
From laser produced Debye layers in plasma to a theory of nuclear forces and quark-gluon plasmas

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Abstract

A new theory for the nuclear forces for confining the nucleons in a nucleus was derived from a generalization of the Debye layer as known from the plasma ablation at laser irradiation where the temperature is substituted by the Fermi energy of the statistics of nucleons. The first convincing proof is by using the empirical density of the nucleons defining their Fermi energy to arrive at a Debye length of about 3 fm as measured by Hofstadter for the decay of the nucleon density at the surface of heavy nuclei. Taking then the surface tension of plasmas with the same steps of substituting temperature by Fermi energy, the surface energy of nuclei is always too small against the nucleon enthalpy to confine the nucleons until equilibrium is reduced at about such high densities reproducing the well known radii of nuclei. The Hofstadter decay can be interpreted as the inhomogeneous wave of the nucleons by Wigner scattering at the nuclear surface similar to the Goos-Haenchen effect. By this way, nuclei are possible only until uranium or curium by a Boltzmann equilibrium process explaining the endothermic generation of heavy nuclei. At about six times higher nucleon density, the Fermi statistics changes into its relativistic branch resulting in a surface energy always smaller than before, and the mass and density independence indicates that one cannot distinguish between the state as in a neutron star or as a quark-gluon plasma. The steps from the ablation of laser produced plasma via a quantum theory of the surface tension in metals to the new nuclear force theory are explained. A consideration of the magic numbers indicates a quark-shell structure of nuclei.

Keywords: Degenerate electrons; Endothermic element synthesis; Laser produced plasmas; Magic numbers; Quark gluon plasma; Theory of nuclei and nucleation

1. INTRODUCTION

In order to merge the knowledge of the Debye layer (Hora, 1991a; Hora *et al.*, 2005) as derived from the ablation in laser produced plasmas (Hora, 1991b; Hora *et al.*, 2005)—in contrast to Debye’s statistical derivation from electrolytic solutions—we summarize first the background theory of fully ionized high temperature plasmas. This leads to the application of electrons in a metal leading to a quantum theory of surface tension (Section 2). After this success of interpretation of temperature and Fermi energy, we perform an application on the Debye layer to the fermions of the nucleons in a nucleus where the empirical values of the nuclear radius and nucleon density are used as an input to show how the resulting Debye lengths have reasonable values and can be compared with the surface properties following Hofstadter’s measurements (Hahn *et al.*, 1956; Hofstadter & Collard, 1967) in Section 3. It is understood

that this first semi-empirical step is now explained as a first basis for the following second step which considerations (Hora, 2004, 2005; Hora *et al.*, 2005; Osman *et al.*, 2005) have to be included in the following.

In clarification of our earlier steps to this problem (Hora, 1991a; Hora *et al.*, 2005, p. 111) the inclusion of the plasma derivation of surface tension (Eliezer & Hora, 1989) based on the double layer theory (Hora *et al.*, 1989; Hora, 1991a, 1991b) is then generalized to the case of the nuclear Debye layer. The then calculated surface energy for confining nucleons at a radius R is compared with the enthalpy of the nucleons showing that both energies are equal when the R shrinks close to the well known value for nuclei. The nuclear Debye layer may then be used to explain the nuclear force as tangling bonds form Yukawa potentials. If a higher compression of the nuclei is done beyond the known value due to the balance with the Debye layer, the just then happening change of the Fermi energy into its relativistic branch diminishes the action of the surface energy. The particles cannot lead to a nucleation and a soup of neutrons as assumed, neutron stars appear on a soup of quark-gluon plasma (Section 4).

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Under conditions of still subrelativistic Fermi energy, a dependence of the nucleon number A in a nucleus for the equalization of the confining Debye layer with the enthalpy indicates that no higher values than for about uranium permit a nucleation under equilibrium conditions. Under this equilibrium a Boltzmann condition can be given, which indicates how an endothermic generation of heavy nuclei is possible. Comparison with the cosmic element distribution and that of laboratory experiments leads to an exponential increment which immediately explains the jump between the two Bagge series (Bagge, 1948; Haxel *et al.*, 1950) for the magic numbers of nuclei as it was described before (Osman *et al.*, 2005).

The nuclear Debye layer may be considered also as an expression of the inhomogeneous wave state for the nucleons in analogy to the optical waves in the thinner medium at total reflection. This aspect was raised for the optical case by the first measurement of the temporal Goos-Haenchen effect (Chauvat *et al.*, 2005). It is shown here for the first time that the nuclei undergo particle scattering at the nuclear surface where the state of the inhomogeneous wave is given by the Wigner (1955) mechanism due to total reflection at perpendicular incidence. This can be considered preferably at reflection at an inhomogeneous medium as familiar to plasma physics. This is also different to the usual Goos-Haenchen effect (Hora, 1960; Carter & Hora, 1971; Chauvat *et al.*, 2005) since only inhomogeneous media permit total reflection at perpendicular incidence (see Eq. (7.52), Hora, 1991b). It is important to understand that the study of the Debye layer is crucial for the case of plasmas at the present studies of sub-picosecond very high power laser-plasma interaction (Wilks *et al.*, 1992, 2001; Chen & Wilks, 2005) while this simultaneously led to the following new theory of the nuclear forces as discussed in Section 5. Application to astrophysics was discussed before (Hora, 2005).

2. DEBYE LAYER AND SURFACE TENSION IN LASER ABLATED PLASMAS

When considering surface tension for fully ionized plasmas, the immediate question is how this is possible since the surface tension for example, of water is due to unsaturated electric dipole of the highly polarized molecules, while fully ionized 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 (Hora, 2000, 2004). For laser powers below about one megawatt (MW), the plasma generated behaved classically when the temperature was about 5 eV, the emitted ions had similar maximum energies of the expected thermalized plasma, and the electron emission followed fully the thermionic Richardson laws with emis-

sion current densities of few mA/cm². When the Q-switched laser provided smooth and reproducible pulses of about 10 ns duration and powers of 10 MW and more, Linlor (see Hora, 1991b, 2000) measured from irradiated carbon, up to 10 keV energy of ions E_i . He found that the ions were non-thermally separated by their charge number Z linearly increasing according $E_i = \text{const } Z$. The Z -separation was first assumed to be due to the ambipolar fields. But these fields could only be 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 (see Hora, 1991b, 2000) measured electron emission current densities of 100 A/cm² and more, that is, 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) (Hora, 1969, 2000) to explain production of the 10 keV ion energies after the laser beam underwent ponderomotive self-focusing (Hora, 1969) 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 emission currents—was an example how to derive the Debye length. Figure 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 fast due to their small mass leaving behind a positive ion cloud such that the charge density due to the Gauss law produces a potential $\Phi(x)$ depending on the depth x and the derivative of Φ results in an electric field $E(x)$ within B. It turns out that the thickness of the area B is just the Debye length

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

where k is the Boltzmann constant, T is the plasma electron temperature, e is the electron charge, and n_e is 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 Figure 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 in the well known thermionic Richardson equation, as known for the electron emission of hot surfaces (most general formulation is Eq. (1.26) in Eliezer *et al.*, 2002) for the electron emission of hot surfaces.

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

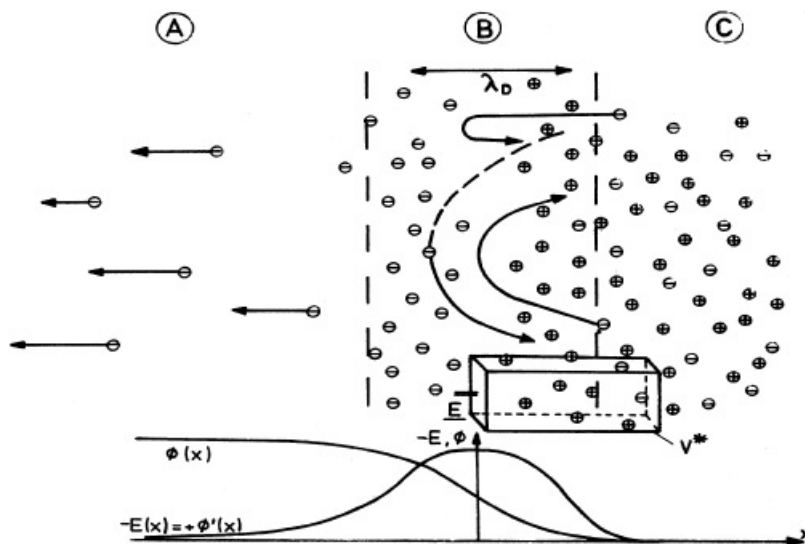


Fig. 1. Expansion of uniform plasma in C of temperature T into vacuum, range A. An Interface is created by the faster electrons leaving the surface area B letting behind positive charges in a double layer of thickness λ_D , Eq. (1), where the electric potential Φ according to a work function is built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

$$\sigma_e = 0.27T^2/(8\pi\epsilon^2\lambda_d), \quad (2)$$

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. (2) (see Hora *et al.*, 1989). 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 Hora, 2000) 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 more detail (Hora *et al.*, 1989; Eliezer & Hora, 1989; see also the first line of page 171 with reference to Kulsrud in Hora (1991b) calling “these fields are intuitively not clear”).

This result of the surface tension for fully ionized classical plasmas was generalized (Hora *et al.*, 1989) for electrons in a metal. The Fermi degenerated electron gas between the lattice of the metal ions acts like the electrons in the plasma of Figure 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 Figure 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; Hora *et al.*, 1989) 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, Hora, 1991b). This surface tension obviously is always positive in contrast to the basically different earlier model of surface tension known as “jellium model” where negative surface tension resulted which could be overcome only by sophisticated additional elaborations (Lang & Kohn, 1970).

3. EMPIRICAL FORMULATION OF A DEBYE-LAYER PROPERTY OF NUCLEI

The next step of generalization considers the nucleons (protons and neutrons) of nuclei instead of electrons and uses instead of the subrelativistic Fermi energy

$$E_F = (3n_{Nu}/\pi)^{2/3}h^2/(8m_{Nu}), \quad (3)$$

instead of the temperature T in Eq. (1) using nucleons with a mass m_{Nu} and density n_{Nu} instead of electron in Eq. (1). The nucleon Debye length is then

$$\lambda_N = [E_F/(4\pi e^2 n_{Nu})]^{1/2} \propto n_{Nu}^{-1/6}. \quad (4)$$

To confirm this as fact we take here the experimentally known values of nucleon densities, scattering very closely around the nucleon density in a nucleus

$$n_{Nu} = 8.5 \times 10^{37} \text{ cm}^{-3}, \quad (5a)$$

resulting in a Fermi energy for nucleons of 36 MeV, we find a Debye length of

$$\lambda_N = 3.4 \times 10^{-13} \text{ cm}. \quad (5b)$$

This length corresponds quite well with Hofstadter's measured density decay of about 3 fm of nucleons at the surface of heavy nuclei down to about calcium (see Fig. 14b of Hahn *et al.*, 1956) in rather good agreement with the nucleon Debye length (5b). One may not consider this fact as a coincidence but as a result of the just given steps for the generalization of the Debye length for the conditions of the nucleons in a nucleus.

After this basic and well convincing result we may consider the fact from Eq. (4) to understand why the 3fm-Hofstadter decay is so highly independent on the compared value of the nucleon Debye length (4). The nucleon density in the inner part of the nuclei is nearly the same for all nuclei between vanadium and bismuth which fact was involved in the average value of Eq. (5). These nuclei show then a rather unchanged decay profile due to the then unchanged Debye length (see Fig. 14b of Hahn *et al.*, 1956). An indication of a Debye layer mechanism can be seen when comparing the measurements of Figure 2 for calcium with the lower central nucleon density than that of gold. While the ratio of the central densities is 1.060, the ratio of the Debye lengths following Eq. (4) is 0.990 and an evaluation from the points in Figure 2 using the original values to minimize the error bars is 0.995 in acceptable agreement.

4. SURFACE ENERGY CONFINING NUCLEI AND QUARK TRANSITION

In the preceding section, the empirical nucleon density (5) was used. Now we are looking for a relation without such empirical input and are using an expression of the surface tension in analogy to the plasmas in order to see how this could confine an ensemble of protons and neutrons, see Figure 3. 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 for the Coulomb repulsion. The Fermi and the Coulomb energy are equal at a radius of 285 fm (Hora, 1991a); such that for smaller radii the Fermi energy is the dominating part of the internal energy of the nuclei. Looking into cases of

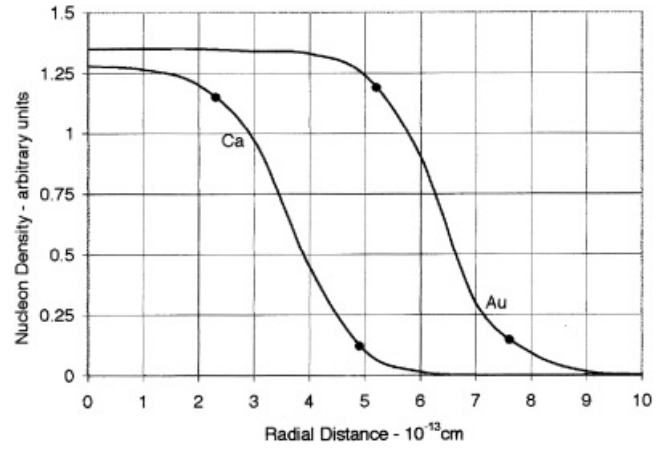


Fig. 2. Nucleon density in Ca and Au nuclei (Hahn *et al.*, 1956) with the decay at the surface using the points for comparison with the nucleon Debye length.

small radii, we can then consider the Coulomb forces and other components as small perturbations which are neglected here.

The following success will justify us to compare the Fermi energy of the proton and neutron ensemble of Figure 3 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 $E_s = E_{surf}$ in the same way from a surface tension as an expression (2) by using the Fermi energy of the nucleons. The surface tension for the nuclei is then

$$\sigma_e = 0.27 E_F^2 / (8\pi\epsilon^2 \lambda_N). \quad (6)$$

The Fermi energy can be expressed generally (see Eq. 1.7, Eliezer & Hora, 1989)

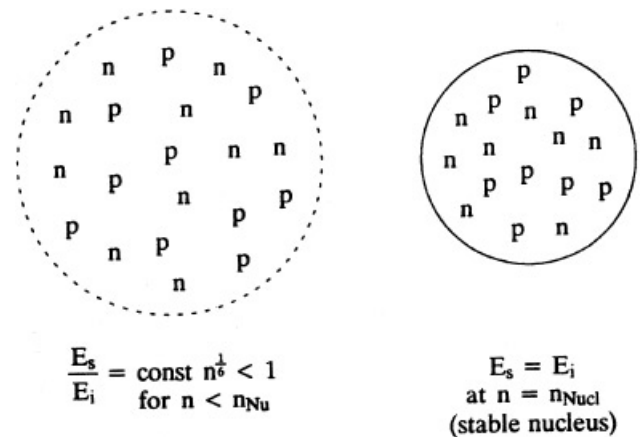


Fig. 3. Confining nucleons (protons p and neutron n) by surface energy E_s against internal energy E_i (\sim Fermi energy E_f) at shrinking radius (Hora, 1991a).

$$E_F = [3/(\pi)^{2/3}/4][h^2 n_{Nu}^{2/3}/(2m_{Nu})] \times (\lambda_C/2)^{-1} [n_{Nu} + \nu/(\lambda_C/2)^3]^{-1/3}, \quad (7a)$$

where n_{Nu} is the nucleon density. This splits into the branches

$$E_F = \begin{cases} [3/(\pi)^{2/3}/4]h^2 n_{Nu}^{2/3}/(2m_{Nu}) & \text{(subrelativistic),} \\ [3/(\pi)^{2/3}/4]hcn_{Nu}^{1/3}/(2\pi) & \text{(relativistic),} \end{cases} \quad (7b)$$

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 (Hora, 1991a). The surface energy of the nucleus is then

$$E_{surf} = 0.27[3A(4\pi)^{1/2}]^{2/3} 3^{1/3} E_F^{2/3} / (\pi^{1/2} 2^{5/2} n_{Nu}^{1/6} e). \quad (8)$$

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

$$E_{surf}/(AE_F) = \begin{cases} 0.27(3^{3/2}/2^{10/3})hn_{Nu}^{1/6}/(em_{Nu}^{1/2} A^{1/3}) & \text{(subrelativistic),} \\ 0.27[3^{8/3}/(2^{7/3}\alpha^{1/2} A^{1/3})] & \text{(relativistic),} \end{cases} \quad (9a)$$

using the fine structure constant $\alpha = 2\pi e^2/(hc)$. From (9a) 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 n_{Nu} where the ratio (9a) is equal to one. This is the case close to the well known value of the nuclear density as checked for example, for bismuth (Hora, 1991a; Osman *et al.*, 2005). The surface “Debye”-layer has a thickness of about 2 to 3 fm, with these not empirically derived parameters close to (5b) again showing 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 (9b) does not depend on the nucleon mass or 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 the nucleation is due to the Debye layer confinement just at the well known nucleon density in nuclei.

Considering the value of (9a) to be unity of the nucleation when reaching the nuclear density, the surface energy will produce sub-relativistic nuclear densities with the limit for this nuclear-chemical equilibrium where 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 (Rauscher *et al.*, 1994). Higher trans-uranium nuclei by heavy ion collisions

as an extremely non-equilibrium process are then really manmade, well following the rule of magic numbers as was shown before (Osman *et al.*, 2005; Hora *et al.*, 2005).

5. DISCUSSION OF PROPERTIES OF THE NUCLEAR DEBYE LAYER

We discuss now whether the nucleus with constant nucleon density in the interior may be considered as a box (Li *et al.*, 2004) where the outside decay of the density as a Debye layer which may permit a description similar to the inhomogeneous wave at total reflection in the lower density medium.

This relates to the matter wave propagation at particle scattering as considered by Wigner (1955) where the wave propagation into the lower density medium was described in analogy to the optical case of the Goos-Haenchen effect. Its optical temporal Goos-Haenchen effect (Chauvat *et al.*, 2005) case was experimentally confirmed with time resolution of femto- to attoseconds (Tzallas *et al.*, 2003). For the case of particle scattering, the effects had to be based on the special second order difference of the matter waves against optical waves (Hora, 1960; Carter & Hora, 1971). While the temporal Goos-Haenchen effect in the optical case shows the clear difference for contrasting polarization, the Wigner (1955) consideration indicates a problem which was evaluated for electron waves (Hora, 1960; Carter & Hora, 1971) that there is a drastic and yet unsolved difference between a phase (Ψ -treatment) against an intensity ($\Psi * \Psi$ -treatment). A further important connection is to the optical cases with respect to the nonlinear conditions (Hora, 2000).

An interpretation of Wigner’s particle scattering for the nucleons in a nucleus at the confining nuclear Debye layer is similar to the total reflection for electrons in the plasma case where, however, the Goos-Haenchen conditions have to be generalized to the total reflection at an inhomogeneous surface. Only then, total reflection is possible even at perpendicular incidence (see Chapter 7, Hora, 1991a) with respect to WKB approximations or the exact case of Rayleigh profiles. It was found that the corresponding wave mechanical response (analog to the dielectric decay in optics) of the hadron waves in the nuclear Debye layer has characteristic lengths very close to the nuclear Debye length if an exact solution with a Rayleigh profile for the inhomogeneous medium is used for approximation of any real profile.

In laser–plasma interaction with sub-picosecond pulses of more than 10 TW focused power and subsequent relativistic self-focusing—in contrast to the sub-relativistic plasma block generation (Hora, 2004; Osman *et al.*, 2004; Hora, 2005; Hora *et al.*, 2005b; Badziak *et al.*, 2005; Glowacz *et al.*, 2006; Jablonski *et al.*, 2005)—a separation of electron clouds from ions causes high electric field which were described similar to the Debye layers. The evaluation was initiated by Wilks *et al.* (1992) using the PIC computation (Greschik & Kull, 2004; Limpouch *et al.*, 2004; Klimo & Limpouch, 2006). Details were summarized by Chen and Wilks (2005) where a generalization to the conditions of the

Debye layer for the hadrons in a nucleus may be indicated in a similar way.

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