis, Quark gluon plasma, Magic numbers

1. INTRODUCTION

Understanding the endothermic synthesis of nuclei heavier than iron in the universe is still considered as a less explored problem while the synthesis up to iron by fusion reactions is exothermic and well understood from the reactions in stars [1] Thus the issue of how endothermic nuclear synthesis is possible for heavier elements than iron is considered as an unsolved problem in astrophysics. It may be very surprising that the fully classical processes of laser plasma interaction and plasma ablation can be used to attack this problem while the theory for forces for confining the nucleons in a nucleus are derived exactly in the well known nuclear density theory. If a Boltzmann distribution for unspecified nuclear-chemical processes is assumed in the stellar plasmas for creation of the heavy nuclei going up and down from the size of nuclei until an equilibrium has been reached, we find from the exponential increment for fitting with the measured standard cosmic abundance distribution, a direct derivation of the magic numbers of nuclei with consequences of a quark property inside nuclei.

This view gains importance and consistency only if we follow up with a relation with the magic numbers of nuclei. While the magic numbers were derived by Bagge [2] by a purely numerological speculation where a first connection with the experimental facts was given by a consideration of spin and spin-orbit properties of nuclei [3], we are discussing the relation of the magic numbers with the exponent of the Boltzmann statistics and are going to

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find an explanation for the jump between the two Bagge sequences [2] without needing the spin and spin-orbit relation. This result alone may prove some reality in the assumption of the Boltzmann description. But a further consequence with respect to a threefold multiplicity comes in connection with quark property of stable shells in nuclei. This provides a further confirming aspect for the properties discussed here for heavy nuclei synthesis in the Universe.

The crucial mechanisms for the equilibrium type generation of all known nuclei in the universe is based on the result that there is a change of the Fermi-Dirac statistics for the nucleons from the relativistic branch [4] at the densities above the nuclear density to the subrelativistic density. This in turn leads to nucleation at the well known nuclear densities. This mechanism is due to the surface energy of the nuclei being combined with the results of the empirically derived Boltzmann increment together with the magic number fit. This results in an explanation of the heavy nuclear synthesis by equilibrium mechanisms with a limit just above uranium and a confirmation of a quark-like shell structure of nuclei. There is also a simultaneous confirmation of the co-existence for the nucleonic (hadronic) nuclear structure.

We will first describe the classical plasma theory of surface tension and show how this leads to the theory of surface tension due to the degenerate electrons in a metal (Section 2) The explanation for how the surface energy confines the nucleons of a nucleus with the consequence of limiting nucleation at higher densities and the conditions of the quark gluon plasma are described in Section 3. This leads to the understanding of the endothermic heavy nuclei generation in the universe, Section 4. The relationship to the magic numbers of nuclei is explained in Section 5. and new magic numbers are derived differing from earlier predictions, Section 6. Then a discussion of the quark and hadron structure of nuclei follows along with some other consequences in Section 7.

2. SURFACE TENSION IN LASER ABLATED PLASMAS

When considering surface tension for fully ionised plasmas, the immediate question is how this is possible since the surface tension e.g. of water is due to unsaturated electric dipole of the highly polarized molecules, while fully ionised plasma do not have these dipoles. This is one of the fascinating facts laser produced plasmas revealed within purely classical physics of the otherwise very complex plasma physics, leading now to basics in nuclear physics, high energy physics and in astrophysics.

One of the first observed anomalies at laser interaction with plasmas produced by irradiation of targets was the fact of nonlinearity [5]. For laser powers below about one megawatt (MW), the plasma generated behaved classically when the temperature was about 5 eV (corresponding 50,000 K), The emitted ions had similar maximum energies of the expected thermalised plasma, and the electron emission followed fully the thermionic Richardson laws with emission current densities of few mA/cm^2. When the Q-switched laser provided smooth and reproducible pulses of about 10 ns duration and powers of 10 MW and more, Linlor (see [5]) measured up to 10 keV energy of ions E_i from irradiated carbon. He found that the ions were non-thermally separated by their charge number Z linearly increasing according E_i = const Z. The Z-separation was first assumed to be due to the ambipolar fields. But these fields could only explained by a number of about 10^8 ions per interaction from the double layer of the plasma surface, while the measured number of ions was 10^{13} and more. Honig [5] measured electron emission current densities of 100 A/cm^2 and more, i.e. more than 10^4 times higher values than permitted by classical electron emission with its Langmuir-Child space charge limit. The non-thermal effects were soon recognized by applying the dielectric modified nonlinear force (of which a simplified case is the ponderomotive force) [5,6] to explain production of the 10 keV ion energies after the laser beam underwent ponderomotive self focusing [7] at a threshold just around the observed MW threshold.

The mechanism of the ambipolar electric field in the surface of the ablated plasma during expansion against vacuum – indeed leading to too low ion emssion currents – was an example how to derive the Debye length. Fig. 1 shows a space charge neutral plasma C expanding against vacuum A. From the plasma surface area B, the electrons of the same temperature as the ions leave fastest due to their small mass leaving behind a positive ion cloud such that the charge density due to the Gauss law produces a potential Φ(x) depending on the depth x and the derivative of Φ results in an electric field E(x) within B. It turns out [5] that the thickness of the area B is just the Debye length

$$\lambda_D = [kT/(4\pi e^2 n_e)]^{1/2} = 743\,[T\{eV\}/n_e\{cm^{-3}\}]^{1/2} \qquad (1a)$$

where k is the Boltzmann constant, T the plasma electron temperature, e the electron charge and n_e the electron density of the plasma. The positive charge in B causes that after the fast electrons have left, that the following electrons from the plasma interior are driven back, see the bent arrows in Fig. 1. The electric double layer of B is acting like a work function for the electrons of which the fast ones of the Maxwellian distribution have to overcome the potential step Φ to reach the vacuum resulting the in the well known thermionic Richardson equation as known for the electron emission of hot surfaces (most general formulation in Eq. (1.26) of Ref. [8]). for the electron emission of hot surfaces.

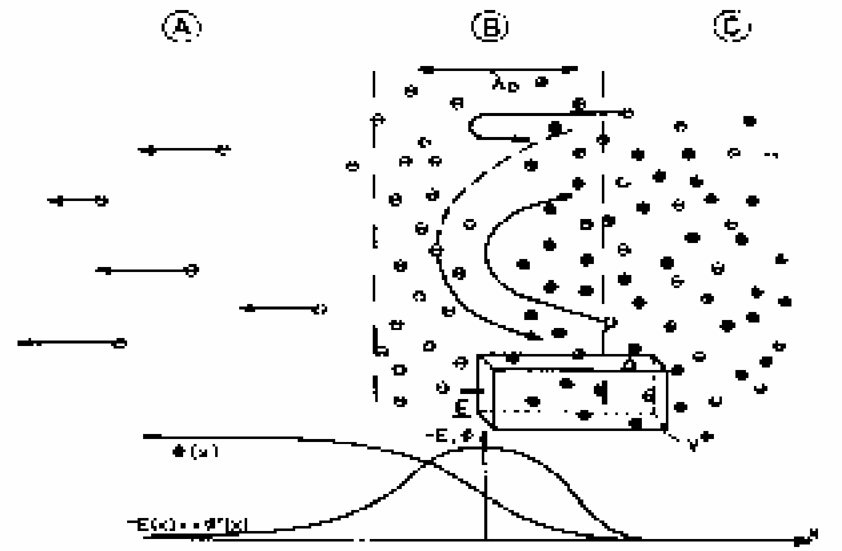

Fig. 1 Expansion of a uniform plasma in C of temperature T into vacuum, range A. An Interface is created by the faster electrons leaving the surface area B letting behind positive charges in a double layer of thickness λ_D, Eq. (1a), where the electric potential Φ according to a work function is built up with and electrostatic field E.

The electric field energy within the volume V of the surface area S of thickness λ_D ($V=S\lambda_D$) is the integral of $E(x)^2/(8\pi)$ integrated over the volume V. The surface tension is defined by this energy within the surface per its area S resulting in

$$\sigma_e = 0.27\, T^2/(8\pi\varepsilon^2\lambda_d) \qquad (1b)$$

where the numerical factor is given by the profile which is chosen in our case for the charge distribution. If the charge distribution between C and A is linearly decaying, the factor is 0.36, while for a Gaussian profile of the electric field, the factor is that in Eq. (1a) [9]. The following examples are best consistent with the Gaussian profile but a more detailed discussion is still to be explored.

The surface tension produces a smooth surface of the ablated plasma as observed where on top a surface stabilization following Landau and Lifshitz (Eq. 8.152 of Ref. [5]) for small wave length surface waves is advantageous similar to the case of water droplets acting against the Rayleigh-Taylor instability. The property of internal electric fields in inhomogeneous and temporally changing plasmas under general dynamics has been elaborated in many details ([10], see also first line of page 171 with reference to Kulsrud in [5] calling “these fields as intuitively not clear”).

This result of the surface tension for fully ionised classical plasmas has been generalized [9] for the electrons in a metal. The Fermi degenerated electron gas between the lattice of the metal ions acts like the electrons in the plasma of Fig. 1, where the electrons with the Fermi energy E_F like to leave the plasma until they are stopped by the generated electric field at the metal surface, producing a swimming electron layer similar to the situation in B of Fig. 1 with the thickness of a Debye length (1a), however where instead of the temperature, the Fermi energy E_F is valid. The surface potential of up to 10 eV is then the work function, well known from the thermionic electron emission of the Richardson equation. The Debye length in this case is in the range of one to two Angstroms. In the same way as for the high temperature classical plasma, we can define a surface tension for the metal by dividing the electrostatic energy in the swimming electron layer per surfaced area. The resulting surface tension shows values in rather good comparison with measured values (see Table 1 of Ref. [9]) though more evaluations need to be done where however the effective mass for crystallized metal surfaces will be of importance for checking (see Appendix A of Ref. [5]). This surface tension obviously is always positive in contrast to the basically earlier model of surface tension kn own as "jellium model" where negative surface tension resulted which could be overcome only by sophisticated additional elaborations [11].

3. SURFACE ENERGY OF NUCLEI AND QUARK-GLUON PLASMA

Up to this point we have considered Debye layers and the resulting surface tension in a plasma and in degenerate electrons in metals only where electric field and double layers [5] were involved. The Fermi energy in the case of the metal electrons (instead of a plasma temperature) motivates one to ask for conditions where the Fermi energy is essential and dominating without specification of other phenomena that may be involved as small perturbations. We consider the ensemble of a number of protons and neutrons and how to squeeze them into a spherical volume, Fig. 2, with a nucleon density n. Obviously there are strong Coulomb forces trying to drive the protons apart. Another force against confinement of the nucleons is the quantum pressure expressed by the Fermi energy when locating a particle into a volume V that from the quantum relation with the necessary momentum corresponding to an energy E_F increases with another exponent for smaller and smaller V than that forthe Coulomb repulsion. The Fermi and the Coulomb energy are equal at a radius of 285 fm [4], such that for smaller radii the Fermi energy is the dominating part of the internal energy of the nuclei. Looking into cases of small readii, we can then consider the Coulomb forces and other components as small perturbations which are discussed later.

The following success will justify us to compare the Fermi energy of the proton and neutron ensemble of Fig. 2 with the surface energy given from a surface tension using a Debye length given by the Fermi energy of the nucleons. Therefore without specifying the detailed interpretations we are defining a surface energy in the same way from a surface tension as an expression (1b) by using the Fermi energy of the nucleons. The surface tension for the nuclei is then

$$\sigma_e = 0.27\, E_F^2/(8\pi\varepsilon^2\lambda_d) \qquad (1c)$$

The Fermi energy can be expressed generally (see Eq. 1.7 of Ref. [8])

$$E_F = [3/(\pi)^{2/3}/4]\, [h^2 n^{2/3}/(2m)]\, (\lambda_C/2)^{-1}[n + 1/(\lambda_C/2)^3]^{-1/3} \qquad (2)$$

where n is the nucleon density. This splits into the branches

$$E_F = \begin{cases} [3/(\pi)^{2/3}/4]\, h^2 n^{2/3}/(2m) & \text{(subrelativistic)} \qquad (2a) \\ [3/(\pi)^{2/3}/4]\, hcn^{1/3}/(2\pi) & \text{(relativistic)} \qquad (2b) \end{cases}$$

using λ_C the Compton wave length $h/(2\pi mc)$ with "2π" which option is just ascertained by the following treatment modifying the preceding work [4]. The surface energy of the nucleus [4] is then

$$E_{surf} = 0.27[3A(4\pi)^{1/2}]^{2/3}\, 3^{1/3}\, E_F^{2/3} /(\pi^{1/2}\, 2^{5/2}\, n^{1/6}\, e) \qquad (3)$$

For comparison between the surface energy and the internal energy we have

$$E_{surf}/(AE_F) = \begin{cases} 0.27\, (3^{3/2}/2^{10/3})\, hn^{1/6}/(em^{1/2}A^{1/3}) & \text{(subrelativistic)} \qquad (4a) \\ 0.27\, [3^{8/3}/(2^{7/3}\, \alpha^{1/2}\, A^{1/3})] & \text{(relativistic)} \qquad (4b) \end{cases}$$

using the fine structure constant $\alpha = e^2(2\pi hc)$. From (4a) we see that the nucleus cannot be confined for too low a density. The nucleus is stable only when the density reaches a value of the density n_n where the ratio (4a) is equal to one. This is the case at the well known value of the nuclear density as checked e.g. for bismuth [4]. The surface “Debye”-layer has a thickness of about 2 to 3 fm, just the measured Hofstadter decay of the surface charge of heavy nuclei.

At relativistic densities just above that of the subrelativistic case reproducing the well known density of nuclei, we see that the value

$$E_{surf}/(AE_F) = 6.28/A^{1/3} \tag{5}$$

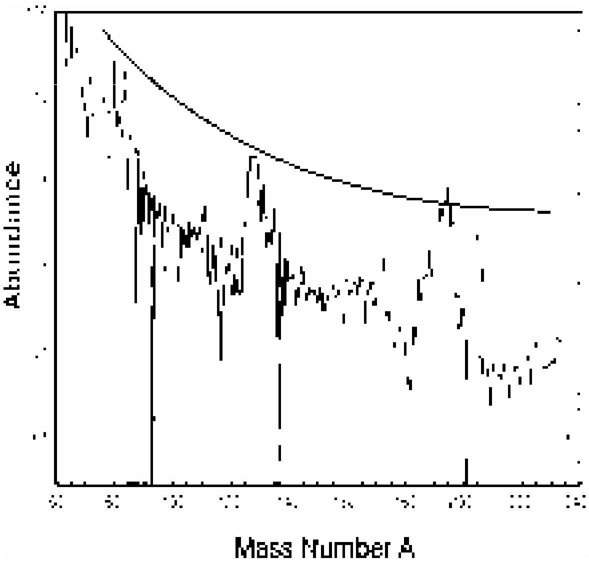

Fig. 2. Measured standard abundance distribution of the elements (SAD) [16] in the Universe where the line follows the exponential Boltzmann dependence of Eq. (6) with Z’=10.

does not longer depend on the nucleon mass nor on the density. We have then no nucleation by the surface energy and a soup of matter. Even the independence of the mass shows that we can either have hadrons (as assumed in neutron stars) or a quark-gluon plasma. Only when this dense matter is expanding at the big bang or from a neutron star in a supernova, when reaching the nuclear density, the surface energy will produce the nucleation. The numerical factor in (5) may mean that higher values for A than 247 are not possible. This may just explain, why the nucleation by expansion of a quark-gluon plasma at higher than nuclear density from the relativistic branch of the nucleon Fermi energy to the lower nuclear density can produce elements only up to uranium of up to curium at the most within such equilibrium processes. Higher trans-uranium nuclei by heavy ion collisions as an extremely non-equilibrium process are then really manmade, but following the rule of magic numbers as shown below.

4. COSMIC HEAVY NUCLEAR GENERATION

It is well known from nuclear astrophysics [13,14] that there is a standard abundance distribution (SAD) of the elements in the Universe (Fig. 2) showing for a nucleon number A> 60 (above about iron), a nearly exponential decay of the maxima on the proton number Z which are close to the magic numbers. Between these maxima the minima are up to 100 times and more lower. For A < 60, the abundance of the elements is very much higher resulting form the thermonuclear fusion processes from protons up to iron well known from the various stages of stellar evolution [1].

Element synthesis for heavier nuclides with A > 60 cannot be due to fusion because these reactions would be endothermic. There are well known reaction chains that could explain how high density background neutrons may produce reactions for the higher than A = 60 element synthesis. One example is given by the reactions in supernovae and in white dwarfs known as r-, s- or p- (rapid, slow or by-pass) processes. Also for these a rather similar abundance for the elements is gained (Fig. 2). There is indeed a discussion whether these heavy elements can be produced only in the later development of the universe e.g. not before the early development of galaxies [15]. Nevertheless there are results that the heavy elements may have been produced in the state of the big bang when the cosmos had a density close to the nuclear density [14] where inhomogeneities provided the conditions for the heavy element generation. This all comes close to the conditions whereby surface energy of nuclei due to the inhomogeneity fields results in stable nuclei of the well known nuclear density while at six times higher density the Fermi energy of the nucleons changes in the relativistic branch forbidding then any nuclear structure and permitting only uniform nucleon or quark-gluon plasmas [4], see preceding Section 3.

Table 1. Sequence n = 0,1,2... of magic numbers with the values exp(Z_n/Z') and R(n) = exp[(Z_{n+1}-Z_n)/Z'] of Eq. (8) with Z'=10 from Eq. (6) as measured.

n	*Magic Number*	*exp (Z/Z')*	*R(n)*	3^n
0	2	1.221	1.822	1
1	8	2.2225	3.321	3
2 (as n+1 in (8))	20	7.389	-----	--
2 (as n in (8))	28	12.1824	9.025	9
3	50	148.413	24.53	27
4	82	3640.95	81.45	81
5	126	296558.5		

The fact that there is a universally equal distribution of the heavy elements - due to a big-bang or later supernova processes - suggests without that the well known detailed single reactions are taken into account. There seems to be a global reaction equilibrium defined by a Boltzmann-like exponential distribution into which all the heavy nuclei within the background of neutrons may emerge. This is then a Boltzmann-like equilibrium process changing any distribution of nuclides into the well observed standard abundance having the exponentially decaying probability for higher A or proton number Z of nuclei. A distribution of the abundance N(Z) depending on the proton number Z of the form

$$N(Z) = N' \exp(Z/Z') \qquad (6)$$

for the maxima of the SAD, drawn as solid line in Fig. 2 for heavy nuclides, is therefore rather trivial. Statistically there is an up and down in nuclides until the exponential distribution has been achieved. One may assume that if this occurs at an early stage of the big bang when nuclei are in some femtometer (Fermi) distance that the reaction times may be between femtoseconds and attoseconds or even less.

For lower densities in supernovae or in white dwarfs the endothermic element synthesis by the s-, the r- or the p-processes results in similar Boltzmann equilibrium as in Eq. (6) as seen e.g. in Fig. VI.1 of Ref. [13] or Fig. 10a in Ref. [14] where, however, the reaction times are up to 10^4 seconds due to the larger distances of the reacting nuclei. Similar conditions may exist in astrophysical ensembles of nuclei at similar distances and time scales if there is a proton background [15] where the Coulomb repulsion is compensated thermally and/or there are sufficiently high densities.

5. RELATION TO MAGIC NUMBERS

We discuss here what consequences it has due to the fact that the drawn curve in Fig. 2 - fitting with the empirical astrophysical observations of the SAD - results in a Z'=10 in Eq. (6) or values nearby. This is now related to the nuclear shell model where we derive an alternative foundation of the magic number compared to the usual explanation by spin and spin-orbit properties of nuclei. The magic numbers of the nuclear shell model are the sequence

$$\text{magic numbers: } M_1 \in 2, 8, 20, 28, 50, 82, 126 \qquad (7)$$

for protons Z in nuclides as well as for neutrons N = A-Z with the measured well known maxima of binding energies (see Fig. 2 of Ref. [14]). We now calculate the ratios R(n) for the astrophysical [13] SAD-Boltzmann probabilities from Eq. (6)

$$R(n) = [N(Z_{n+1})/N(Z_n)]^{-1} = \exp[(Z_{n+1}-Z_n)/Z'] \qquad (8)$$

where the magic numbers Z_n of the protons are taken with the following indices n (0,1,2,3...)

$$Z_o=2,\ Z_1=8,\ Z_2=20, \qquad \text{for relation up to the magic number 20} \qquad (9)$$

$$Z_2=28,\ Z_3=50,\ Z_4=82,\ Z_5=126 \qquad \text{for the magic numbers above 20} \qquad (10)$$

As seen from Table 1 for Z' = 10 in Eq. (6), the ratios R, Eq. (8) result in values very close to

$$R(n) = 3^n \qquad (11)$$

shown in Fig. 3. The good fit with Z' = 10 compared with other numbers can be seen for the magic number 82 at n = 4. Instead of R=81.45 (being very close to 3^4 for Z'=10) we find R=224.69 for Z'=8; R=132.80 for Z'=9, R=54.598 for Z'=11.

6. NEW MAGIC NUMBERS AND EXPLANATION OF THE BAGGE JUMP

Extending the procedure with the 3^n-law (11) to higher magic numbers - see the extension of the fully drawn line by the dashed line in Fig. 2 - one arrives at the following higher magic numbers indicated by open circles as closest values to the line. The result is that for n = 6 one arrives at a magic number 180, for n= 7 at 246 and for n = 8 at 324,

$$\text{New magic numbers} \quad 180;\ 246;\ 324 \qquad (12)$$

shown by circles in Fig. 3. This can be compared with the earlier predicted magic numbers [19] 114, 184 and 228 (crosses in Fig. 3) which by far do not fit so well the relation (11).

The first conclusion of these results derived from this fitting of the Boltzmann probability (6) with the standard abundance distribution of the heavier elements observed in the Universe, Fig. 2, refers to the curious jumping procedure with the magic numbers 20 and 28 in Table 1. This is exactly what was necessary to be explained when the magic numbers were discovered numerologically by Bagge. [2,3]. In order to explain the maximum binding energy of some nuclei, which can not be explained so easily as e.g. the electron shells in atoms from the Schrödinger equation with the well known $2n^2$-relation (n=1,2,3...) for the electron shells so estimates were needed. It is most remarkable that a purely speculative combination of the sequences 2; 3, 4; 5; 6;.... and of the sequence 1; 2; 3; 4; 5;.... and their combinations [3] led Bagge [2] to the result of the following sequences (13) and (14) for the magic numbers. In the first case taking the sequence 2,3,4,5,6… as differences to produce 1,3,6,10,15,21…and then taking them as differences , one arrives at 0,1,4,10,20,25,56…and doubling these values,

$$M_2 \in \mathbf{2, 8, 20}, 40, 70, 112 \qquad (13)$$

Beginning with the sequence 1,2,3,4,5,6,…as the differences one arrives as 1,2,4,7,11,16,22…and again using these as differences leads to 0,1,3,7,14,25,41,63…which elements doubled arrives at

$$M_3 \in 2, 6, 14, \mathbf{28, 50, 82, 126} \qquad (14)$$

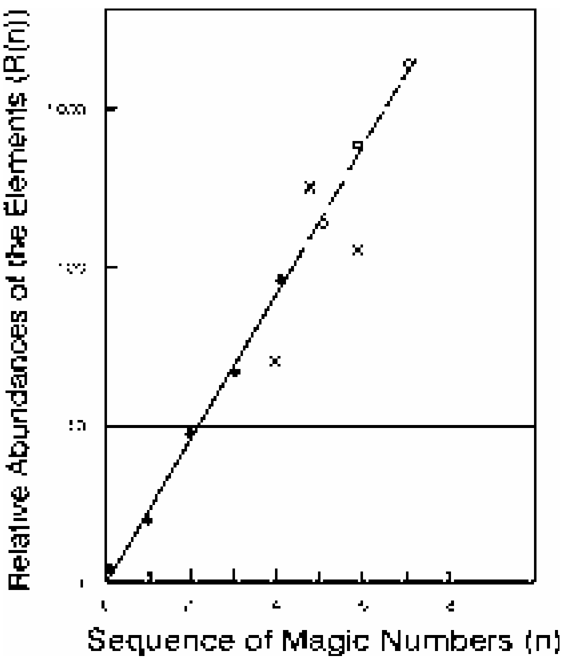

Fig. 3. Values $R(n) = \exp[(Z_{n+1}-Z_n)/Z']$ for the sequence of magic numbers n with specially defined exception of 20 and with the fitting value $Z'=10$, (dots) compared with the 3^n-relation (Eq. 11) [18, 19] straight line. Circles are for derivation of new magic numbers (180; 246 and 324), Eq. (12) and crosses for earlier considered [16,20] numbers 114, 184 and 228.

Bagge's question was why did the bold numbers fit the observed magic numbers and how to explain the jump from the Bagge sequence (13) to (14) after the first three elements. A well known explanation was given [3] by Jensen and Maria Goeppert-Mayer who noted that there is a difference in the spin and orbit configurations in the nuclei preferring in the one case the lower numbers of Eq. (13) and in the other case the higher numbers of Eq. (14).

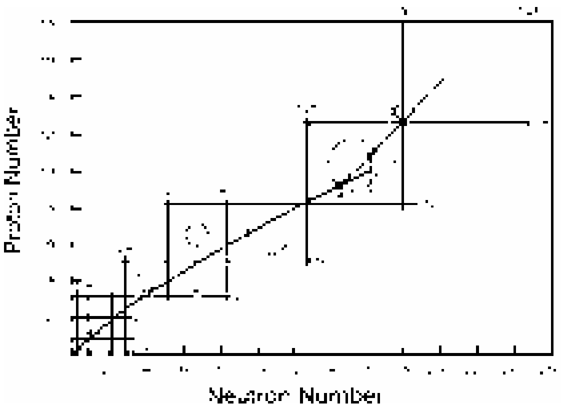

Fig. 4. Stable nuclides for various protonand neutron number up to about curium point A, see Fig. 9 of Ref. [17]) with extension [21] and standard magic numbers, Eq. (7), including new magic numbers, Eq. (12).

In contrast to this explanation, we see now that the jump between the magic numbers 20 and 28 results systematically from the procedure of Table 1 without any need of a physical explanation of the spin etc.. If our explanation for a quark structure of the nuclear shells is the reason, this would be well different form the spin model and one has to learn again from a co-existence of basically different properties for the phenomena of the nucleus. Vice versa one may find an explanation of the spin-orbit phenomenon related to the threefold multiplicity of Eq.

(11) concluding that the stable nuclear shells are combined each with three quark links of the higher shell to one quark in the low shell.

7. QUARK AND HADRON STRUCTURE OF NUCLEI AND RELATED QUESTIONS

The combination of research “from quarks to the cosmos” and “how were the elements from iron to uranium made” is in the focus of a panel of astronomers and physicists and listed as one of the key questions [22] or “to understand how everything in the cosmos to heavy elements was formed” [23] to which the considerations in this paper may offer a contribution. The Boltzmann equilibrium process of the nucleation when matter of higher density (known from the big bang or neutron stars) than that of nuclei is expanding and merging in the nucleation process, determines then the generation of all elements observed in the Universe. The surface energy mechanism is well explaining why no much larger nuclei than that of uranium were produced. From Fig. 4 the normal distribution of the nuclei until uranium or curium based on Eq. (5) is then a Boltzmann equilibrium nucleation process covering all these elements without distinguishing between exothermic or endothermic nuclei. What follows above curium in Fig. 4 are then manmade nonequilibrium produced nuclei from collisions of heavy nuclei. In this case again the new magic numbers of Eq. (12) are confirmed [21].

For the properties of nuclei it is interesting to know that both conflicting properties are co-existent, the hadron structure as well as the quark structure. The proton-neutron structure is determined their Fermi-Dirac statistics and its transition into the relativistic branch by the mass of the hadrons forbidding smaller masses, while the relation for the shell structure for the magic numbers, Eq. (11) indicated the quark property within nuclei by the threefold multiplicity. We further found the decay of the density of the nuclei at their surface as measured by Hofstadter theoretically reproduced for large nuclear surfaces by the here modified Debye length of 2 to 3 fm thickness [4]. This may indicate also the range of the Yukawa potentials of about 2 fm as tangling bonds at the surface not mutually saturated as within the nucleus by mutual hadron interaction.

This general result on nuclear theory is indeed a combination of several preceding steps presented here as a consequence of the Debye length derived from the surface of laser ablated plasma [5]. This derivation is basically different from the statistical studies of electrolytes as it was pioneered by Milner [24] before Debye and as it was underlined by Denis Gabor [25] in connection with the collective theory of the stopping power [26] leading now to nuclear theory and the quark state at supernuclear densities.

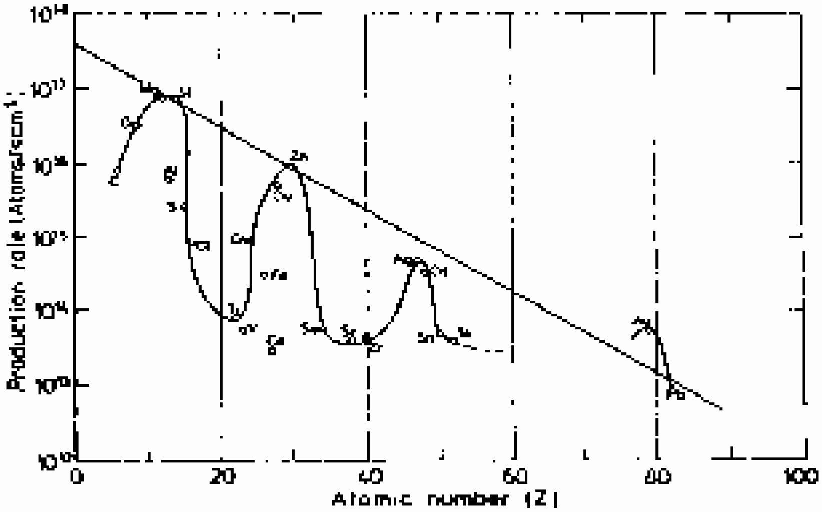

Fig. 5. Elements produced in palladium at very high concentrations of protons within several weeks of interactions by low energy nuclear reactions [27] in pm distance [28] similar to the electron capture of nuclei. The line shows the same Boltzmann decay as that of Fig. 2 with a Z’ = 10 of Eq. (6).

It should be mentioned that the motivation to study the Boltzmann plots from Eq. (6) using the empirically given maxima of Fig. 2, was initially motivated by similar measurements of element distribution produced (Fig. 5) in a fully reproducible way by low energy nuclear reactions, LENR, of high density protons in palladium, nickel and zirconium [27]. This first observation of these maxima for conditions of the magic numbers were confirmed later by other authors and are some of the clarified points within the otherwise not fully explored properties of these mechanisms [28]. A further convincing observation was the minimum of the production rate of the heavy nuclei similar to the fission but at the higher A-number of 153, where the local maximum of this measured function at 153 was very significant for the fission process (see Fig. 11 of Ref. [28]. Another substantial result from this research direction was that for the very first time, a consequent theory of the deuterium-tritium fusion cross section could be derived from an optical nuclear model with an imaginary potential in the Schrödinger equation [29] and a clear gas discharge result of the properties of loading palladium with hydrogen [30].

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