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Physical discussion of the Mössbauer effect

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Abstract

In order to interpret the peculiarities of the Mössbauer effect, both an approach based on the wave nature of the emitted (or absorbed) γ radiation and an approach based on its corpuscular nature are currently employed in the specialized literature. However, while the former appears to be contradicted by the experimental evidence and by the uncertainty principle, the latter appears to hit the target, provided one takes into account the zero-point momentum reservoir of the mechanical oscillators forming the crystal lattice. Such a reservoir, indeed, appears to lend itself to the interpretation of all kinds of microscopic elastic phenomena in solids.

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1. Introduction

During his experiments on the nuclear resonance scattering of the γ-rays emitted in the decay of many nuclei (previously excited, for instance, in a nuclear reactor) Mössbauer observed, in 1958 [1–4], that a fraction of the emitted photons exhibited an *increased* resonant absorption in cases where no effect was expected at all. Since, indeed, the absorption and emission energy distribution maxima were thought to be separated by twice the free recoil energy, E_R of the emitting (or absorbing) nuclei, no overlapping between them was a priori supposed to occur when their thermal widths were reduced by a suitable cooling.

A novel physical effect – the Mössbauer effect (ME) – was thereby discovered, whose properties, in view of the discussion in the present paper, may be summarized as follows:

- The ME occurs without any observable recoil of the emitting (or absorbing) nuclei. This fact leads to a zero shift (with respect to the energy E_γ of the excited nuclear state) of the emission (and absorption) lines.

  One could imagine that the absence of recoil is due to the fact that the atom is very strongly bound in the crystal lattice; but the analysis of the binding forces shows that they are so weak as to be practically negligible during the momentum and energy transfer, as in fact they are currently considered to be in the ordinary, non-ME emission/absorption processes occurring in the same crystal where an ME is observed.

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- The ME occurs, even in individual emission/absorption processes, without any *Doppler shift*. This fact leads to a negligible *Doppler broadening* of the observed spectral lines, which present an energy line width Γ_{obs} very close to the natural minimum value Γ_0 due to the uncertainty principle ($\Gamma_0 \cong \hbar/\tau$, where τ is the mean lifetime of the excited nuclear state). One could expect, in fact [5], a Doppler broadening of the order of vE_γ/c, where v is the velocity of the emitting nucleus. In order to evaluate such an expected broadening let us consider, for instance, the case of the Zn nucleus, and assume a nuclear kinetic energy of the order, at least, of the zero-point oscillation energy ($\cong 5 \times 10^{-2}$ eV). Recalling that $E_\gamma \cong$ 93.3 keV, and that the nuclear mass of Zn is $M \cong 1.086 \times 10^{-22}$ g, we find that $vE_\gamma/c \cong 5.3 \times 10^{-2}$ eV, a value nine orders of magnitude larger than Γ_{obs}, which is about 5×10^{-11} eV. The absence of Doppler broadening, indeed, is the very property which allows to employ the ME in extremely high-precision physical measurements.
- The *emission* Mössbauer peak strongly enhances approaching 0 K, and turns out to be exactly centered on the (unshifted) *absorption* peak.

  The complete emission spectrum includes, besides the very narrow line of Mössbauer radiation, a non-Mössbauer bulk, whose maximum is endowed with an ordinary thermal Doppler broadening, and is shifted by an amount equal to E_R with respect to the ME peak.
- The ME is an *elastic* phenomenon, which does not excite any normal mode of mechanical vibration of the lattice where the atom, whose nucleus emits (or absorbs) the radiation, is inserted.

  In *emission*, therefore, the ME yields photons whose energy is exactly equal to the difference between the nuclear excited level and the ground state.

  The proof of this property is given in the *absorption* phase, which occurs, contrary to other elastic phenomena (such as the recoilless Rayleigh scattering of photons [6], or the elastic scattering of neutrons), in a *resonant* way (and therefore at a frequency equal to that of *emission*) with a large absorption cross section and a high visibility.
- The ME *does not* occur [7,8] in gases; in liquids; in solids not endowed with sufficiently rigid interatomic bonds. The ME progressively vanishes by reducing the dimensions of the solid below 1 μm^3 (i.e. for crystals containing less than, say, 10^9 atoms). There is, moreover, an upper limit to the γ energy ($\cong$ 130–140 keV) beyond which the probability of ME becomes vanishingly small.
- The ME affects (under the same initial conditions) the nuclei of the lattice with a well defined probability. Such a probability is provided by an expression completely analogous to the Debye–Waller (D–W) factor [9,10], originally obtained, much before the discovery of the ME, for the description of a large set of elastic phenomena, such as the X-ray scattering, the nuclear scattering of neutrons and the electron scattering by crystal atoms.

We shall analyze here to what extent the properties of the ME may be assumed to be well understood.

The absence of Doppler broadening indicates, for instance, an apparent immobility of the emitting nucleus [5]. Along any space direction x, indeed, the momentum of the nucleus (and therefore its *momentum uncertainty* Δp_x) is by far too small (even assuming for the *position* an uncertainty $\Delta x \cong 0.4$ μm, ranging all over the employed microcrystal) to be compatible with the uncertainty principle. The absence of recoil, in its turn, requires a check of the momentum conservation mechanism.

We finally observe that for the deduction of the D–W formula, and, more specifically, for the interpretation of the ME, both wave-like models and models based on the corpuscular nature of the emitted (or absorbed) γ radiation are employed in current literature: the experimental evidences, in fact, are not universally recognized to be reducible to only one of the two complementary aspects of quantum reality.

This fact is expressly and critically stressed in the present work, where we propose, for the entire set of properties of the ME, a unitary interpretation based on a transient deformation (without energy exchanges) of the zero-point energy spectrum of the lattice oscillations.

2. Wave-like approach

According to the wave-like approach [11,12], the excited nuclei emit coherent wave trains (whose frequency we shall call ν_0) with an average time-length of the order of the lifetime τ ($\approx 10^{-6}$–10^{-8} s, in the case of γ radiation) of the excited nuclear state. Since such a time is quite longer than the oscillation period ($\approx 10^{-19}$–10^{-20} s) of the emitted waves, it appears plausible to treat the emitting nucleus as a continuous source of monochromatic radiation, linked with a mechanical oscillator inserted in a three-dimensional lattice composed of N identical oscillators.

Let us recall here that each atom of the crystal is submitted, at thermal equilibrium, to a spectrum of $3N$ mechanical oscillations. The frequencies of such a spectrum lie between a *minimum* value ω_{min}, corresponding to wavelengths of the order of the crystal linear dimensions, and a *maximum* value $\omega_{max} = \omega_D$ (where $\omega_D \approx 10^{13}$–10^{14} Hz is the Debye frequency of the lattice), corresponding to a wavelength equal to twice the equilibrium interatomic spacing, and determined by the atomic mass M and by the elastic constants of the interatomic forces.

At low enough temperatures, the high-frequency *thermal* oscillations cannot be excited: when the crystal is close to 0 K, indeed, the only possible mechanical oscillations, for *any* spectral frequency, are the zero-point ones, due to the uncertainty principle.

According to the wave-like model, the continuous electromagnetic wave train emitted (at frequency ν_0) by the excited nucleus is modulated by each of the mechanical oscillations of the crystal, thus leading to the formation, along each space direction, of a spectrum composed of $2N$ sets of lines around ν_0.

Recalling now that the ME is characterized by a line spectrum without any Doppler broadening, we may evaluate the probability of such a process by simply looking for the un-modulated part of the spectrum, i.e. for the energy fraction f emitted exactly at the frequency ν_0. The modulated part should obviously represent the energy fraction corresponding to the ordinary radiation, emitted with the usual Doppler effect.

Referring to a lattice at a temperature of the order of 0 K, where, as we wrote above, only the zero-point atomic motions must be taken into account, and expressing the mean-square displacement of the radiating nucleus in terms of its average mechanical energy, one obtains

$$f = \exp[-3E_R/(4k_B T_D)], \tag{2.1}$$

where k_B is the Boltzmann constant, $T_D = \hbar\omega_D/k_B$ is the Debye temperature of the lattice [13,14] and finally, for emission/absorption elastic processes, the quantity

$$E_R = E_\gamma^2/2Mc^2 \tag{2.2}$$

represents the recoil energy received by a free atom with mass M. Eq. (2.1) is the well-known D–W expression, in the form holding at 0 K.

The value obtained from Eqs. (2.1) and (2.2) is in excellent agreement with the experimentally observed probability of a Mössbauer process. It is seen, for instance, that the probability of ME vanishes for very large values of E_γ.

For higher temperatures an analogous deduction of the D–W expression may be obtained, provided one recalls that even over a few Kelvin degrees an increasing number of thermal modes of oscillation turns out to be excited, so that interactions with no energy exchange (as required by the ME) become less and less probable.

Concerning the recoilless nature of the ME some authors claim [15], within the undulatory approach, that momentum is transferred (in the case of a *resonant* process such as the ME) over a time of the order of τ, long enough to transfer the recoil momentum to the whole lattice, via the interatomic binding forces.

3. Comments on the wave-like approach

The wave-like model described in the previous section suggests the following observations:

(1) Such a model basically aims to obtain, within a unique generation and auto-modulation process, the γ energy fraction f emitted without any frequency shift, and therefore submitted to ME.

This picture, however, is contradicted by the experimental observation that while the Mössbauer radiation is not affected by the shift E_R due to the recoil of the emitting nucleus, such a shift is present in the rest of the spectrum. Any kind of modulation, indeed, should lead to the creation of sets of lines symmetrical with respect to the carrier frequency, and therefore *unshifted* whenever, as in the case of the ME, such a carrier exhibits no shift.

Let us mention here the experimental results obtained by Ruby and Bolef [16] in their early researches on the ME, based on the application of a high-frequency mechanical modulation to a Mössbauer source. In these experiments a 10 μm thick foil of stainless steel, containing (by a process of thermal diffusion) atoms of Co^{57}, was glued on a quartz piezoelectric crystal, put in vibration by means of alternating electric fields at 20 MHz (with a root-mean-square voltage up to about 3.6 V). The obtained results evidenced the formation of a modulation spectrum, symmetrical with respect to the original Mössbauer line, where no side-band line presented a shift due to the nuclear recoil. The modulation predicted by the undulatory model turns out therefore to be contradicted by the experimental evidence.

The unshifted side-band lines observed in Ref. [16], moreover, correspond to frequencies quite far from the Mössbauer resonance, thus contradicting the assumption that the lack of frequency shift is due to the long interaction time allowed by a resonant process.

(2) The model of Ref. [11] involves a semi-classical process which could be apt to describe the modulation of an ordinary, low-frequency and high-intensity electromagnetic wave train, containing a large amount of photons. However, because of the very nature of the ME, every wave train emitted by a nucleus may be coherent only with itself, and contain *a single photon* at a time [12]. The modulation predicted by the undulatory model should therefore be impressed on each monophotonic wave train, which would virtually contain both the (coherent) Mössbauer line and the incoherent part of the entire γ emission spectrum.

This viewpoint, however, appears to be hard to reconcile with by the uncertainty principle, expressed in the form [17]

$$\Delta n \Delta \phi \geqslant 1, \quad (3.1)$$

where Δn is the uncertainty of the number of radiation quanta and $\Delta\phi$ is the uncertainty of the phase of the associated wave. According to such a principle, in fact, "the phase ϕ of a quantized light wave is only determined if the number of light quanta is undetermined, corresponding to the uncertainty relation. We could check the phase relations if we considered a wave with a large enough number of quanta" [17].

(3) In certain cases (such as that of Fe^{57}) the γ decay of the nucleus occurs in two successive stages, with an emission, first, of a high-energy photon (at 124.4 keV in the case of Fe^{57}), with a very low probability of undergoing the ME, and then, within a characteristic average time τ, of another γ particle, with low energy (14.41 keV for Fe^{57}) and high ME probability [18–20]. The modulation process should therefore begin immediately after the emission of the first γ particle, while the mechanical oscillations stimulated by the anelastic recoil due to such an emission should be still active and effective. But no trace is found of these oscillations [21] in the emission spectrum of the second γ. As Imbert says, in fact: "The recoil energy is generally spread over a considerable number of atoms in a time typically $\approx 10^{-13}$ s, and cooling the heat spike associated to the recoil process needs 10^{-12}–10^{-11} s, so that the energy dissipation through the lattice usually occurs before the Mössbauer emission. However, the possible existence of long lived localized vibrational modes, and the influence of their decay on the D–W factor, as well as on the emission line shape, have been thoroughly discussed in the literature although experimental evidence seems to be questionable."

(4) Finally, the undulatory model provides no explanation of the need, for the ME, of a crystal containing a number of atoms $N \geqslant 10^9$ and of very strong interatomic bonds.

4. Particle-like approach

According to quantum mechanics, energy and momentum cannot be conceived as continuously diluted along a wave train: the wave describes the probability of the presence of the associated particle, which reveals itself in a sudden way when an interaction occurs. The lifetime τ of the excited nuclear state has therefore nothing to do with the time needed for momentum transfer, which can be assumed to be instantaneous [22–24].

This consideration suggests a corpuscular and purely quantistic model of the ME, where such a zero-energy process corresponds to a *ground state → ground state* transition of the mechanical oscillator containing the emitting nucleus, with a probability which turns out to be given, once more, by the D–W factor.

The case for sudden emission was treated in its most exhaustive form by Lipkin [23,24], whose approach develops in two successive stages.

The first stage treats the case of a single, unidimensional harmonic oscillator, perturbed by the emission process. "This simple model" Lipkin says "already contains the basic features of the ME."

The second stage extends the treatment to a set of coupled oscillators, and expresses the eigenfunctions of their Hamiltonian in terms of the complete set composed by the eigen functions of a system of uncoupled oscillators.

In Lipkin's approach the emission process cannot, on the one hand, draw energy from the ground-state mechanical oscillations of the atom, and is not able, on the other hand (for the fraction undergoing ME), to bring the atom from the lowest (mechanical) energy level to higher ones, because "the oscillator energy level spacing is large compared with the free recoil energy" [23,24].

The observed lack of Doppler effect is therefore due to the fact that any frequency shift $\Delta\nu$ affecting the radiation would be associated to an illicit (positive or negative) energy exchange $\Delta E = h\Delta\nu$.

While, in conclusion, the atom does oscillate with its zero-point energy, thus satisfying the uncertainty principle, such a state of motion cannot be revealed by a corresponding Doppler shift of the radiation itself.

5. Comments on the particle-like approach

Though satisfying a part of the doubts connected with the ME, Lipkin's approach leaves a few basic questions unsolved, and raises a set of new puzzling problems. The most important points requiring an explication are the following:

(1) If the ME is possible even for a single, isolated oscillator, why does the experimental evidence say that the emitting nuclei must belong to a rigid crystal, composed of more than 10^9 atoms?

(2) If we admit that the ME occurs with no energy exchange, how can the momentum due to the emitted quantum be conserved?

We observe, in fact, that a *single harmonic oscillator*, in its usual acceptation, has at its disposal an unlimited momentum absorber (behaving like a rigid object of macroscopic dimensions): the force field corresponding to the harmonic potential where the oscillator is placed. Such a single oscillator may be realized, for instance [25], by means of a trapped and cooled single ion, providing a system close to the theoretical models in quantum mechanics and quantum optics.

In the case of a *lattice* (i.e. of a macroscopic aggregation of oscillators), the assumption which Lipkin fails to declare is that an analogous potential is generated by such a macro-object, which is supposed to *instantaneously* absorb the recoil momentum. This picture, however, does not appear to be physically realistic: the impulse due to the emitted quantum may generate at most an acoustic perturbation, which cannot grant a suitable reaction of the medium within the sudden emission time.

(3) Thermal phonons, with energies lower than E_R, are already present, even at temperatures below T_D, at which the probability of the ME is still appreciable. Why, then, does the emission/absorption process not cause the excitation of the accessible vibrational levels? Should such an excitation occur, in fact, the ME would turn out to be impossible.

(4) The large energy level spacing invoked by Lipkin in order to exclude the oscillator excitation above the ground state is, indeed, the one of a single oscillator, and does not reflect the real lattice case.

6. The zero-point reservoir

In order to meet the objections raised in the previous sections, let us recall, to begin with, that a crystal composed of N atoms may be classically described by means of the local *geometrical variables* expressing the displacements of the single atoms from their equilibrium positions. Because of the *not-separable* character of the corresponding dynamical equations of the physical system, it is expedient to pass to the so-called *normal variables*, each one obtained by a suitable linear superposition of the full set of the geometrical ones, under the condition of leading to separable dynamical equations.

The normal variables naturally lend themselves to the overall, non-local description of the small oscillations of the entire crystal (viewed as a unique physical system) around its equilibrium configuration [26,27]. Their use, indeed, implies the final return – as made by Hamilton – to the local physical variables describing the individual atom behavior. A bi-univocal correspondence is also established between the new variables and the mechanical oscillation eigenfrequencies of the crystal.

The passage to a quantum treatment turns out to be a practicable task only by starting from the normal variables: the use of the local, geometrical variables may be shown to encounter, in fact, at quantum level, almost insurmountable difficulties [28]. The quantum treatment provides therefore a representation of the crystal as a unique quantum object, much more unitary than the corresponding classical concept introduced by the normal variables.

In order to fix ideas, let us consider the simple case of a linear crystal [29,30], whose atoms may oscillate along a single direction.

If Q_j are the normal variables of such a system, and ω_j (with $j = 1, \ldots, N$) the corresponding eigenfrequencies, the relevant time-independent quantum Hamiltonian operator may be written in the form

$$H = \sum_{j=1}^{N} \frac{1}{2}[-M^{-1}\hbar^2\partial^2/\partial Q_j^2 + M\omega_j^2 Q_j^2]. \tag{6.1}$$

One gets now, by variable separation, a system of N Schrödinger equations, each one associated to a particular eigenfrequency ω_j, and therefore to the eigenenergies

$$E_j = (n + \tfrac{1}{2})\hbar\omega_j, \quad n = 0, 1, \ldots, \tag{6.2}$$

representing sets of energy levels referred to as the *entire lattice*.

Let us observe here that the ME concerns the behavior of *single atoms*. Each one of them perceives the fact of belonging to a particular lattice (composed of many other atoms) through its oscillation spectrum. While, however, the possible *thermal* oscillation spectrum cannot involve, for $T < T_D$, the full set of eigenfrequencies (being limited to the lowest ones), the entire frequency spectrum is always, and necessarily, active in the zero-point oscillation motions.

The zero-point oscillations (of purely quantum origin) are, therefore, a complete source of information, acquainting each atom with the characteristics of the lattice to which it belongs – including its irregularities, which strongly affect the spectral structure of the crystal [31].

We recall that, according to Debye's theory [13,14], the spectral density of the mechanica oscillations of an isotropic solid (regarding the crystal, and therefore the frequency spectrum, as a continuum, with frequency-independent elastic constants) is roughly approximated by the expression

$$D(\omega) = 9N\omega^2/\omega_D^3. \tag{6.3}$$

Since the zero-point oscillation energy of each normal mode ω_j (involving all the atoms of the lattice) is equal to $\hbar\omega_j/2$, the continuous approximation provided by Eq. (6.3) leads to a total zero-point energy of the entire crystal given by

$$E_0 \cong \frac{1}{2}\int_0^{\omega_D} \hbar\omega D(\omega)\,d\omega = \left(\frac{9}{8}\right)N\hbar\omega_D, \tag{6.4}$$

where we assumed that $\omega_{min} \cong 0$.

The total zero-point energy of every atom is therefore

$$E_0^{(at)} \cong (9/8)\hbar\omega_D. \tag{6.5}$$

That said, let us consider now the transient and highly localized phenomenon (as far as momentum exchange is concerned) consisting in the emission (or absorption) of a γ particle by a nucleus.

Given that a zero-point *energy spectrum* pertains to the crystal, and therefore an average zero-point kinetic energy $\langle E_{k0}\rangle = E_0^{(at)}/2$ pertains to each one of its atoms, we are induced to infer that a ground-state *momentum spectrum* must also exist, whose absolute mean-square value, for each atom, is

$$\langle P_0^2\rangle = 2M\langle E_{k0}\rangle. \tag{6.6}$$

The set of $3N$ mechanical oscillation frequencies of the crystal constitutes, in the ground state, a temperature-independent reservoir of momentum, in any possible direction, virtually available to those interactions which do not modify the total zero-point energy. These interactions turn out to be possible in the absence of thermal phonons, i.e. at temperatures lower than T_D. At these temperatures, and for large enough values of N, the local impulse due to the emission/absorption of a γ particle will have a finite probability of finding a zero-point oscillation of the atom with a momentum equal and opposite to that imparted by the γ radiation. This exact and instantaneous compensation of the recoil momentum, giving origin to the ME, preserves the total energy of the system, limiting itself to a transient, non-dissipative re-distribution of the energy spectrum.

Such a process avoids the excitation of phonon energy levels lower than E_R and allows the elastic properties of the ME, including the absence of Doppler effect.

The momentum imparted to the nucleus may be successively elastically conveyed to the lattice, thus restoring the initial equilibrium distribution.

The zero-point reservoir contains, in conclusion, a complete information about the crystal structure, constituting a sort of (purely quantistic) coalescence of matter, which requires no message between nuclei and lattice: such a message, which could only travel at the speed of the sound, could not explain, in fact, the sudden character of the Mössbauer process. Even the well-known reciprocal vector g, currently employed in the description of the dynamical features of crystals lattices [29,30], appears to be physically justified by such a coalescence.

The ME, involving photons with a very large momentum, will require high-momentum (and therefore high-frequency) mechanical oscillations, at which almost no thermal phonon is present up to temperatures of the order of T_D; and of course high frequencies can only be present for large enough ω_D, i.e. for rigid enough interatomic bonds.

The lowest frequencies, on the other hand – at which thermal phonons may exist even close to 0 K – have no chance at all to take part in the process. When emissions occur (within the same lattice) not submitted to ME, both Doppler broadening and recoil are present in the radiation spectra, since mechanical phonons are then generated, causing a sudden mechanical impulse on the emitting nucleus.

This point of view can also provide an explanation of the fact that the ME requires a lattice composed of a very large number of atoms. This is indeed, for each individual emission process, a condition granting a choice (among the $3N$ modes of oscillation, with different intensities and directions) large enough to meet an oscillation able to exactly balance the momentum due to the emitted (or absorbed) photon. It is seen in particular, from Eq. (6.4), that the momentum reservoir increases with increasing ω_D, i.e. when the stiffness of the interatomic bonds is increased.

We also observe that in phenomena involving – contrary to the case of the ME – low-momentum photons (as, for instance, in the emission, reflection or absorption of optical radiation [32]), a strong temperature dependence is found, which confines to temperatures very close to 0 K the probability of occurring in an elastic way. In this case, indeed, a momentum compensation could only be granted by zero-point oscillations at the lowest frequencies: frequencies which, however, could easily turn out to be already excited by thermal phonons.

We finally observe that, in the model proposed here, if E_γ is the energy of the photon, the momentum $P_\gamma = E_\gamma/c$ is exactly and instantaneously balanced by the momentum P_ω provided by the zero-point reservoir, so that, making use of Eq. (6.6)

$$(P_\omega)^2/2M = (E_\gamma/c)^2/2M < E_0^{(at)} \cong (9/8)\hbar\omega_D. \tag{6.7}$$

The term $(E_\gamma/c)^2/2M$ is seen to coincide with the free recoil energy E_R given by Eq. (2.2).

The radiation momentum may be therefore balanced (leading to an ME) below a maximum energy value $E_{\gamma max}$ of the emitted (or absorbed) quantum

$$E_{\gamma max} \cong c[(9/4)\hbar\omega_D M]^{1/2}. \quad (6.8)$$

Values slightly larger than $E_{\gamma max}$ could also be compensated, of course, according to the quantum statistics of the emission process.

7. Elastic phenomena and zero-point energy

The content of the previous sections suggests that all the microscopic elastic processes could be founded on the role of the zero-point oscillations. Among these processes we typically recall the case of *superconductivity* [33–36], determined by the fact that, under certain conditions, the conduction electrons exchange no energy with the atoms of the lattice. These atoms may be plausibly thought of as interacting with the conduction electrons via the local zero-order oscillations, whose spectrum is distorted without altering the total energy of the system.

In the superconducting phase, as is well known, the electron–electron interaction generates the so-called *Cooper pairs* of electrons. In this interaction the repulsive Coulomb field is screened by (virtual) phonons at frequencies as high as 10^{11} Hz.

The creation of the Cooper pairs may be described by assuming that, around 0 K (and therefore in the absence of thermal phonons) a first electron polarizes the lattice, without any phonon generation, limiting itself to the distortion of the zero-point phonon spectrum. A second electron, then, interacts with such a polarization (i.e. with the zero-point spectral distortion due to the first one), giving rise to the coupling phenomenon.

The ME is profoundly analogous to this phenomenology, although it involves frequencies ($\approx 10^{13}$ Hz) larger by two orders of magnitude, allowing, therefore, to occur even over T_D, as long as there exists a fraction of atoms vibrating close to ω_D (i.e. at the maximum possible frequencies) not submitted to thermal oscillations.

Just like superconductivity, indeed, the ME must not encounter thermal phonons at the involved frequencies (whatever they may be), as shown by the temperature dependence of the D–W factor. And, just like superconductivity, the ME is associated with a temporary and non-dissipative distortion of the zero-point energy spectrum.

8. Conclusions

As we stress in the present work, the same properties of the ME are alternatively and indifferently dealt with, in current literature, by means of wave-like and particle-like models of the emitted and absorbed γ radiation.

It is our opinion that the mixture and co-existence of these models do not reflect the spirit of the complementarity principle, on which quantum mechanics is still based. According to this principle, in fact, two different and complementary aspects of physical reality (the wave and the particle one) ought to be invoked for the description of different and separate phenomena, leading to a mutual integration (without superposition) in a global harmonic vision.

The very concept of photon (sometimes as a particle, sometimes as a wave train suddenly interacting with matter, sometimes as a wave train submitted to a long and diluted exchange of energy and momentum) appears to be somewhat blurred by such a theoretical ambiguity.

As we have seen, moreover, both the wave-like and the particle-like models lay themselves open to serious objections.

In the present work we opt for a particle-like approach, which however, with respect to the one of Lipkin, excludes any possibility of ME for a single, isolated oscillator. This approach is made self-consistent by the assumption (impossible in a classical treatment) of a coalescence occurring at the zero-point level: an assumption which seems to suggest the way to be taken, in order to understand the full set of properties of the ME.

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