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Ultra low momentum neutron catalyzed nuclear reactions on metallic hydride surfaces

A. Widom[1,a], L. Larsen[2]

[1] Physics Department, Northeastern University, 110 Forsyth Street, Boston MA 02115, USA
[2] Lattice Energy LLC, 175 North Harbor Drive, Chicago IL 60601, USA

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Abstract. Ultra low momentum neutron catalyzed nuclear reactions in metallic hydride system surfaces are discussed. Weak interaction catalysis initially occurs when neutrons (along with neutrinos) are produced from the protons that capture "heavy" electrons. Surface electron masses are shifted upwards by localized condensed matter electromagnetic fields. Condensed matter quantum electrodynamic processes may also shift the densities of final states, allowing an appreciable production of extremely low momentum neutrons, which are thereby efficiently absorbed by nearby nuclei. No Coulomb barriers exist for the weak interaction neutron production or other resulting catalytic processes.

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1 Introduction

It is very well-known that a proton p^+ can capture a charged lepton l^- and produce a neutron and a neutrino from the resulting process [1]

$$\mathrm{l}^- + \mathrm{p}^+ \to n + \nu_\mathrm{l}\,. \tag{1}$$

A common form of nuclear transmutation in condensed matter is understood in terms of (1). An electron e^- that wanders into a nucleus with Z protons and $N = A - Z$ neutrons can be captured, producing an electron neutrino ν_e and leaving behind a nucleus with $Z-1$ protons and $N+1 = A-(Z-1)$ neutrons. The electron capture process in a condensed matter nucleus may be described by the nuclear transmutation reaction [2,3]

$$\mathrm{e}^- + (A, Z) \to (A, Z-1) + \nu_\mathrm{e}\,. \tag{2}$$

Note the absence of a Coulomb barrier to such a weak interaction nuclear process. It is this feature that makes the neutron induced nuclear transmutations more likely than other nuclear reactions that are impeded by Coulomb barriers. In fact, a strong Coulomb *attraction* that can exist between an electron and a nucleus *helps* the nuclear transmutation (2) proceed. While the process (1) is experimentally known to occur when muons are mixed into hydrogen systems [4–6], i.e. $\mu^- + \mathrm{p}^+ \to n + \nu_\mu$, it is regarded as difficult for nature to play the same trick with electrons and protons at virtual rest. For (1) to spontaneously occur it is required that the lepton mass obey a threshold condition,

$$M_\mathrm{l} c^2 > M_n c^2 - M_\mathrm{p} c^2 \approx 1.293\,\mathrm{MeV} \approx 2.531 M_\mathrm{e} c^2\,, \tag{3}$$

which holds true by a large margin for the muon, but is certainly not true for the vacuum mass of the electron. On the other hand, the electron mass in condensed matter can be modified by local electromagnetic field fluctuations. To see what is involved, one may employ a quasi-classical argument wherein the electron four momentum $p_\mu = \partial_\mu S$ in an electromagnetic field $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$ obeys the Hamilton–Jacobi equation [7]

$$-\left(p_\mu - \frac{\mathrm{e}}{c} A_\mu\right)\left(p^\mu - \frac{\mathrm{e}}{c} A^\mu\right) = M_\mathrm{e}^2 c^2. \tag{4}$$

If the field fluctuations average to zero $\overline{A_\mu} = 0$, then the remaining mean square fluctuations can on average add mass to the electron $M_\mathrm{e} \to \tilde{M}_\mathrm{e}$ according to a previously established rule [7,8]

$$-\tilde{p}_\mu \tilde{p}^\mu = \tilde{M}_\mathrm{e}^2 c^2 = M_\mathrm{e}^2 c^2 + \left(\frac{\mathrm{e}}{c}\right)^2 \overline{A^\mu A_\mu}\,. \tag{5}$$

For example, laser light fields can "dress" an electron in a non-perturbation theoretical fashion with an additional mass as in (5). Such mass modifications must be applied to electrons and positrons when pairs can in principle be blasted out of the vacuum [9,10] employing colliding laser beams. The mass growth in the theory appears in a classic treatise on quantum electrodynamics [8]. The theory in terms of condensed matter photon propagators is discussed

[a] e-mail: allan.widom@gmail.com

below. For surface electromagnetic field fluctuations in metallic hydrides, the laser drives the coupled proton oscillations and the electron surface plasma oscillations.

The mass modified hydrogen atom can decay into a neutron and a neutrino if the mass growth obeys a threshold condition given by

$$\beta \equiv \frac{\tilde{M}_{\rm e}}{M_{\rm e}} = \left[1 + \left(\frac{e}{M_{\rm e}c^2}\right)^2 \overline{A^\mu A_\mu}\right]^{1/2}, \quad \beta > 2.531 \text{ (neutron production)}. \tag{6}$$

The sources of the electron mass renormalization via electromagnetic field fluctuations on metallic hydride surfaces and the resulting neutron production are the main subject matters of this work. The surface states of metallic hydrides are of central importance: (i) Collective surface plasma [11] modes are involved in the condensed matter weak interaction density of final states. The radiation frequencies of such modes range from the infrared to the soft X-ray spectra. (ii) The breakdown [12] of the conventional Born–Oppenheimer approximation for the surface hydrogen atoms contributes to the large magnitude of electromagnetic fluctuations. (iii) The neutrons are born with an ultra low momentum due to the size of the coherence domain of the oscillating protons. The coherence domains may be estimated to vary from about one to ten microns in length. The domains form a comfortable *cavity* in which to fit the neutron wavelength. The long final state neutron wave length allows for a *large* neutron wave function overlap with *many* protons, which increases the coherent neutron rate. Some comments regarding nuclear transmutation reactions that result from ultra low momentum neutron production will conclude our discussion of neutron catalyzed reactions.

2 Electromagnetic field fluctuations

The rigorous condensed matter definition of electron mass growth due to the metallic hydride electromagnetic fields depends on the non-local self energy insertion $\mathcal{M}$ in the electron Green's function [13] G, i.e.

$$-i\gamma^\mu \partial_\mu G(x,y) + \frac{c}{\hbar}\int \mathcal{M}(x,z)G(z,y)d^4z = \delta(x-y),$$
$$\mathcal{M}(x,y) = M_{\rm e}\delta(x-y) + \frac{\hbar}{c}\Sigma(x,y), \tag{7}$$

wherein the non-local mass shift operator

$$\sum(x,y) = i\left(\frac{e^2}{\hbar c}\right)\left(D_{\mu\nu}(x,y) - D^{(0)}_{\mu\nu}(x,y)\right)\gamma^\mu G(x,y)\gamma^\nu + \dots \tag{8}$$

depends on the difference between the photon propagator

$$D_{\mu\nu}(x,y) = \frac{i}{\hbar c}\left\langle A_\mu(x)A_\mu(y)\right\rangle_+ \tag{9}$$

in the presence of condensed matter and the photon propagator $D^{(0)}_{\mu\nu}(x,y)$ in the vacuum. In (9), "+" denotes time ordering. The source of the differences in the photon propagators

$$D_{\mu\nu}(x,y) - D^{(0)}_{\mu\nu}(x,y) = \iint D^{(0)}_{\mu\sigma}(x,x')\mathcal{P}^{\sigma\lambda}(x',y')D^{(0)}_{\lambda\nu}(y',y){\rm d}^4x'{\rm d}^4y' \tag{10}$$

defines the polarization response function $\mathcal{P}^{\sigma\lambda}(x,y)$ arising from condensed matter currents

$$\mathcal{P}^{\mu\nu}(x,y) = \frac{i}{\hbar c^3}\left\langle J^\mu(x)J^\nu(y)\right\rangle_+ . \tag{11}$$

The gauge invariant currents in (11) give rise to the electromagnetic fluctuations, which only at first sight appear not to be gauge invariant. The average of the field fluctuations appearing in (6) is in reality what is obtained after subtracting the vacuum field fluctuations that partially induce the physical vacuum electron mass; i.e.

$$\overline{A^\mu(x)A_\mu(x)} = \left\langle A^\mu(x)A_\mu(x)\right\rangle - \left\langle A^\mu(x)A_\mu(x)\right\rangle_{\rm vac},$$
$$\frac{i}{\hbar c}\overline{A^\mu(x)A_\mu(x)} = D^\mu_\mu(x,x) - D^{(0)\mu}_\mu(x,x). \tag{12}$$

The notion of replacing classical radiation fluctuations with quantum fluctuations in the above manner is implicit within Feynman's formulation [14] of quantum electrodynamics. The manner in which the method is used to compute electronic mass shifts has been previously discussed [15]. The effective mass renormalization in solid state physics is very well-known to shift thresholds, since it is the electron band energy and not the vacuum electron energy which enters into kinematic energy conservation within condensed matter.

In terms of the spectral function $S(\mathbf{r},\omega)$ defined by the electric field anti-commutator

$$2\int_{-\infty}^{\infty} S_{\mathbf{EE}}(\mathbf{r},\omega)\cos(\omega t){\rm d}\omega = \overline{\{\mathbf{E}(\mathbf{r},t);\mathbf{E}(\mathbf{r},0)\}}, \tag{13}$$

the local electronic mass enhancement factor (6) is given by

$$\beta(\mathbf{r}) = \left[1 + \left(\frac{e}{M_{\rm e}c}\right)^2 \int_{-\infty}^{\infty} S_{\mathbf{EE}}(\mathbf{r},\omega)\frac{{\rm d}\omega}{\omega^2}\right]^{1/2}. \tag{14}$$

The frequency scale $\tilde{\Omega}$ of the electric field oscillations may be defined via

$$\frac{1}{\tilde{\Omega}^2}\overline{|\mathbf{E}(\mathbf{r})|^2} \equiv \int_{-\infty}^{\infty} S_{\mathbf{EE}}(\mathbf{r},\omega)\frac{{\rm d}\omega}{\omega^2}, \tag{15}$$

so that

$$\beta(\mathbf{r}) = \sqrt{1 + \frac{\overline{|\mathbf{E}(\mathbf{r})|^2}}{\mathcal{E}^2}} \text{ wherein } \mathcal{E} = \left|\frac{M_{\rm e}c\tilde{\Omega}}{e}\right|, \tag{16}$$

which is an obviously gauge invariant result. When an electron wanders into a proton to produce a neutron and a neutrino, the electric fields forcing oscillations of the electrons

are largely due to the protons themselves. Considerable experimental information about the proton oscillations in metallic hydride systems is available from neutron beams scattering off protons.

3 Proton oscillations

A neutron scattering from N protons in metallic hydride systems probes the quantum oscillations of protons as described by the correlation function [16]

$$G(\mathbf{Q},\omega)=\frac{1}{N}\sum_{k=1}^{N}\int_{-\infty}^{\infty}\left\langle e^{-i\mathbf{Q}\cdot\mathbf{R}_k(t)}e^{i\mathbf{Q}\cdot\mathbf{R}_k(0)}\right\rangle e^{i\omega t}\frac{\mathrm{d}t}{2\pi}\,. \tag{17}$$

Here, $\mathbf{R}_k(t)$ is the position of the k-th proton at time t. The differential extinction coefficient for a neutron to scatter from the metallic hydride with momentum transfer $\hbar\mathbf{Q}=\mathbf{p}_i-\mathbf{p}_\mathrm{f}$ and energy transfer $\hbar\omega=\epsilon_i-\epsilon_\mathrm{f}$ is given by

$$\frac{d^2h}{d\Omega_\mathrm{f}d\epsilon_\mathrm{f}}\approx\frac{\bar\rho}{\hbar}\left[\frac{d\sigma}{d\Omega_\mathrm{f}}\right]G(\mathbf{Q},\omega)\,, \tag{18}$$

wherein $\bar\rho$ is the mean number of protons per unit volume and $d\sigma$ is the elastic differential cross-section for a neutron to scatter off a single proton into a final solid angle $d\Omega_\mathrm{f}$.

While the weak interaction neutron production may occur for a number of metallic hydrides, palladium hydrides are particularly well-studied. For a highly loaded hydride, there will be a full proton layer on the hydride surface. The frequency scale $\tilde\Omega$ of oscillating surface protons may be computed on the basis of neutron scattering data [17, 18]. The electric field scale in (16) may be estimated by

$$\mathcal{E}\approx 1.4\times10^{11}\,\mathrm{V/m}\quad(\text{hydrogen monolayer})\,. \tag{19}$$

To obtain the magnitude of the electric field, first consider the oscillations of a proton within a sphere of electronic charge density $-|e|\tilde n$. The Gauss law electric field providing a force on the proton when it is displaced from the center by $\mathbf{u}$ is given by

$$\mathbf{E}=-\left(\frac{4\pi|e|\tilde n}{3}\right)\mathbf{u}\,. \tag{20}$$

The resulting classical oscillation equation of motion is $\ddot{\mathbf{u}}+\tilde\Omega^2\mathbf{u}=0$, where

$$\tilde\Omega^2=\left(\frac{4\pi e^2\tilde n}{3M_p}\right)\,. \tag{21}$$

The classical equation (21) holds true in the fully quantum mechanical theory if the electron density $\tilde n$ represents the *electron density* at the *proton position*

$$\tilde n=\left\langle\psi^\dagger(\mathbf{R}_p)\psi(\mathbf{R}_p)\right\rangle\,. \tag{22}$$

For a bare hydrogen atom, $\tilde n=1/(\pi a^3)$. Thus, the magnitude of the electric field impressed on the electronic system due to the collective proton layer oscillations on the surface of the palladium may be estimated by

$$\sqrt{\overline{|\mathbf{E}|^2}}\approx\frac{4|e|\sqrt{\overline{|\mathbf{u}|^2}}}{3a^3}\quad(\text{hydrogen monolayer})\,, \tag{23}$$

where $\mathbf{u}$ is the displacement of the collective proton oscillations and the Bohr radius is given by

$$a=\frac{\hbar^2}{e^2M_\mathrm{e}}\approx0.5292\times10^{-8}\,\mathrm{cm}\,. \tag{24}$$

Thus,

$$\sqrt{\overline{|\mathbf{E}|^2}}\approx6.86\times10^{11}\,(\mathrm{V/m})\sqrt{\frac{\overline{|\mathbf{u}|^2}}{a^2}}\,. \tag{25}$$

One may again appeal to neutron scattering from protons in palladium for the room temperature estimate

$$\sqrt{\frac{\overline{|\mathbf{u}|^2}}{a^2}}\approx4.2\quad(\text{hydrogen monolayer})\,. \tag{26}$$

From (16), (19), (25) and (26) follows the electron mass enhancement

$$\beta\approx20.6\quad(\text{palladium hydride surface})\,. \tag{27}$$

The threshold criteria derived from (6) is satisfied. On palladium, surface protons can capture a heavy electron producing an ultra low momentum neutron plus a neutrino; i.e.

$$(\mathrm{e^-p^+})\equiv H\to n+\nu_\mathrm{e}\,. \tag{28}$$

Several comments are worthy of note: (i) The collective proton motions for a completed hydrogen monolayer on the palladium surface require a loose coupling between electronic surface plasma modes and the proton oscillation modes. The often assumed Born–Oppenheimer approximation is thereby violated. This is in fact the usual situation for surface electronic states, as has been recently discussed. It is not possible for electrons to follow the nuclear vibrations on surfaces very well, since the surface geometry precludes the usual very short Coulomb screening lengths. (ii) The above arguments can be extended to heavy hydrogen $(\mathrm{e^-p^+}n)\equiv(\mathrm{e^-}d^+)\equiv D$, wherein the neutron producing heavy electron capture has the threshold electron mass enhancement

$$\frac{\tilde M_\mathrm{e}'}{M_\mathrm{e}}=\beta'(D\to n+n+\nu_\mathrm{e})>6.88\,. \tag{29}$$

(29) also holds true. The value of β in (27) is similar in magnitude for both the proton and the deuterium oscillation cases at hand. Since each deuterium electron capture yields two ultra low momentum neutrons, the nuclear catalytic reactions are somewhat more efficient for

the case of deuterium. (iii) However, one seeks to have either nearly pure proton or nearly pure deuterium systems, since only the isotopically pure systems will easily support the required coherent collective oscillations. (iv) An enforced chemical potential difference or pressure difference across a palladium surface will pack the surface layer to a single compact layer allowing for the required coherent electric field producing motions. (v) The proton electric field producing oscillations can be amplified by inducing an enhancement in the weakly coupled electronic surface plasma modes. Thus, appropriate frequencies of laser light incident on a palladium surface launching surface plasma waves can enhance the production of catalytic neutrons. (vi) The captured electron is removed from the collective surface plasma oscillation creating a large density of final states for the weak interactions. Most of the heat of reaction is to be found in these surface electronic modes. (vii) The neutrons themselves are produced at very low momenta, or equivalently, with very long wavelengths. Such neutrons exhibit very large absorption cross-sections that are inversely proportional to neutron velocity. Very few such neutrons will escape the immediate vicinity. These will rarely be experimentally detected. In this regard, ultra low momentum neutrons may produce "neutron rich" nuclei in substantial quantities. These neutrons can yield interesting reaction sequences [19, 20]. Other examples are discussed below in the concluding section.

The wavelength of the ultra low momentum neutrons is estimated to be of the order of perhaps one to ten microns, which is the approximate size of a coherent surface domain of oscillating protons. Such micro-surface domains may act as a comfortable coherent electromagnetic cavity in which the neutrons may comfortably reside. The cavity is also a surface domain of coherent electromagnetic soft radiation. In the context of a theoretically postulated strong interaction cold fusion, the notion of bulk coherent electromagnetic domains has been previously discussed [21]. Within the context of the weak interaction neutron induced low energy nuclear reactions here being considered, the electrodynamic surface cavity coherent domains may serve to diffuse the nuclear reaction induced heating to the point wherein the condensed matter lattice is not utterly destroyed. Every so often one might expect the nuclear heating to actually be concentrated in sufficiently small regions of space, so that pieces of the metal are indeed destroyed. Hard radiation and other hard nuclear products may then be present.

4 Low energy nuclear reactions

The production of ultra low momentum neutrons can induce chains of nuclear reactions in neighboring condensed matter [22, 23]. Our brief discussion below describes only a part of the possible reaction networks. For our example, let us suppose that an initial concentration of lithium very near a suitable metallic hydride surface is employed to impose a substantial chemical potential difference across the hydride surface. In such a case, the existence of weak interaction produced surface neutrons allows for the following chain of reactions

$$\begin{aligned} {}^{6}_{3}\mathrm{Li} + n &\to {}^{7}_{3}\mathrm{Li}\,, \\ {}^{7}_{3}\mathrm{Li} + n &\to {}^{8}_{3}\mathrm{Li}\,, \\ {}^{8}_{3}\mathrm{Li} &\to {}^{8}_{4}\mathrm{Be} + \mathrm{e}^{-} + \bar{\nu}_{\mathrm{e}}\,, \\ {}^{8}_{4}\mathrm{Be} &\to {}^{4}_{2}\mathrm{He} + {}^{4}_{2}\mathrm{He}\,. \end{aligned} \tag{30}$$

The chain (30) yields a quite large heat Q for the net nuclear reaction

$$Q\big\{\,{}^{6}_{3}\mathrm{Li} + 2n \to 2\,{}^{4}_{2}\mathrm{He} + \mathrm{e}^{-} + \bar{\nu}_{\mathrm{e}}\big\} \approx 26.9\,\mathrm{MeV}\,. \tag{31}$$

Having produced ^{4}He products, further neutrons may be employed to build heavy helium "halo nuclei" yielding

$$\begin{aligned} {}^{4}_{2}\mathrm{He} + n &\to {}^{5}_{2}\mathrm{He}\,, \\ {}^{5}_{2}\mathrm{He} + n &\to {}^{6}_{2}\mathrm{He}\,, \\ {}^{6}_{2}\mathrm{He} &\to {}^{6}_{3}\mathrm{Li} + \mathrm{e}^{-} + \bar{\nu}_{\mathrm{e}}\,. \end{aligned} \tag{32}$$

The chain (32) yields a moderate heat for the net $^6_3$Li producing reaction

$$Q\big\{{}^{4}_{2}\mathrm{He} + 2n \to {}^{6}_{3}\mathrm{Li} + \mathrm{e}^{-} + \bar{\nu}_{\mathrm{e}}\big\} \approx 2.95\,\mathrm{MeV}\,. \tag{33}$$

The reactions (30) and (32) taken together form a nuclear reaction cycle. Other possibilities include the direct lithium reaction

$$\begin{aligned} {}^{6}_{3}\mathrm{Li} + n &\to {}^{4}_{2}\mathrm{He} + {}^{3}_{1}\mathrm{H}\,, \\ {}^{3}_{1}\mathrm{H} &\to {}^{3}_{2}\mathrm{He} + \mathrm{e}^{-} + \bar{\nu}_{\mathrm{e}}\,, \end{aligned} \tag{34}$$

with the heat of net reaction

$$Q\big\{\,{}^{6}_{3}\mathrm{Li} + n \to {}^{4}_{2}\mathrm{He} + {}^{3}_{2}\mathrm{He} + \mathrm{e}^{-} + \bar{\nu}_{\mathrm{e}}\big\} \approx 4.29\,\mathrm{MeV}\,. \tag{35}$$

This reaction yields both ^{4}He and ^{3}He products. All of the above reactions depend on the original production of neutrons. Of the above possible reactions, the lithium beta decay $Q\{{}^{8}_{3}\mathrm{Li} \to {}^{8}_{4}\mathrm{Be} + \mathrm{e}^{-} + \bar{\nu}_{\mathrm{e}}\} \approx 16.003\,\mathrm{MeV}$ in (30) yields the greatest of the above heat of nuclear fuel burning.

In summary, weak interactions can produce neutrons and neutrinos via the capture by protons of heavy electrons. The collective motions of the surface metallic hydride protons produce the oscillating electric fields that renormalize the electron self energy, adding significantly to the effective mass. There is no Coulomb barrier obstruction to the resulting neutron catalyzed nuclear reactions. The final products ${}^{\mathrm{A}}_{\mathrm{Z}}\mathrm{X}$ in some reaction chains may have fairly high A. The above examples show that final products such as ${}^{4}_{2}\mathrm{He}$ do not necessarily constitute evidence for the direct fusion $D + D \to {}^{4}_{2}\mathrm{He}$. Direct fusion requires tunneling through a high Coulomb barrier. By contrast, there are no such barriers to weak interactions and ultra low momentum neutron catalysis. Final products such as ${}^{4}_{2}\mathrm{He}$ and/or ${}^{3}_{2}\mathrm{He}$ and/or ${}^{3}_{1}\mathrm{H}$ may be detected.

References

1. R.E. Marshak, Riazuddin, C.P. Ryan, *Theory of Weak Interaction of Elementary Particles* (Interscience, New York, 1969)
2. H. Yukawa, Proc. Phys. Mater. Soc. Japan **17**, 48 (1935)
3. C. Möller, Physik. Z. Sowjetunion **11**, 9 (1937)
4. J.E. Rothberg, E.W. Anderson, E.J. Bleser, L.M. Lederman, S.L. Meyer, J.L. Rosen, I.-T. Wang, Phys. Rev. **132**, 2664 (1963)
5. A.A. Quaranta, A. Bertin, G. Matone, F. Palmonari, G. Torelli, P. Dalpiaz, A. Placci, E. Zavattini, Phys. Rev. **177**, 2118 (1969)
6. S. Ando, F. Myhrer, K. Kubodera, Phys. Rev. C **63**, 015 203 (2000)
7. L.D. Landau, E.M. Lifshitz, *The Classical Theory of Fields*, Sects. 17 and 47, Prob. 2 (Pergamon Press, Oxford, 1975)
8. V.B. Berestetskii, E.M. Lifshitz, L.P. Pitaevskii, *Quantum Electrodynamics*, Sect. 40, Eq. (40.15) (Butterworth Heinmann, Oxford, 1997)
9. A. Ringwald, Phys. Lett. B **510**, 107 (2001)
10. V.S. Popov, JEPT Lett. **74**, 133 (2002)
11. E.A. Stren, R.A. Ferrell, Phys. Rev. **110**, 130 (1960)
12. J.D. White, J. Chen, D. Matsiev, D.J. Auerbach, A.M. Wadke, Nature **433**, 503 (2005)
13. J. Schwinger, Proc. Natl. Acad. Sci. USA **37**, 452 (1951)
14. R.P. Feynman, Phys. Rev. **80**, 440 (1950)
15. O. Panella, A. Widom, Y.N. Srivastava, Phys. Rev. B **42**, 9790 (1990)
16. G.L. Squires, *Introduction to the Theory of Thermal Neutron Scattering* (Dover Publications, New York, 1996)
17. B. Hauer, R. Hempelmann, T.J. Udovic, J.J. Rush, W. Kockelmann, W. Schäfer, R. Jansen, D. Richter, J. Phys. Condens. Matter **16** 5205 (2004)
18. M. Kemali, J.E. Totalici, D.K. Ross, I. Morrison, Phys. Rev. Lett. **84**, 1531 (2000)
19. Y. Iwamura, M. Sakano, T. Itoh, Japan J. Appl. Phys. **41**, 4642 (2002)
20. G.H. Miley, G. Narne, T. Woo, J. Radiat. Nucl. Chem. **263**, 691 (2005)
21. G. Preparata, *QED Coherence in Matter*, Chap. 8 (World Scientific, Singapore, 1995)
22. D.R. Lide (ed.), *Handbook of Chemistry and Physics*, 81st edn., Sect. 11 (CRC Press, Boca Raton, 2000)
23. R. Firestone, V. Shirley (eds.), *Table of Radioactive Isotopes* (John Wiley and Sons, New York, 1999)