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Anomalies in fracture experiments, and energy exchange between vibrations and nuclei

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Abstract A variety of anomalies have been reported in recent years in fracture experiments, including neutron emission, elemental anomalies, and alpha emission. Such anomalies are similar to those studied in condensed matter nuclear science, which has been of interest to us in the development of theoretical models. In this work a brief review of the new theoretical approach is given, along with connections to both anomalies in fracture experiments and anomalies in other experiments. The fracture anomalies in this picture arise naturally as a result of the relevativistic interaction between vibrations and internal nuclear degrees of freedom, and up-conversion of vibrational quanta. A major conclusion of this work is that the elemental anomalies cannot be accounted for by disintegration as an incoherent process; since the observed products show a high degree of selectivity, while disintegration is very much non-selective. The possibility of disintegration as a coherent quantum process is introduced, and a suggestions for new experiments and measurements are put forth that can help to clarify underlying mechanisms.

Keywords Fracture · Anomalies · Phonon-nuclear coupling · Fractionation of a large quantum

1 Introduction

Quite a few papers have been published in recent years describing observations of a variety of anomalies associated with fractures [1–12]. The different anomalies include neutron emission [1, 2]; low-frequency electromagnetic emission [3, 5]; elemental anomalies [6, 8]; and alpha emission [11, 12]. Elemental concentrations seen in the earth's crust are proposed to involve anomalies similar in origin to those seen in the laboratory [13–15]. Anomalies have also been reported in samples undergoing ultrasonic stimulation [16–21]. There have appeared numerous publications which review these experiments [22–30].

It is useful to recall here that elemental anomalies attributed to nuclear disintegration, as conjectured in the interpretation of some elemental anomalies [2, 6] are not expected based on what is known about condensed matter and nuclear physics as in the literature and summarized in text books. Some objections were given previously by Spallone et al. [31]; and the interpretation of the experimental results has been questioned [31–36].

Two groups have so far pursued theoretical explanations for the anomalies in fracture experiments: Cardone et al. [23, 37, 38] based their approach on a

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model involving deformed spacetime; and Widom et al. [39–42] have proposed that collective phenomena in condensed matter can produce energetic electrons capable of inducing nuclear disintegration. Our focus has in recent years been on the development of a theoretical model for anomalies (including elemental anomalies) in condensed matter nuclear science; here we consider the possibility of accounting for the elemental anomalies in fracture experiments in terms of the associated theoretical picture.

Ultimately, there are three theoretical issues to be addressed: interaction; energetics; and dynamics. A direct (relativistic) coupling between vibrations and internal nuclear degrees of freedom is described in Sect. 2, which constitutes the interaction of interest. The up-conversion of vibrational plays a key role in all of the anomalies, which motivates a discussion of fractionation and inverse fractionation in Sects. 3 and 4. In Sect. 5 there is an extended discussion that is focused on the connection between the theoretical picture and anomalies in fracture experiments. Within the framework of the model, all of the anomalies are closely related, so that understanding gained from a consideration of anomalies in non-fracture experiments helps focus our attention on specific issues in anomalies in the fracture experiments. Disintegration in the nuclear literature is modeled as an incoherent process, with rates computed using the Golden rule formula; our approach is instead based on coherent quantum dynamics (widely used in quantum optics in recent years) which can be much faster than incoherent processes. Incoherent disintegration is very much not selective, which motivates us to consider the possibility of a new kind of reaction that involves nuclear disintegration as a coherent process. The discussion of Sect. 6 is focused on what might be done experimentally to clarify theoretical issues in studies of anomalies in fracture experiments.

2 Phonon-nuclear coupling

The anomalies reported in the fracture experiments can be interpreted to implicate vibrations (associated with the fracture), and also internal nuclear excitation (associated with neutron emission, alpha emission, and nuclear disintegration). In this regard, these anomalies seem similar to other anomalies reported in very different kinds of experiments, which we have interpreted as also involving vibrations and nuclear excitation. There is no difficulty in identifying second-order interactions between vibrations and internal nuclear degrees of freedom; however, in earlier work it was found that a higher-order coupling is too weak to account for them quantitatively. In order to connect with experiment, a much stronger coupling was needed.

2.1 Fundamental Hamiltonian

Ultimately attention was focused on the strongest coupling possible under any conditions, which is that present in a relativistic description. For example, the coupling between the center of mass momentum and internal degrees of freedom in the Dirac equation for an electron is well known; a similar coupling is present in the Dirac phenomenology as is sometimes used for neutrons and protons. For more general (relativistic) models, it is possible to work in terms of nuclear basis states in the rest frame, and write [43]

$$\hat{H} = \sum_j \left(\mathbf{M}c^2 + \mathbf{a}\cdot c\hat{\mathbf{P}}\right)_j + \sum_\alpha \frac{|\mathbf{p}_\alpha|^2}{2m} + \sum_{j<k} \frac{Z_j Z_k e^2}{|\mathbf{R}_k - \mathbf{R}_j|} + \sum_{\alpha<\beta} \frac{e^2}{|\mathbf{r}_\beta - \mathbf{R}_\alpha|} - \sum_{\alpha,j} \frac{Z_j e^2}{|\mathbf{R}_j - \mathbf{r}_\alpha|} \quad (1)$$

One sees that this is very nearly a normal condensed matter Hamiltonian, with a nonrelativistic description of the electron kinetic energy, Coulomb interactions between electrons, between nuclei, and between electrons and nuclei. In place of the nuclear kinetic energy there appears a relativistic generalization; where $\mathbf{M}$ is a diagonal matrix that contains the masses of the different rest frame basis states; and where $\mathbf{a}\cdot c\hat{\mathbf{P}}$ describes the coupling between the rest frame states associated with the motion of the nucleus. What is interesting about this model is the strong coupling between the vibrational degrees of freedom and the internal nuclear degrees of freedom that is present naturally in a proper relativistic model.

2.2 Born–Oppenheimer approximation

Since electrons have a low mass, they move much faster than the nuclei, and it is possible to make an adiabatic approximation. This is often done for condensed matter problems, and there is no reason that one cannot use the same approach here. This is implemented by making use of an adiabatic wavefunction of the form

$$\Psi(\{\mathbf{R}\},\{\mathbf{r}\}) = \Phi(\{\mathbf{R}\})\psi(\{\mathbf{r}\};\{\mathbf{R}\}) \tag{2}$$

where the electronic wavefunction is assumed to satisfy the Schrödinger equation with fixed nuclei

$$E_e(\{\mathbf{R}\})\psi(\{\mathbf{r}\};\{\mathbf{R}\}) = \left[\sum_\alpha \frac{|\mathbf{p}_\alpha|^2}{2m} + \sum_{\alpha<\beta}\frac{e^2}{|\mathbf{r}_\beta - \mathbf{R}_\alpha|} - \sum_{\alpha,j}\frac{Z_j e^2}{|\mathbf{R}_j - \mathbf{r}_\alpha|}\right]\psi(\{\mathbf{r}\};\{\mathbf{R}\}) \tag{3}$$

The nuclear degrees of freedom are described in the Born–Oppenheimer approximation (for this model) by the Hamiltonian [43, 44]

$$\hat{H} = \sum_j \left(\mathbf{M}c^2 + \mathbf{a}\cdot c\hat{\mathbf{P}}\right)_j + \sum_{j<k}\frac{Z_j Z_k e^2}{|\mathbf{R}_k - \mathbf{R}_j|} + E_e(\{\mathbf{R}\}) \tag{4}$$

One sees in this a description of the nuclear center of mass degrees of freedom with explicit coupling to the internal nuclear degrees of freedom.

2.3 Separation under normal conditions

Under normal conditions there is an approximate separation of the center of mass degrees of freedom and the internal nuclear degrees of freedom that eliminates the strong first-order coupling in the relativistic model. This can be implemented with a generalized Foldy–Wouthuysen transformation which can be written as [43]

$$\hat{H}' = \mathcal{U}^\dagger \hat{H}\mathcal{U} = \sum_j \left(\mathbf{M}c^2\sqrt{1+\frac{|\hat{\mathbf{P}}|^2}{(\mathbf{M}c)^2}}\right)_j + \mathcal{U}^\dagger\left[\sum_{j<k}\frac{Z_j Z_k e^2}{|\mathbf{R}_k - \mathbf{R}_j|} + E_e(\{\mathbf{R}\})\right]\mathcal{U} \tag{5}$$

Even though a strong coupling between the vibrations and internal nuclear degrees of freedom is present in the relativistic problem above, under conditions where this strong coupling can be rotated out then there is hardly any residual coupling. This decoupling underlies the intuition that one would not expect vibrations to affect the internal nuclear degrees of freedom. It is understood from this argument that even though there is a strong coupling between the vibrational and internal nuclear degrees of freedom in the initial relativistic fundamental Hamiltonian, one cannot take advantage of it unless there are special conditions under which the generalized Foldy–Wouthuysen transformation somehow is unable to remove it [43].

3 Possibility of a regime without separation

The discussion above motivates us to ask whether there might be conditions under which the strong first-order coupling in the relativistic model above might not be eliminated with a unitary transformation. The easy answer is that a unitary transformation simply implements a change of basis, so that as a mathematical operation it is always possible to make use of a generalized Foldy–Wouthuysen transformation. In a sense, the formulation that solid state physics in the literature is based requires a nearly clean separation of the vibrational and internal nuclear degrees of freedom. This suggests that it is taken as axiomatic that a generalized Foldy–Wouthuysen transformation can always be used to separate these different degrees of freedom; if this were so, there would be nothing further to discuss.

3.1 Transformation for the spin-boson model

A "toy" model have been found which appears to provide a counter example. Consider a model in which many two-level systems are coupled to an oscillator, in which the coupling is linear; this model in the literature is often referred to as the spin-boson model [45]

$$\hat{H} = \Delta E\frac{\hat{S}_z}{\hbar} + \hbar\omega_0\hat{a}^\dagger\hat{a} + V\frac{2\hat{S}_x}{\hbar}\left(\hat{a}+\hat{a}^\dagger\right) \tag{6}$$

The terms on the RHS describe a set of two-level systems with a transition energy ΔE, an oscillator with a characteristic energy $\hbar\omega_0$, and linear coupling (which raises or lowers a two-level system, coupled with the creation or annihilation of an oscillator quantum) with strength V. If V is large, the coupling between the two-level systems and the oscillator can be strong. Such a model could describe the coupling between vibrations, represented by a single oscillator mode, and internal nuclear degrees of freedom, represented by a set of identical equivalent two-level systems.

It is possible to make use of a unitary transformation (of the form of a Foldy–Wouthusyen transformation) that removes the strong first-order coupling between the two different degrees of freedom; an example of this is given in [46] in the case of one two-level system, but a trivial generalization works in the case of many identical two-level systems. After the rotation, there is a small second-order residual coupling; this can be used to analyze coherent energy exchange in the multi-photon regime of the model with excellent results. In this case, a Foldy–Wouthuysen type of transformation can be applied to rotate the problem into a frame where there is no strong first-order coupling, very much analogous to the relativistic model of the previous section.

3.2 Spin-boson model augmented with loss

Now consider an augmentation of the spin-boson model with a (Brillouin–Wigner) loss model [47]

$$\hat{H} = \Delta E \frac{\hat{S}_z}{\hbar} + \hbar\omega_0 \hat{a}^{\dagger}\hat{a} + V\frac{2\hat{S}_x}{\hbar}\left(\hat{a} + \hat{a}^{\dagger}\right) - i\frac{\hbar\hat{\Gamma}(E)}{\hbar} \tag{7}$$

In the spin-boson model, the different degrees of freedom are naturally mixed by the first-order coupling. In a model in which the two-level system transition energy is large, and the oscillator energy is low, it is possible for oscillator transitions to occur under conditions where the energy exchange can be greater than a vibrational quantum $\hbar\omega_0$. Under conditions where the loss is fast when the energy exchange is large, this lossy spin boson model behaves very differently than the original spin-boson model [47–51]. Coherent energy exchange is found to be much more efficient in the multi-quantum regime of the model.

However, what is most interesting in this context is that the Brillouin–Wigner loss does not rotate into anything useful under the unitary transformation. Instead, it is much more convenient to analyze the model in the original unrotated frame. The strong first-order coupling persists in the analysis, and can show up in the behavior of the model if the oscillator is highly excited.

3.3 Fundamental Hamiltonian augmented with loss

The big conclusion that follows from the discussion above is that conditions exist under which one might expect the generalized Foldy–Wouthuysen transformation not to be useful in connection with the relativistic fundamental Hamiltonian. Note that with a more precise development loss terms would have appeared naturally in the fundamental Hamiltonian Hamiltonian above; the nuclear Hamiltonian in the Born–Oppenheimer approximation should be augmented with loss due to phonon-electron coupling [43]

$$\hat{H} = \sum_j \left(\mathbf{M}c^2 + \mathbf{a}\cdot c\hat{\mathbf{P}}\right)_j + \sum_{j<k} \frac{Z_j Z_k e^2}{|\mathbf{R}_k - \mathbf{R}_j|} + E_e(\{\mathbf{R}\}) - i\frac{\hbar\hat{\Gamma}(E)}{2} \tag{8}$$

where the last term accounts for loss in a Brillouin–Wigner formalism [43, 47].

It is understood that resonant single-phonon exchange can be mediated by electron-phonon coupling, and that such loss would be included naturally in this kind of treatment. However, it is only when the loss is both large and dependent on how far off of resonance constituent basis states are that one expects a generalized Foldy–Wouthuysen transformation not to be effective. Simply put, the strong coupling between the internal nuclear degrees of freedom and phonons produces a mixed system in which a single phonon interaction can occur far off of resonance; in this case the loss can be much faster when more energy is available to drive the loss off of resonance, which produces a system incompatible with a generalized Foldy–Wouthuysen transformation. When this happens, one expects that coherent dynamics can be mediated by the phonon-nuclear coupling, and that the coupled system has the potential to fractionate a large quantum (as discussed below).

3.4 Loss can interfere with the rotation

Given how fundamental an issue that is being dealt with in this discussion (the possibility that conditions might exist in which the strong first-order coupling of the relativistic model can not be usefully rotated out with a generalized Foldy–Wouthuysen transformation), there is motivation to understand better why this might occur.

A generalized Foldy–Wouthuysen transformation can be applied directly seeking to eliminate the strong first-order interaction

$$
\begin{aligned}
\hat{H}' = \mathcal{U}^\dagger \hat{H} \mathcal{U} = \sum_j \left(\mathbf{M}c^2 \sqrt{1 + \frac{|\hat{\mathbf{P}}|^2}{(\mathbf{M}c)^2}} \right)_j \\
+ \mathcal{U}^\dagger \left[\sum_{j<k} \frac{Z_j Z_k e^2}{|\mathbf{R}_k - \mathbf{R}_j|} + E_e(\{\mathbf{R}\}) \right] \mathcal{U} \\
- \mathcal{U}^\dagger i \frac{\hbar \hat{\Gamma}(E)}{2} \mathcal{U}
\end{aligned} \tag{9}
$$

There is no difficulty in the application of the rotation to the loss-free part of the model; however, the generalized Foldy–Wouthuysen transformation must also apply to the loss on the same footing, and this is problematic, especially if the off-resonant loss is very fast [43].

This can also be understood from a different perspective. The original relativistic Hamiltonian produces a coupling between a large number of states, and all contribute under normal conditions to individual dressed states in the rotated basis. However, if strong loss is present, a subset of these states will not be able to maintain their normal occupation; so instead of getting back a clean decoupled problem, the generalized Foldy–Wouthuysen transformation creates a mess. Under these conditions one must analyze the problem that results in the unrotated picture; the strong first-order coupling between vibrational and internal nuclear degrees of freedom persists, and can mediate transitions that result in anomalies.

4 Inverse fractionation

From the discussion above it is clear that there is a strong coupling between the vibrational and nuclear degrees of freedom in the relativistic Hamiltonian that can be important under conditions where a vibrational mode is highly excited. However, by itself one would not expect much in the way of consequences associated with such coupling, since the nuclear states that might contribute to an anomaly occur at energies which are a large multiple of a phonon energy quantum. In this case a simple adiabatic approximation would be expected to apply, so that some minor “polarization” of the nuclear transitions due to coupling with vibrations occurs.

4.1 Weak fractionation in the spin-boson model

Coherent energy exchange is predicted in the spin-boson model under conditions where the (dressed) transition energy is an odd multiple of the characteristic energy of the oscillator $\hbar\omega_0$ [46, 52]. This effect is weak; it requires a highly-excited oscillator, strong-coupling, and a mathematically precise resonance. One can fractionate a large two-level system quantum into an odd number of oscillator quanta up to about 31, but fractionating a large quantum into 101 smaller quanta is just not practical.

This provided motivation to understand what limited fractionation in the spin-boson model. Things are clearest under conditions where perturbation theory can be used. One finds that coherent energy exchange under conditions of fractionation is determined by the indirect coupling between two distant basis states, where the coupling in perturbation theory is made up of the sum of contributions from the different individual paths. A massive interference effect shows up in the perturbation calculation, where the total indirect coupling matrix element is orders of magnitude less than the contributions from different individual pathways [47].

4.2 Fractionation in the lossy spin-boson model

Modifications of the spin-boson model were analyzed, seeking ways to dispel this destructive interference effect, in attempts to find a new model that could fractionate a large quantum more efficiently. This included using nonlinear coupling, a nonlinear oscillator, sets of different two-level systems, multiple oscillators, as well as other modifications. While some minor improvements in fractionation power were found, this approach did not succeed in eliminating the destructive interference. It was only when the model was augmented with loss that the problem was solved. The new model from the beginning showed efficient energy exchange under conditions of fractionation.

By now fractionation in the lossy spin-boson model has been analyzed in weak coupling, intermediate coupling, and in the strong coupling limits; numerical and analytic methods were used; and scaling laws [47–51, 53] have been established. In the strong coupling limit the normalized indirect matrix element scales as $1/(\Delta n)^2$, which indicates that the penalty associated with coherent energy exchange under conditions of fractionation is algebraic and reasonably gentle. There is nothing in the model preventing the fractionation of a large quantum into a million smaller quanta, except that the rate becomes algebraically lower the more fractionation is required.

4.3 Inverse fractionation of vibrational energy and model

As discussed above, a relativistic fundamental Hamiltonian gives strong coupling between vibrations and internal nuclear degrees of freedom, and the (closely related) lossy spin-boson model and analysis describes fractionation. On the face of it this suggests that one should be able to use a highly-excited vibrational mode to induce excitation in nuclei. Such an effect goes against intuition from solid state physics, so if it is really possible then it needs to be demonstrated unambiguously.

This motivates a contemplation of a physics experiment to be designed in order to demonstrate lattice-induced nuclear excitation unambiguously. In what follows, the elemental anomalies in fracture experiments will be viewed as an example of lattice-induced disintegration, which is closely related conceptually. To minimize the amount of inverse fractionation required (to make the experiment as "easy" as possible) one would like to work with the lowest energy transition from the ground state of a stable nucleus [54]; this turns out to be the 1,565 eV transition in ^{201}Hg [55]. Since the 1,565 eV transitions couples weakly to vibrations, much more strongly-coupled transitions in a substrate carry out the inverse fractionation in the models, with energy transfer to the 1,565 eV level allowed if the inverse fractionation is sufficient to up-convert from the acoustic frequency.

To model the up-conversion, a derivation of a lossy spin-boson model from the new fundamental Hamiltonian is needed in order to proceed. This was done in [56], leading to

$$\hat{H} \rightarrow \Delta Mc^2 \frac{\hat{S}_z}{\hbar} + \hbar\omega_0 \hat{a}^\dagger \hat{a} + \mathbf{a} \cdot c \frac{d\mathbf{P}}{da} \frac{2\hat{S}_x}{\hbar} \left(\frac{\hat{a} - \hat{a}^\dagger}{i} \right) - i\frac{\hbar}{2}\hat{\Gamma}(E) \qquad (10)$$

The fundamental Hamiltonian is general, and can describe complicated physical systems; but is in general not easy to work with. This simpler idealized model focuses on the interaction between the highly-excited vibrational model and uniform interaction with many identical equivalent two-level systems; it has been analyzed in some detail (with a loss model known to give the best inverse fractionation), with the result that efficient up-conversion is predicted.

Returning now back to the proposed physics demonstration, if the up-conversion involved a low-order vibrational mode with uniform normal motion at the surface (where the Hg would be placed), one would expect that the emission would be collimated normal to the surface. From the models studied so far, the emission line is predicted to be 10s–100s of eV wide. From this it became clear that the physics demonstration under discussion may already have been done, but not recognized as such. Some years ago Karabut reported collimated emission of X-rays from cathode surfaces in high-current glow discharge experiments [57–62], with a broad emission feature near 1.5 keV. At present, excitation of impurity surface Hg by up-conversion of vibrational energy is a candidate explanation, but has not been proven unambiguously.

4.4 Threshold for inverse fractionation

The solutions for the simple inverse fractionation model of Eq. (10) fall into two regimes: one is a conventional regime in which inverse fractionation is possible, but "hard" to achieve; the other is an anomalous regime in which inverse fractionation is both possible and relatively "easy" to achieve. In modeling inverse fractionation associated with collimated X-ray emission in the Karabut experiment, quantitative consistency with experiment is possible only in the anomalous regime of the model. It is expected that the same will be true for lattice-induced disintegration in fracture experiments.

In the version of the model analyzed so far (one which assumes that the loss becomes infinitely strong when the basis state energy is less than the state energy) the threshold for inverse fractionation in the anomalous regime can be expressed as [56]

$$\frac{rN_0}{16} \geq 4 \times 10^{-4} \left(\frac{\Delta Mc^2}{\hbar\omega_0} \right)^2 = 4 \times 10^{-4} (\Delta n)^2 \qquad (11)$$

This threshold can be understood by first focusing on the RHS; the ratio $\Delta Mc^2/\hbar\omega_0$ is the number of (low energy) phonons Δn that make up the two-level transition energy ΔMc^2. Intuitively one would expect it to be easier to fractionate a quantum the fewer phonons are involved in the fractionation; in this constraint for the anomalous regime, it becomes harder to fractionate by the square of this number of phonons.

On the LHS, one sees a parameter r defined by

$$r = 4|\mathbf{a}|^2 \frac{Mc^2}{\Delta Mc^2} \frac{N_0}{N} \tag{12}$$

which is made up of the square of the matrix element for the phonon-coupled internal nuclear transition, the nuclear mass energy divided by the nuclear transition energy, and a dilution factor. The parameter r itself determines whether the system is in the conventional regime ($r < 1$) or in the anomalous regime ($r > 1$). The number of nuclei with the transition that mediates the fractionation is N_0. An additional requirement that does not explicitly appear in the constraint (but is clear from the model above) is that there must be a (uniform) vibrational mode that is highly-excited for the model to apply. In related models for applications, the strongly-coupled transitions are involved in fractionation, and energy is ultimately transferred to transitions more weakly-coupled.

5 Anomalies in fracture experiments, and also in other experiments

Essential features of the theoretical approach have been outlined in the sections above, and now the task is develop a connection with experiment. To be addressed at the outset is the important issue of whether the anomalies observed in fracture experiments are connected with, or are not connected with, anomalies in condensed matter nuclear science. For example, a reviewer has suggested that any discussion of other anomalies is irrelevant, and should be dispensed with. However, if there is a connection it would be quite useful, as one could then learn important things about one experiment by examining the results of another. The theoretical ideas outlined above suggests there may be a deep connection between the different anomalies; in what follows links to a few non-fracture experiments will be noted, along with the motivation for making the connections.

5.1 Vibrational excitation in fracture experiments

A prerequisite for observing any new effects within the framework of the inverse fractionation model is to have a highly-excited oscillator; the large amplitude vibrations produced as a result of a fracture seems to be particularly well matched for this. Also of interest are high frequency vibrations; one would expect large amplitude excitation of the highest frequency vibrational modes available in close proximity to a fracture plane, which is where evidence for elemental anomalies is found. In the inverse fractionation model with uniform conditions outlined above, having more nuclei moving is helpful; once again, in the fracture experiments a large number of atoms are involved in the large amplitude vibrations since the samples are macroscopic.

On the other hand, the (simple) model favors (in the r parameter) samples in which the nuclear transition responsible for the fractionation is present in more of the nuclei, which would seem to suggest that elemental samples might be preferred. However, in a more sophisticated model including multiple nuclear transitions in different isotopes, one expects a modified constraint involving a weighted sum of r values for all of the different transitions of the different isotopes to be present.

5.2 Ultrasonic stimulation

In ultrasonic experiments reported in the recent relevant literature [16–21], stimulation at 20 kHz is used. The relevant vibrational energy quantum in this case is 8.3×10^{-11} eV, which means that an up-conversion of $\Delta n = 3 \times 10^{17}$ is required to develop a large 25 MeV nuclear scale quantum. The number of nuclei required under the (most favorable) conditions of the constraint above in this case is $6 \times 10^{32}/r$, which is more than present in the experiment. One would conclude from this analysis that the use of higher frequency stimulation would be of interest in similar experiments in the future.

In connection with this discussion is Karabut's experiment [57–62] in which collimated X-ray emission near 1.5 keV is observed from cathodes during, and following, glow discharge operation in the high-current regime. Fast sub-ns voltage spikes occur in Karabut's discharge which can couple to the drum head mode near a few hundred KHz, or to compressional modes in the vicinity of 100 MHz. The vibrational energy quantum at 200 KHz is 8.3×10^{-10} eV, and at 100 MHz is 4.1×10^{-7} eV; up-conversion in these two cases would require $\Delta n = 1.8 \times 10^{12}$ and $\Delta n = 3.7 \times 10^{9}$. The number of nuclei required (under the most favorable conditions of the constraint) for the inverse fractionation to a 1,500 eV quantum is $2.1 \times 10^{22}/r$, and $8.6 \times 10^{16}/r$. The number of nuclei required is available in the cathode in this case for the higher frequency vibrations. If the underlying inverse fractionation mechanism is the same, one can understand the fracture experiments better from a study of Karabut's experiment.

5.3 THz excitation and anomalies

By this point it is clear that up-conversion of vibrational quanta is "easier" the fewer quanta are involved, which naturally directs attention to THz vibrations. In the field of condensed matter nuclear science, a correlation between THz vibrations and the presence of anomalies can be made in many cases, as outlined in the "Appendix".

The relevance of this to the fracture experiments is that there are observations of anomalies in common (elemental anomalies, neutron emission, and alpha emission), and that the issue of excitation of high-frequency modes in the fracture experiments becomes of interest. For example, the elemental anomalies in the fracture experiments are highly endothermic (as discussed further below), which suggests that the excitation of high frequency modes in the GHz and THz regimes is of interest. Since THz vibrational excitation is short-lived, elemental anomalies produced through the up-conversion of THz radiation should be strongly localized (nm scale) in the vicinity of the fracture. GHz excitation is much longer lived, and hence can extend much further (μ-scale) away. Because of this the spatial localization of the elemental anomalies in the transverse direction from the fracture plane potentially provides information about which mode frequencies are involved in their production.

5.4 Nuclear disintegration

Proposed by Carpinteri et al. [2] is the possibility of a specific disintegration process

$$^{56}\mathrm{Fe} + 42.36\,\mathrm{MeV} \rightarrow {}^{27}\mathrm{Al} + {}^{27}\mathrm{Al} + 2\mathrm{n} \qquad (13)$$

The big issue in such a proposal is that one would expect to see a broad distribution of products if an incoherent collisional process were involved. Perhaps it is useful in connection with this to consider the spallation studies on ^{56}Fe in [63] and [64] which illustrate this point. In the case of incident electrons, the cross section for gamma emission is substantially larger than for proton ejection; and the cross section for proton ejection is larger than for alpha ejection below 100 MeV [65]. One would expect the fission reaction proposed by Carpinteri et al. to have a very low cross section for incident electrons even up to a few GeV (see [66]).

Even though one might not expect transmutation at all under more benign conditions, by now there have many reports of elemental anomalies in condensed matter nuclear science. For example, in the NiH experiments of the Piantelli group elemental anomalies are present consistent with the disintegration of Ni nuclei [67, 108]. Elemental anomalies have been reported for years in electrochemical, gas loading, and glow discharge experiments [68–73]. Previously noted in papers on the fracture experiments are the anomalies reported by Urutskoev et al. [74]. The issue here is that elemental anomalies qualitatively similar to those observed by Carpinteri et al. in fracture experiments have been reported in electrochemical and in glow discharge experiments.

The biggest effect of this kind comes in the recent experiments of Didyk and Wisniewski [75–77], who report a massive transmutation effect in PdD which cannot be accounted for by (direct) interactions with the incident gamma beam. Compton scattering of the incident gammas would be effective in causing atomic displacements [78], which provides a source of high frequency THz acoustic vibrations; an interpretation of these experiments is that nuclear energy is going into the acoustic modes (in contrast to the two-laser experiment mentioned above) since the receive the majority of the external stimulation, which results in (coherent) disintegration of the host metal atoms through inverse fractionation. Implicit in this discussion is that elemental transmutations in the fracture experiments share the same underlying mechanism with these experiments.

5.5 Incoherent disintegration mechanism

A consideration of mechanism profitably begins with the case of photo-disintegration (electro-disintegration is closely related). In the simplest terms, there are two basic processes observed in experiment: the gamma can interact with a single nucleon or alpha particle, leading to proton, neutron or alpha ejection; in addition the absorption of the gamma quantum can produce an excited (thermal) compound state, which cools by the emission of neutrons, protons, alphas, and other products in proportion to the associated statistical weight and tunneling factors [79–82]. There are a few papers in the literature which discuss photo-disintegration specifically in the Fe isotopes; for example see [83–86]. For incident X-rays in the vicinity of the giant dipole resonance, one sees primarily protons, neutrons and alphas ejected; with much higher energy X-rays one sees a wider spread of photo-fission products [87].

To account for elemental anomalies in PdD experiments, Mizuno [68] and Takahashi [88] proposed that selective photo-fission of Pd produced by multi-photon absorption of lower energy X-rays might produce stable nuclei. A measure of consistency is claimed between model calculations and experiment for induced fission in the case of PdH [89] (one would of course expect unstable nuclei, and many neutrons and gammas to be produced as well). Induced fission of ^{56}Fe was modeled by Cook and Dallacasa [90]. Independently, Widom et al. [42] have proposed photo-fission of ^{56}Fe from X-rays produced by fast electrons in connection with the fracture experiments of Carpinteri et al. Given that photo-fission to roughly equal charge and mass daughters requires GeV energy X-rays, and lacks selectivity [87], how these issues are addressed in such proposals is at issue.

These arguments lead ultimately to the fundamental point. Incoherent nuclear disintegration is well studied in the literature (in the case of electron, ion, and photon induced disintegration as under discussion here); it is definitely not selective at energies where roughly equal fission occurs; while many experimental results in fracture experiments, electrochemical experiments, and in glow discharge experiments show elemental anomalies that are extremely selective. The ultimate conclusion is that incoherent nuclear disintegration simply cannot be an explanation for these observations.

5.6 Coherent disintegration mechanism

If the elemental anomalies (involving lower mass products) are real, then the only possible explanation is nuclear disintegration as a coherent process. This is the only route to selectivity in the product nuclei. There are a number of issues involved in modeling this kind of process, so it makes sense to consider the different issues one at a time.

Discussed above in Sects. 3 and 4 is a mechanism that can fractionate a quantum, and up-convert many vibrational quanta to produce excitation in the MeV regime. Discussed in Sect. 2 is an interaction which in the presence of a highly-excited vibrational mode and an appropriate loss mechanism can couple vibrational and internal nuclear degrees of freedom. Given this mechanism and interaction, one can contemplate the up-conversion of vibrational energy to produce an incoherent disintegration process. For example, hydrogen flux in Pd or Ti produces strong excitation of optical phonon modes near 10 THz, which under appropriate conditions is up-converted into excitation in the MeV regime. The strongest incoherent response to this excitation in Pd or Ti is in the giant dipole resonance region, and the dominant incoherent decay products are p, n, and α emission above 10 MeV. Such emission has been described by Lipson et al. [109] as mentioned above (and also reported by Mosier-Boss at a colloquium at MIT a few months ago). These constitute incoherent disintegration processes driven by inverse fractionation (where the up-conversion process itself could be considered to be coherent).

Coherent disintegration as proposed here takes advantage of the same up-conversion of vibrational energy, the same coupling between vibrational and internal nuclear degrees of freedom, but does not involve a fast incoherent decay at the end. Unfortunately, there are no examples known in the nuclear literature of long-lived nuclear states that separate into near equal mass daughters in the vicinity of Fe. However, there are examples of long-lived nuclear states near Fe that are observed to be stable against gamma decay, but unstable against highly asymmetric fission. The closest relevant studies involve high rotational bands in Co, Ni and Cu isotopes by Rudolph et al. [92–96], where states at the band edges are deformed, relatively long-lived, and decay slowly through exotic high spin proton or alpha ejection. Consider the situation where up-conversion by inverse fractionation is effective in coupling to transitions at lower energy (6–10 MeV) where these longer-lived states can be accessed. In the absence of a fast decay, these excited states can accumulate substantial probability from the ground state through a coherent interaction with the highly-excited vibrational model. This kind of mechanism can account for the elemental anomalies reported by the Piantelli group in NiH [67].

The resulting slow disintegration itself is incoherent; however, because the decay is slow the accumulation of probability in the state can be considered as coherent dynamics. Since each individual transition in such a process is near resonance, the coherent dynamics described in [91] applies. A consequence of this kind of near resonant dynamics is that states that decay rapidly do not accumulate much population (and hence there are few products); and also the evolution of nearly degenerate coherent dynamics tends to drive the system in the direction where the coherent rate is maximum.

It seems clear that there should be exist more strongly deformed states, also long-lived (and stable against gamma emission), which decay at different band edges with more nearly equal fission products.

Examples of candidate fission reactions that might be considered are listed in Table 1, including the reaction proposed in [2]. For ^{54}Fe there are several candidate reactions with threshold energies near 20 MeV, including

$$^{54}\mathrm{Fe} + 21.85\,\mathrm{MeV} \rightarrow {}^{27}\mathrm{Al} + {}^{27}\mathrm{Al} \tag{14}$$

The threshold energy in this case is not so different from the lattice energy transfer needed for low-level energetic alpha emission [109]. This reaction is a more compelling candidate than Eq. (13), and suggests that it would be important to monitor the isotopic composition of the Fe isotopes at the surface of fracture planes where Al is observed.

The simplest way a (coherent) symmetric fission reaction could be mediated is if there were a finite **a**-matrix element between the ground state of ^{54}Fe and a long-lived excited state above the ^{27}Al +^{27} Al threshold which which was stable against gamma decay and asymmetric fission, and which decayed slowly through symmetric fission. Unfortunately this seems extremely unlikely. So, a much more likely scheme is one involving multiple (coherent) transitions between stable intermediate states (such as the band edge states studied by Rudolph et al. mentioned above), involving rotation and deformation, leading ultimately to a band edge state with a slow symmetric fission decay channel.

Table 1 Candidate lattice-induced fission reactions

^ZA_i	$\sum_f {}^ZA_f$	ΔE(MeV)
^{54}Fe	^{30}Si + ^{24}Mg	17.88
^{54}Fe	^{29}Si + ^{25}Mg	21.16
^{54}Fe	^{28}Si + ^{26}Mg	18.54
^{54}Fe	^{27}Al + ^{27}Al	21.85
^{56}Fe	^{30}Si + ^{26}Mg	19.95
^{56}Fe	^{29}Si + ^{26}Mg + n	30.56
^{56}Fe	^{28}Si + ^{26}Mg + 2n	39.04
^{56}Fe	^{27}Al + ^{27}Al + 2n	42.35
^{57}Fe	^{30}Si + ^{26}Mg + n	27.60
^{58}Fe	^{30}Si + ^{26}Mg + 2n	37.64

6 Discussion

The observation of anomalies in fracture experiments is an exciting development, leading to a new field that should be considered as emergent at this time. As these anomalies would not be expected based on textbook physics, the observations suggest new physical mechanisms at work; this motivates an interest in providing clarification of the new physics. The observations are still relatively new, so given the magnitude of the associated theoretical problem, theoretical proposals at this point (including those described above) are speculative.

A big advantage is possible if a connection can be made between the anomalies in fracture experiments, and similar anomalies observed in other experiments. The relevance of anomalies in the field of low energy nuclear reactions has been discussed previously [97, 98]. A large amount of experimental and theoretical work has been reported on anomalies in electrochemical, gas loading and discharge experiments; so it is natural to draw from this field to take advantage of results that have become available over the years. From the brief review of one of the theoretical approaches given above, one has some intuition as to what the models are based on, how they work, the origin of a variety of anomalies within the theoretical framework, and why fracture experiments are of interest. If anomalies are a result of the up-conversion of vibrational quanta, then the strong excitation of high-frequency vibrational modes that occurs in a fracture is the key issue that makes such experiments interesting.

This theoretical picture points to a variety of issues with experimental implications, which is the focus of the discussion in this section. In response to experiments in which neutron emission is observed, and in which Al is observed, the reaction

$$^{56}\mathrm{Fe} + 42.36\,\mathrm{MeV} \rightarrow {}^{27}\mathrm{Al} + {}^{27}\mathrm{Al} + 2\mathrm{n}$$

has been proposed [2]. The lower energy reaction

$$^{54}\mathrm{Fe} + 21.85\,\mathrm{MeV} \rightarrow {}^{27}\mathrm{Al} + {}^{27}\mathrm{Al}$$

would seem to be preferred in connection with Al production since the threshold energy is lower. Clarification could result from carrying out an isotopic assay of the Fe isotopes in regions showing a depletion of Fe and new Al. Clarification could also result from quantifying the number of new Al, and comparing it with an estimate for the number of source neutrons.

One wonders what might be observed if one started with a concrete made of lower mass isotopes, and included (when making) a heavier isotope in a controlled fashion. Consider a study in which concrete samples were made such individual samples only contained one of the stable Fe isotopes. If elemental anomalies were seen in fracture experiments with such samples, a correlation could be established between product and Fe isotope, which could aid considerably in the determination of the mechanism. For example, the threshold for Al production from ^{54}Fe is 21.85 MeV, while from ^{56}Fe the threshold is 42.36 MeV; one would expect this threshold energy to make a difference, so the question is whether this is the case in an experiment. Going further, what would happen if the concrete was doped with Ni or Cu isotopes instead? Or for that matter, suppose that the sample were doped with Pb; is it possible to arrange for fracture-induced disintegration of a heavy nucleus. The issues in this case are very different; fission is exothermic, but the fission barriers are much higher.

Clarification might also come from a determination of the source neutron energy spectrum, which is probably not so easy to determine in a fracture experiment with a large rock sample due to inelastic scattering. Nevertheless, if successful, then it may be possible to develop constraints on candidate theoretical reaction mechanisms. For example, low-level energetic neutron emission above 10 MeV is consistent with energy exchange in the giant dipole resonance region.

In a model based on phonon up-conversion, the magnitude of the quantum exchanged depends most strongly on the vibrational frequency, on the number of nuclei involved in the vibration, and also the level of the vibrational excitation. If so, then one might expect that weaker fractures involving rocks containing iron should result in less Al, and instead isotopes involving more asymmetric fission with a lower threshold energy.

Mentioned above is the importance of determining the spatial distribution of elemental anomalies as a function of the transverse distance from the fracture plane. If the elemental anomalies are localized on the nm scale, then THz frequencies would be implicated; localization on the micron scale would implicate lower GHz frequencies. Such measurements would also help to provide constraints that would clarify what range of energies accelerated ions are consistent with experiment in theoretical models put forth based on collisions.

Within the theoretical picture, the importance of the fracture is to produce high amplitude and high frequency vibrations in a large number of nuclei. If so, one might consider a different kind of experiment in which samples were driven externally at high amplitude and high frequency. If elemental anomalies and neutron emission were seen, then it would be easier to study the new effects systematically. The model suggests that THz vibrations are more effective at producing anomalies; consequently, driving a monatomic crystal sample in the highest vibrational modes with an intense THz source to induce anomalies would be of interest.

In the case of alpha emission, it is problematic to bring a charged ion detector close to a fault plane, which means that it is difficult to quantify the number of energetic ions produced. A similar issue occurs in the case of PdD electrochemical experiments, where a detector in close proximity impacts the electrochemistry negatively. It was proposed in this case to have the PdD itself serve as the detector [99]. This suggests a similar approach in a fracture experiment; one might use a deuterated sample, or an appropriate metal deuteride, as a test sample to fracture. Energetic ions hitting deuterons will result in neutron emission from secondary deuteron-deuteron fusion reactions, and these neutrons can be detected outside of the sample.

Appendix: Anomalies involving THz vibrations

In the two-laser experiment of Letts [101, 102] excess heat events are stimulated at difference frequencies of

8.2, 15.1, and 20.8 THz (the first two of which are good matches for Γ-point and L-point of the optical phonon mode spectrum); this is relevant if fractionation is involved in excess heat generation. These experiments are consistent with the interpretation that nuclear energy is being fractionated and going into these vibrational modes modes [102].

When there is a net hydrogen (or deuterium) flux in a metal hydride (or deuteride), one expects excitation of high frequency (THz) optical phonon modes. If this excitation is sufficiently strong, it may be that energy exchange under conditions of inverse fractionation occurs, with the possibility that anomalies may be produced. In connection with this issue, excess heat in Fleischmann–Pons experiments is observed to be correlated with deuterium flux at the cathode surface [103, 104]. Also of interest in this discussion are the many anomalies reported by Piantelli et al. [105–108] in NiH gas loading experiments. Excess heat, elemental anomalies, and effects are triggered by temperature or pressure cycles, that can be interpreted as inducing a flux of hydrogen inside the metal. In this case the hydrogen solubility is low, so that excitation of THz acoustic modes is predominant (localized optical phonon excitation in this case is not of interest since the total amount of excitation is limited).

There have been reported anomalies in experiments with ion bombardment, which generates strong THz excitation near the surface. Low-level energetic alpha emission near 15 MeV was reported in glow discharge experiments with PdH and TiH by Lipson et al. [109], which can be interpreted as due to the up-conversion of THz vibrational quanta to MeV-level quanta in the vicinity of the giant dipole resonance above 20 MeV. Storms and Scanlan have observed energetic particle emission from metal samples with a hydrogen discharge [110, 111], which permits a similar interpretation. Karabut has reported a variety of anomalies (other than collimated X-ray emission) in his glow discharge experiments [112] that can be interpreted as resulting from the up-conversion of THz vibrational quanta.

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