Absorption of Nuclear Gamma Radiation by Heavy Electrons on Metallic Hydride Surfaces

A. Widom
Physics Department, Northeastern University, 110 Forsyth Street, Boston MA 02115

L. Larsen
Lattice Energy LLC, 175 North Harbor Drive, Chicago IL 60601

Low energy nuclear reactions in the neighborhood of metallic hydride surfaces may be induced by ultra-low momentum neutrons. Heavy electrons are absorbed by protons or deuterons producing ultra low momentum neutrons and neutrinos. The required electron mass renormalization is provided by the interaction between surface electron plasma oscillations and surface proton oscillations. The resulting neutron catalyzed low energy nuclear reactions emit copious prompt gamma radiation. The heavy electrons which induce the initially produced neutrons also strongly absorb the prompt nuclear gamma radiation, re-emitting soft photons. Nuclear hard photon radiation away from the metallic hydride surfaces is thereby strongly suppressed.

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I. INTRODUCTION

Low energy nuclear reactions (LENR) may take place in the neighborhood of metallic hydride surfaces[1, 2]. The combined action of surface electron density plasma oscillations and surface proton oscillations allow for the production of heavy mass renormalized electrons. A heavy electron, here denoted by $\tilde{e}^-$, may produce ultra-low momentum neutrons via the reaction[3]

$$\tilde{e}^- + p^+ \to n + \nu_e. \tag{1}$$

Once the ultra low momentum neutrons are created, other more complex low energy nuclear reactions may be catalyzed[4]. Typically, neutron catalyzed nuclear reactions release energy in large part by the emission of prompt hard gamma radiation. However, the copious gamma radiation and neutrons have not been observed away from the metallic hydride surface. Our purpose is to theoretically explain this experimental state of affairs. In particular, we wish to explore the theoretical reasons why copious prompt hard gamma radiation has *not* been observed for LENR on metallic hydride surfaces. The experimental fact that a *known* product particle is not observed far from the metallic hydride surface is related to the fact that the mean free path of the product particle to be converted to other particles is short. As an example of such arguments, we review in Sec. II, why the mean free path of an ultra low momentum neutron is so short. A short mean free path implies that the product particle never appears very far from the surface in which it was first created.

For hard gamma radiation, the mean free path computation in metals is well known[5, 6]. For normal metals, there exists *three* processes determining prompt gamma photon mean free path. The processes are as follows:
(1) *The photoelectric effect:* The hard photon blasts a bound core electron out of the atom.
(2) *Compton scattering from normal conduction electrons:* The hard photon scatters off a very slowly moving conduction electron giving up a finite fraction of its energy to this electron.

$$\gamma + e_i^- \to \gamma' + e_f^- \tag{2}$$

The final photon γ' is nonetheless fairly hard.
(3) *Creation of electron-positron pairs:* The hard gamma photon creates an electron-positron pair. Kinematics disallows this one photon process in the vacuum. Pair production can take place in a metal wherein other charged particles can recoil during the pair production process. Roughly, the resulting mean free paths of hard prompt gamma photons is of the order of centimeters when all of the above above mechanisms are taken into account.

Let us now consider the situation in the presence of heavy electrons. The processes are as follows:
(1) *The absence of a heavy electron photoelectric effect:* The surface heavy electrons are all conduction electrons. They do not occupy bound core states since the energy is much too high. Thus, there should be no heavy electron photoelectric effect. There will be an anomalously high surface electrical conductivity due to these heavy conduction electrons. This anomaly occurs as the threshold proton (or deuteron) density for neutron catalyzed LENR is approached.
(2) *Compton scattering from heavy conduction electrons:* When the hard gamma photon is scattered from a heavy electron, the final state of the radiation field consists of very many very soft photons; i.e. the Compton Eq.(2) is replaced by

$$\gamma + \tilde{e}_i^- \to \sum \gamma_{soft} + \tilde{e}_f^-. \tag{3}$$

It is the final state soft radiation, shed from the mass renormalized electrons, that is a signature for the heavy electron Compton scattering.
(3) *Creation of heavy electron-hole pairs:* In order to achieve heavy electron pair energies of several MeV, it

is not required to reach way down into the vacuum Dirac electron sea[7]. The energy differences between electron states in the heavy electron conduction states is sufficient to pick up the "particle-hole" energies of the order of MeV. Such particle-hole pair production in conduction states of metals is in conventional condensed matter physics described by electrical conductivity.

In Sec. III, the theory of electromagnetic propagation in metals is explored. We show that an optical photon within a metal has a very short mean free path for absorption. The short mean free path makes metals opaque to optical photons. The effect can be understood on the basis of the Bohr energy rule

$$\Delta E = \hbar\omega. \tag{4}$$

For optical frequencies, $\hbar\omega$ is of the order of a few electron volts and typical particle-hole pair creation energies near the Fermi surface are also of the order of a few electron volts. The resulting strong electronic absorption of optical photons is most easily described by the metallic electrical conductivity. For hard photons with an energy of the order of a few MeV, there are ordinarily no electronic particle-hole solid state excitations with an energy spread which is so very large. A normal metal is thus ordinarily transparent to hard gamma rays.

On the other hand, the non-equilibrium neutron catalysis of LENR near metallic hydride surfaces is due to heavy electrons with a renormalized mass having energy spreads of several MeV. These large energy spreads for the heavy surface electrons yield the mechanism for hard gamma ray absorption. This mechanism is explained in detail in Secs. IV and V. In Sec. IV A, we review the reasons for which a single electron in the vacuum *cannot* absorb a hard single massless photon. In Sec. IV B, we review the reasons why a single electron within a plain wave radiation beam *can* absorb a hard single massless photon. The proof requires the well established exact solutions of the Dirac wave functions in a plane wave radiation field[8] and contains also the proof of the induced electron mass renormalization in this radiation field. The electrical conductivity of induced non-equilibrium heavy electrons on the metallic hydride surface as seen by hard photons will explored in Sec. V. The energy spread of heavy electron-hole pair excitations implies that a high conductivity near the surface can persist well into the MeV photon energy range strongly absorbing prompt gamma radiation. An absorbed *hard* gamma photon can be re-emitted as a very large number of *soft* photons, e.g. infrared and/or X-ray. The mean free path of a hard gamma photon estimated from physical kinetics[9] has the form

$$L_\gamma \approx \left(\frac{3}{\pi}\right)^{1/3} \left(\frac{1}{4\alpha}\right) \frac{1}{\tilde{n}^{2/3}\tilde{l}} \approx \frac{33.7}{\tilde{n}^{2/3}\tilde{l}}\ , \tag{5}$$

where $\tilde{n}$ is the number of heavy electrons per unit volume, $\tilde{l}$ is the mean free path of a heavy electron and the quantum electrodynamic coupling strength is

$$\alpha = \frac{e^2 R_{vac}}{4\pi\hbar} = \frac{e^2}{\hbar c} \approx \frac{1}{137.036}\ . \tag{6}$$

The number density of heavy electrons on a metallic hydride surface is of the order of the number density of surface hydrogen atoms when there is a proton or deuteron flux moving through the surface and LENR are being neutron catalyzed. These added heavy electrons produce an anomalously high surface electrical conductivity at the LENR threshold. Roughly, $\tilde{n}^{2/3} \sim 10^{15}/\text{cm}^2$, $\tilde{l} \sim 10^{-6}$ cm so that the mean free path of a hard prompt gamma ray is $L_\gamma \sim 3.4 \times 10^{-8}$ cm. Thus, prompt hard gamma photons get absorbed within less than a nanometer from the place wherein they were first created. The energy spread of the excited particle hole pair will have a cutoff of about 10 MeV based on the mass renormalization of the original electron. The excited heavy electron hole pair will annihilate, producing very many soft photons based on the photon spectrum which produced such a mass renormalization. The dual role of the heavy electrons is discussed in the concluding Sec. VI. In detail, the heavy electrons are absorbed by protons creating ultra-low momentum neutrons and neutrinos which catalyze further LENR, e.g. subsequent neutron captures on nearby nuclei. The heavy electrons also allow for the strong absorption of prompt hard gamma radiation produced from LENR.

II. NEUTRON MEAN FREE PATH

Suppose there are n neutron absorbers per unit volume with an absorption cross section Σ. The mean free path Λ of the neutron is then given by

$$\Lambda^{-1} = n\Sigma = \frac{4\pi\hbar n}{p} \Im m\ \mathcal{F}(0) = \frac{4\pi\hbar n b}{p}\ , \tag{7}$$

where p is the neutron momentum and $\mathcal{F}(0)$ is the forward scattering amplitude. The imaginary part of the scattering length is denoted by b. In terms of the ultra low momentum neutron wave length $\lambda = (2\pi\hbar/p)$, Eq.(7) implies

$$\Lambda = \frac{1}{2n\lambda b}\ . \tag{8}$$

The ultra low momentum neutron is created when a heavy electron is absorbed by one of many protons participating in a collective surface oscillation. The neutron wave length is thus comparable to the spatial size of the collective oscillation, say $\lambda \sim 10^{-3}$ cm. With (for example) $b \sim 10^{-13}$ cm and $n \sim 10^{22}$ cm^{-3}, one finds a neutron mean free path of $\Lambda \sim 10^{-6}$ cm. An ultra low momentum neutron is thus absorbed within about ten nanometers from where it was first created. The likelihood that ultra low momentum neutrons will escape capture and thermalize via phonon interactions is very small.

III. OPTICAL PHOTON MEAN FREE PATH

Consider an optical photon propagating within a metal with conductivity σ. From Maxwell's equations

$$\begin{aligned} curl\mathbf{E} &= -\frac{1}{c}\frac{\partial \mathbf{B}}{\partial t}, \\ div\mathbf{B} &= 0, \\ curl\mathbf{B} &= \frac{1}{c}\left\{\frac{\partial \mathbf{E}}{\partial t} + 4\pi\mathbf{J}\right\}, \end{aligned} \tag{9}$$

it follows that

$$\left\{\frac{1}{c^2}\left(\frac{\partial}{\partial t}\right)^2 - \Delta\right\}\mathbf{B} - \frac{4\pi}{c}curl\mathbf{J} = 0. \tag{10}$$

Employing Ohms law in the form

$$\begin{aligned} \mathbf{J} &= \sigma\mathbf{E} \\ curl\ \mathbf{J} &= -\frac{\sigma}{c}\left(\frac{\partial \mathbf{B}}{\partial t}\right), \end{aligned} \tag{11}$$

yields the wave equation with dissipative damping

$$\left\{\left(\frac{\partial}{\partial t}\right)^2 + 4\pi\sigma\left(\frac{\partial}{\partial t}\right) - c^2\Delta\right\}\mathbf{B} = 0. \tag{12}$$

The transition rate per unit time for the optical photon absorption is then $4\pi\sigma$. This argument yields an optical photon mean free path L given by

$$\frac{1}{L} = \frac{4\pi\sigma}{c} = R_{vac}\sigma \tag{13}$$

wherein R_{vac} is the vacuum impedance. In SI units, the optical photon mean free path is given by

$$L = \frac{1}{R_{vac}\sigma} \quad \text{where} \quad \frac{R_{vac}}{4\pi} \equiv 29.9792458 \text{ Ohm}. \tag{14}$$

For a metal with low resistivity

$$\sigma^{-1} \lesssim 10^{-5} \text{ Ohm cm}, \tag{15}$$

the mean free path length of an optical photon obeys

$$L \lesssim 3 \times 10^{-8} \text{ cm}. \tag{16}$$

An optical photon in a metal is absorbed in less than a nanometer away from the spot in which it was born. Thus, normal metals are opaque to visible light.

To see what is involved from a microscopic viewpoint, let us suppose an independent electron model in which occupation numbers are in thermal equilibrium with a Fermi distribution

$$f(E) = \frac{1}{e^{(E-\mu)/k_B T} + 1}\ . \tag{17}$$

If the conductivity is described in terms of elastic electron scattering from impurities or phonons, then the conductivity in a volume Ω containing conduction electrons is described by the Kubo formula[10]

$$\begin{aligned} &\Re e\{\sigma(\omega + i0^+)\} = -\frac{\pi}{6}\left(\frac{e^2}{\Omega}\right) \times \\ &\sum_{i,f}\left[\frac{f(E_f) - f(E_i)}{E_f - E_i}\right]|\mathbf{v}_{fi}|^2[\delta(\omega - \omega_{fi}) + \delta(\omega + \omega_{fi})], \\ &\hbar\omega_{fi} = E_f - E_i, \end{aligned} \tag{18}$$

wherein $\mathbf{v}_{fi}$ is a matrix element of the electron velocity operator $\mathbf{v}$. If one starts from the interaction between an electron and a photon in the form

$$H_{int} = -\frac{e}{c}\mathbf{A}\cdot\mathbf{v}, \tag{19}$$

applies Fermi's Golden rule for photon absorption, averages over initial states and sums over final states, then the result for the frequency dependent optical photon mean free path $L(\omega)$ is

$$\frac{1}{L(\omega)} = \frac{4\pi}{c}\Re e\{\sigma(\omega + i0^+)\} = R_{vac}\Re e\{\sigma(\omega + i0^+)\}, \tag{20}$$

where Eq.(18) has been taken into account. Eqs.(18) and (20) are merely the microscopic version of Eq.(13) which followed directly from Maxwell's equations and Ohm's law. In thermal equilibrium , the energy differences between electron states are of the order of electron volts. As the photon frequency is increased to the nuclear physics scale of MeV, the electrical conductivity $\Re e\{\sigma(\omega + i0^+)\}$ rapidly approaches zero. Thus, a metal in thermal equilibrium is almost transparent to hard nuclear gamma radiation. As will be discussed in what follows, for the surfaces of metallic hydrides in non-equilibrium situations with heavy electrons, strong absorption of nuclear gamma radiation can occur.

IV. HARD PHOTONS - HEAVY ELECTRONS

Heavy electrons appear on the surface of a metallic hydride in non-equilibrium situations. Sufficient conditions include (i) intense LASER radiation incident on a suitably rough metallic hydride surface, (ii) high chemical potential differences across the surface due electrolytic voltage gradients and (iii) high chemical potential differences across the surface due to pressure gradients. Under such non-equilibrium conditions, weakly coupled surface plasmon polariton oscillations and proton oscillations induce an oscillating electromagnetic field

$$F_{\mu\nu}(x) = \partial_\mu A_\nu(x) - \partial_\nu A_\mu(x) \tag{21}$$

felt by surface electrons. From a classical viewpoint, the electrons obey the Lorentz force equation

$$\frac{d^2x^\mu}{d\tau^2} = \frac{e}{c}F^\mu{}_\nu(x)\frac{dx^\nu}{d\tau}. \tag{22}$$

From the quantum mechanical viewpoint, the electron wave function obeys the Dirac equation

$$\left\{\gamma^\mu\left(-i\hbar\partial_\mu - \frac{e}{c}A_\mu(x)\right) + mc\right\}\psi(x) = 0. \tag{23}$$

The quantum motions are intimately related to the classical motions as can be seen by formulating the problem in terms of the Hamilton-Jacobi action $S(x)$. To describe the classical orbits according to Eq.(22), one seeks a classical velocity field $v^\mu(x)$ obeying the Hamilton-Jacobi equations[11]

$$\begin{aligned} mv_\mu(x) &= \partial_\mu S(x) - \frac{e}{c}A_\mu(x), \\ v^\mu(x)v_\mu(x) &= -c^2. \end{aligned} \tag{24}$$

The orbits implicit in the second order Eqs.(22) may now be obtained by solving the first order equations of motion

$$\frac{dx^\mu}{d\tau} = v^\mu(x). \tag{25}$$

From the quantum mechanical biewpoint, one seeks a solution to the Dirac Eq.(24) having the form

$$\psi(x) = u(x)e^{iS(x)/\hbar}. \tag{26}$$

The classical velocity field $v^\mu(x)$ makes its appearance in the equation of motion for the spinor $u(x)$; It is exactly

$$\left\{\gamma^\mu\big(-i\hbar\partial_\mu + mv^\mu(x)\big) + mc\right\}u(x) = 0. \tag{27}$$

Eqs.(24), (26) and (27) constitute the "unperturbed" electron states in the classical electromagnetic field $F_{\mu\nu}$ describing *soft* radiation from a non-perturbation theory viewpoint. The *hard* gamma photons may *thereafter* be treated employing low order perturbation theory. Two specific examples should suffice to illustrate the point.

A. Free Electrons in the Vacuum

A classical free electron has a Hamilton-Jacobi action which obeys

$$\begin{aligned} \partial_\mu S(x)\partial^\mu S(x) &+ m^2c^2 = 0, \\ S(x) &= p_\mu x^\mu, \\ p_\mu p^\mu &= -m^2c^2. \end{aligned} \tag{28}$$

For a classical free electron, the velocity field is uniform in space and time; i.e.

$$\begin{aligned} \frac{dx^\mu}{d\tau} &= v^\mu = \frac{p^\mu}{m}\ , \\ x^\mu &= \left(\frac{p^\mu}{m}\right)\tau. \end{aligned} \tag{29}$$

The free particle quantum theory solutions follow from Eqs.(26), (27), (28) and (29) according to

$$\begin{aligned} \psi(x) &= u(p)e^{ip\cdot x/\hbar}, \\ \big(\gamma^\mu p_\mu &+ mc\big)u(p) = 0. \end{aligned} \tag{30}$$

Eq.(30) serves as the starting point for the computation of a single hard photon absorption (with wave vector k and polarization ϵ) by an electron in the vacuum. The *vanishing* amplitude is computed as

$$\begin{aligned} \mathcal{F}(e_i^- + \gamma \to e_f^-) &= \frac{i}{\hbar c^2}\int J^\mu_{fi}(x)A_\mu(x)d^4x, \\ \mathcal{F}(e_i^- + \gamma \to e_f^-) &= \frac{ie}{\hbar c}\int \bar{\psi}_f\ (x)\gamma^\mu\psi_i(x)A_\mu(x)d^4x, \\ \mathcal{F}(e_i^- + \gamma \to e_f^-) &= \left(\frac{ieA_\gamma}{\hbar c}\right)\epsilon_\mu\bar{u}(p_f)\gamma^\mu u(p_i)\times \\ &\quad \int e^{i(p_i+\hbar k-p_f)\cdot x/\hbar}d^4x, \\ \mathcal{F}(e_i^- + \gamma \to e_f^-) &= \left(\frac{ieA_\gamma}{\hbar c}\right)\epsilon_\mu\bar{u}(p_f)\gamma^\mu u(p_i)\times \\ &\quad (2\pi\hbar)^4\delta(p_i+\hbar k-p_f), \\ \mathcal{F}(e_i^- + \gamma \to e_f^-) &= 0. \end{aligned} \tag{31}$$

Of central importance is the impossibility of satisfying the four momentum conservation law $p_i + \hbar k = p_f$ for fixed electron mass $p_i^2 = p_f^2 = -m^2c^2$ and zero photon mass,

$$k^\mu k_\mu = 0. \tag{32}$$

Thus, hard photon absorption by a single electron in the vacuum is not possible.

B. Electrons and Electromagnetic Oscillations

Suppose that the electron is in the field of *soft* radiation. For example, the electron may be within a plane wave laser radiation beam. Further suppose an additional *hard* gamma photon is incident upon the electron. In this case (unlike the vacuum case) the hard photon can indeed be absorbed. For a plane wave electromagnetic oscillation of the form

$$\begin{aligned} A^\mu_{soft}(x) &= a^\mu(\phi), \\ \phi &= q_\mu x^\mu \quad \text{where} \quad q^\mu q_\mu = 0, \\ \partial_\mu A^\mu_{soft}(x) &= q_\mu\frac{da^\mu(\phi)}{d\phi} = 0, \end{aligned} \tag{33}$$

the action function is[12]

$$S(x) = p_\mu x^\mu + W_p(\phi). \tag{34}$$

To find the function $W_p(\phi)$, one may compute the velocity field

$$mv^\mu(x) = p^\mu - \frac{e}{c}a^\mu(\phi) + q^\mu W_p'(\phi), \tag{35}$$

and impose the Hamilton-Jacobi condition $v^\mu v_\mu = -c^2$. Solving this condition for $W_p(\phi)$ taking Eq.(33) into account yields

$$2(p\cdot q)W_p'(\phi) = \frac{2ep\cdot a(\phi)}{c} - \left\{m^2c^2 + p^2 + \frac{e^2a^2(\phi)}{c^2}\right\},$$

$$W_p(\phi) \;=\; \int_0^{\phi} W_p'(\tilde{\phi})d\tilde{\phi}. \qquad (36)$$

If $W_p'(\phi)$ remaines finite during a oscillation period, then on phase averaging $\overline{W_p'} = \tilde{p} - p$. This leads to mass renormalization $m \to \tilde{m}$ of the electron in the laser field

$$\begin{aligned} \tilde{p}^2 + (\tilde{m}c)^2 &= 0, \\ (\tilde{m}c)^2 &= (mc)^2 + \left(\frac{e}{c}\right)\overline{a^2(\phi)}. \end{aligned} \qquad (37)$$

Importantly, the same electromagnetic oscillations which increase the electron mass, also allow for the absorption of hard gamma photons by the surface heavy electron. The gamma ray absorption amplitude for a heavy electron has the form[13]

$$\begin{aligned} \mathcal{F}(\tilde{e}_i^- + \gamma \to \tilde{e}_f^-) &= \frac{i}{\hbar c^2}\int J^{\mu}_{fi}(x)A_{\mu}(x)d^4x, \\ \mathcal{F}(\tilde{e}_i^- + \gamma \to \tilde{e}_f^-) &= \left(\frac{ieA_\gamma}{\hbar c}\right)\epsilon_\mu \times \\ &\int \bar{u}_f\gamma u_i e^{i(\tilde{p}_i+\hbar k-\tilde{p}_f)\cdot x/\hbar} \times \\ &e^{i(\tilde{W}_i(\phi)-\tilde{W}_f(\phi))/\hbar}d^4x, \\ \mathcal{F}(\tilde{e}_i^- + \gamma \to \tilde{e}_f^-) &= \sum_n \epsilon_\mu \mathcal{F}^{\mu}_{i\to f}(n) \times \\ &\delta(\tilde{p}_i + \hbar k - \tilde{p}_f - \hbar n q). \end{aligned} \qquad (38)$$

The conservation of four momentum for heavy electrons $\tilde{p}_i + \hbar k = \tilde{p}_f + n\hbar q$ as in Eq.(38) differs the conservation of four momentum $p_i + \hbar k = p_f$ for the vacuum case in Eq.(31). Only the heavy electrons can absorb a hard photon with four momentum $\hbar k$ emitting n photons each with four momentum $\hbar q$. The transition rate per unit time per unit volume for the reaction

$$\tilde{e}_i^- + \gamma \to \tilde{e}_f^- + n\gamma_{soft} \qquad (39)$$

is given by

$$\begin{aligned} \nu_{i\to f}(n) &= \frac{(2\pi)^4}{c}\left|\epsilon_\mu \mathcal{F}^{\mu}_{i\to f}(n)\right|^2 \times \\ &\delta\left(\frac{\tilde{p}_f - \tilde{p}_i}{\hbar} + nq - k\right), \\ \tilde{p}_i^2 &= \tilde{p}_f^2 = -(\tilde{m}c)^2, \\ \nu_{i\to f} &= \sum_n \nu_{i\to f}(n). \end{aligned} \qquad (40)$$

with a renormalized electron mass given in Eq.(37). Thus, for the exactly soluble plane wave low frequency oscillation, we have shown how a high frequency hard photon cam scatter off a heavy electron producing many low frequency soft photons.

V. HARD PHOTON ABSORPTION

Let us now return to the heavy electron oscillations on the surface of metallic hydrides. The same heavy electrons required to produce neutrons for catalyzed LENR are also capable of absorbing prompt gamma radiation via the electrical conductivity which now extends to frequencies as high as about $\hbar\omega_{max} \sim 10$ MeV. Just as for the optical photon case of Sec. III, we may proceed via Maxwell's equations for the hard photon field

$$\begin{aligned} \delta F_{\mu\nu} &= \partial_\mu \delta A_\nu - \partial_\nu \delta A_\mu, \\ \partial_\mu \delta A^\nu &= 0, \\ \partial_\mu \delta F^{\mu\nu} &= -R_{vac}\delta J^\mu. \end{aligned} \qquad (41)$$

The heavy electron current response to the prompt hard photon may be written as

$$R_{vac}\delta J^\mu(x) = \int \Pi^{\mu\nu}(x,y;A)\delta A_\nu(y)d^4y. \qquad (42)$$

Especially note that the heavy electron current response function Π depends on the soft radiation field which renormalized the electron mass in the first place. To lowest order in the quantum electrodynamic coupling in Eq.(6), we have the independent electron model relativistic Kubo formula in the one loop insertion form[14]

$$\begin{aligned} &\left\{-i\gamma^\mu\left(\partial_\mu - i\frac{eA_\mu(x)}{\hbar c}\right) + \frac{mc}{\hbar}\right\}\mathcal{G}(x,y,;A) = \delta(x-y), \\ &\Pi^{\mu\nu}(x,y;A) = 4\pi i\alpha\; tr\left\{\gamma^\mu \mathcal{G}(x,y;A)\gamma^\nu \mathcal{G}(y,x;A)\right\}. \end{aligned} \qquad (43)$$

The equation of motion for the hard prompt gamma photon is thereby

$$-(\partial_\lambda \partial^\lambda)\delta A^\nu(x) - \int \Pi^{\mu\nu}(x,y;A)\delta A_\nu(y)d^4y = 0, \qquad (44)$$

wherein the damping is contained in Π which in turn depends on background electromagnetic field oscillations.

The *physical kinetics* estimate[15] of the hard prompt gamma photon absorption is as follows: (i) In the energy regime of the heavy electron mass renormalization, the conductivity obeys

$$\begin{aligned} \sigma_\gamma &\approx \frac{1}{(3\pi^2)^{1/3}}\left(\frac{e^2}{\hbar}\right)(\tilde{n}^{2/3}\tilde{l}), \\ \text{for energies} \quad & 0.5 \text{ MeV} \lesssim \hbar\omega_\gamma \lesssim 10 \text{ MeV}, \end{aligned} \qquad (45)$$

where the heavy electrons have a density per unit volume of $\tilde{n}$ and an electronic mean free path of $\tilde{l}$. (ii) We estimate for typical metallic hydride LENR, the values

$$\tilde{n}^{2/3} \sim 10^{15}/\text{cm}^2 \quad \text{and} \quad \tilde{l} \sim 10^{-6} \text{ cm}. \qquad (46)$$

(iii) The hard prompt photon mean free path is then

$$\frac{1}{L_\gamma} = R_{vac}\sigma_\gamma \approx 4\alpha\left(\frac{\pi}{3}\right)^{1/3}(\tilde{n}^{2/3}\tilde{l}) \qquad (47)$$

in agreement with Eqs.(5) and (6). (iv) The final estimate for the mean free path of a hard prompt gamma photon follows from Eqs.(46) and (47) to be

$$L_\gamma \sim 3.4 \times 10^{-8} \text{ cm}. \qquad (48)$$

Thus, the hard photon is absorbed at a distance of less than a nanometer away from where it was first created. This constitutes the central result of this work.

VI. CONCLUSION

Our picture of LENR in non-equilibrium situations near the surface of metallic hydrides may be described in the following manner: from the weakly coupled proton and electronic surface plasmon polariton oscillations, the electrons have their mass substantially renormalized upward. This allows for the production of ultra low momentum neutrons and neutrinos from heavy electrons interacting with protons or deuterons

$$\begin{aligned} \tilde{e}^- + p^+ &\rightarrow n + \nu_e, \\ \tilde{e}^- + d^+ &\rightarrow n + n + \nu_e. \end{aligned} \qquad (49)$$

The resulting ultra low momentum neutrons catalyze a variety of different nuclear reactions, creating complex nuclear reaction networks and related transmutations over time. The prompt hard gamma radiation which accompanies the neutron absorption is absorbed by the heavy electrons which drastically lowers the radiation frequencies of the finally produced photons via

$$\tilde{e}_i^- + \gamma_{hard} \rightarrow \tilde{e}_f^- + \sum \gamma_{soft}. \qquad (50)$$

In the range of energies $\hbar\omega_\gamma$ less than the renormalized energy of the heavy electrons, the prompt photon in Eq.(50) impies a prompt hard gamma mean free path of less than a nanometer. The metallic hydride surface is thus opaque to hard photons but not to softer X-ray radiation in the KeV regime. In certain non-equilibrium metallic hydride systems, surface heavy electrons play a dual role in allowing both Eqs,(49) for catalyzing LENR and Eq.(50) for absorbing the resulting hard prompt photons. Thus, the heavy surface electrons can act as a gamma ray shield. Once the non-equilibrium conditions creating heavy electrons cease, ultra low momentum neutron production and gamma absorption both stop very rapidly.

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