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Research Article

Candidates for Near-Resonant Subdivision Experiments

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Abstract

In a subdivision process, the excitation from a nucleus in an excited state is transferred so as to produce excitation in two or more nuclei as a result of multi step excitation transfer. This has been proposed as a key component of excess heat models, where a large 24-MeV quantum needs to be broken down into many lower energy quanta. Here, we consider candidates for a new laboratory experiment in which subdivision might be studied in isolation. In such an experiment, the alpha or beta decay of a radioactive source produces an initially excited nucleus, and multiple excitation transfer steps lead to two excited nuclei with lower energy excitations, such that the total excitation energy approximately matches the initial excited state energy. A suitable candidate must include an initially excited nucleus that can be produced from a commercially available radioactive source, and two final excited states in stable nuclei, where the energy mismatch is sufficiently small that it can be made up by the exchange of a few optical laser photons. We searched through all relevant transitions in the NUDAT2 database below 250 keV and found four candidates for a laboratory subdivision experiment.

Keywords: subdivision, excitation transfer, phonon-nuclear interaction, model for excess heat, plasmon-phonon-nuclear interaction

1. Introduction

To account for excess heat in the Fleischmann–Pons experiment, we have focused on models in which a relativistic phonon–nuclear interaction [1] mediates excitation transfer steps [2]. The first step involves a $D_2/^4He$ transition, with the 24-MeV excitation being transferred to a nucleus in the host lattice [3], [4] (or perhaps excitation being transferred to a ^4He nucleus to produce a compact D_2 state prior to be transferred to a nucleus in the host lattice [5]). Next, in the model are a series of subdivision steps, where in such a step, the excitation from an excited nucleus is transferred to produced excitation at a lower energy in two (or more) nuclei. After many such subdivision steps, the initial large 24-MeV quantum has been subdivided into a great many (1000's) quanta in low-energy nuclear transitions at the 10s of keV level, from which in the model, the energy is down-converted (based on fast sequential non resonant excitation transfer steps) into THz phonons [3]–[5]. Note that only ten subdivision matches would be required to reduce a 24-MeV quantum down to 24 keV if each involved a factor of 2, since $2^{10} = 1024$ (but it is unlikely that suitable relatively long-lived nuclear-excited states could be found for the precise factor of 2 subdivisions at each step). The thought is that subdivision near resonances are likely to be rare, so that subdivision making use of a particular near-resonance set of states would occur over and over again. The large number of individual subdivisions required for this part of the reduction of the large 24-MeV quantum would be accelerated if more nuclei were involved, which may be problematic in the absence of phonon gain due to the small coherence volume for THz phonon modes. However, in the presence of phonon gain (which is consistent with the experiment and with our models), the coherence volume can be mesoscopic or macroscopic (in which case subdivision can be accelerated by collective enhancements).

In our lab, we have been interested in experiments in which phonon-mediated excitation transfer occurs. In one such experiment, ^{57}Co beta decays (through the capture of a K-shell electron) to produce excited states in ^{57}Fe, where when appropriate stimulation is present (thought to produce THz vibrations), resonant excitation transfer of the 136-keV state leads to angular anisotropy, and fast non resonant excitation transfer of the 14.4-keV state leads to observable delocalization [6]–[8]. This experiment potentially permits the interpretation that the proposed phonon–nuclear coupling is real (although we do not at this point have a quantitative agreement between the model and experiment), and that phonon-mediated nuclear excitation transfer occurs and can be fast.

We have also developed an ion beam experiment in which a beam of low-energy (sub 1 keV) deuterons is incident on a metal target, where charged particle detectors monitor for low-level energetic ion emission, and where a Wendi-2 neutron detector monitors for energetic neutron emission. In this experiment, a goal is to test whether energetic nuclear particle emission is a result of excitation transfer from the $D_2/^4He$ transition to produce excitation in nuclei in the lattice which subsequently decays.

These two experiments address important pieces of the proposed model. For example, at the foundation of the model is the phonon–nuclear interaction, which at this point needs experimental confirmation. All of the important steps in the excess heat model involve phonon-mediated excitation transfer processes, for which additional experimental confirmation is of interest to gain confidence that the effect occurs. In the ion beam experiment, there is the possibility of studying the first excitation transfer step in the excess heat model. We have discussed previously the possibility of studying down conversion based upon experiments involving collimated x-ray emission, which permits the interpretation of being due to the closely related up conversion effect [9].

What has been missing in this discussion are new experiments in which subdivision might be studied. For this, we would like to see the excitation from a nuclear transition be transferred to produce excitation in two or more other nuclei at lower energy. In this work, we examine prospects for near resonances that might be suitable for new experiments where the subdivision effect might be demonstrated.

2. Unconstrained (and Naive) Search

To develop a new experiment in which subdivisions can be studied in the lab, we require nuclear transitions from the ground state which satisfy

$$E_i = E_{f1} + E_{f2} + Q \tag{1}$$

where the mismatch Q is minimized.

To study this, we have created a list of excited state energies taken from the NUDAT2 database [10], [11] that includes all listed excited state energies in the stable (or long-lived) nuclei below 250 keV. A simple computer code was written to read in the levels and to search for approximate resonances. Results for the closest match in each case are shown graphically in Figure 1, where the Q values are determined simply from a subtraction of the listed energy levels.

Since there are only a few transitions at low energy, we expect few possibilities that two transitions will add up in such a way to be close to a given low energy E_i. As the transition energy increases there is an increasing number of pairs whose transition energies add up to be close to E_i. This leads to the general shape of the results shown in Figure 1, where there are no close matches at low energy, and an increasing collection of close matches as E_i increases.

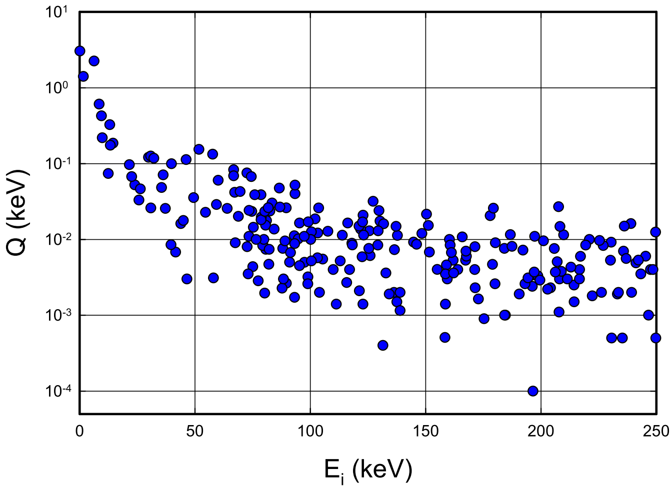

Figure 1. Energy mismatch Q as a function of the initial transition energy E_i. Note that the energy mismatch in this plot is estimated from the difference in listed state energies, and the uncertainty in mismatch in general is much larger.

Table 1. Subdivision resonances with the smallest mismatches. Note that the mismatch listed assumed exact energies to all digits, under conditions where the energies were reported to only a few digits. While the mismatch reported for the ^{199}Hg transition at 158.3791 keV is 0.0005 keV, the associated uncertainty is at least 0.05 keV.

$\|Q\|$(keV)	^AZ_i	E_i(keV)	$^AZ_{f1}$	E_{f1}(keV)	$^AZ_{f2}$	E_{f2}(keV)
0	^{205}Tl	203.70	^{101}Ru	127.229	^{174}Yb	76.471
0.0001	^{151}Eu	196.54	^{153}Eu	151.6293	^{238}U	44.916
0.0004	^{157}Gd	131.451	^{119}Sn	23.871	^{155}Gd	107.5804
0.0005	^{77}Se	249.7885	^{127}I	57.608	^{138}La	192.18
0.0005	^{153}Eu	235.2807	^{188}Os	155.043	^{193}Ir	80.238
0.0005	^{171}Yb	230.631	^{107}Ag	93.125	^{159}Tb	137.5055
0.0005	^{199}Hg	158.3791	^{95}Mo	59.3	^{183}W	99.0791
0.0009	^{77}Se	175.3059	^{154}Sm	81.981	^{180}Hf	93.3240

A short list of the closest matches is given in Table 1. We see that there are differences in the number of digits given for the different excitation energies, so that in none of the cases do we have confidence that any of the resonances are good to better than 1 eV.

The general conclusion is that we would expect there to be sets of subdivision candidates with transition energies on the order of a few eV, but there are issues as to how well the excited state energies are known.

An additional headache is that ideally we would like to have a radioactive source which is capable of producing nuclei in the initial excited state. If we make use of the list of available isotopes from Eckert and Ziegler, then we find that there are no obvious radioisotopes which allow for an experiment with the ^{205}Tl state at 203.70 keV, or for most of the other near resonances found from this search.

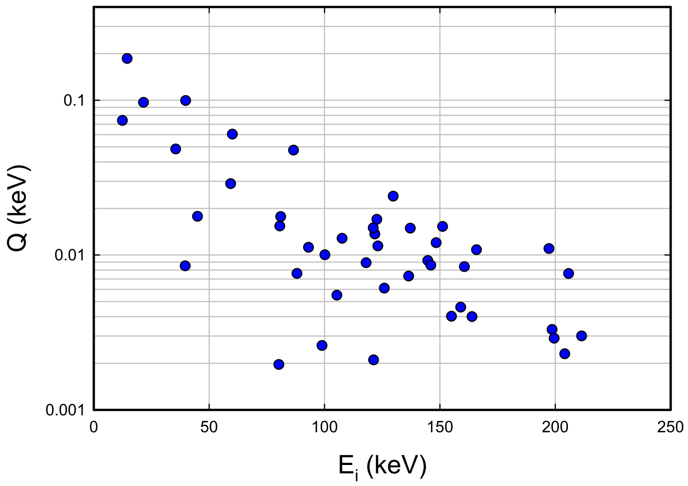

Figure 2. Energy mismatch Q as a function of the initial transition energy E_i. Note that the energy mismatch in this plot is estimated from the difference in listed state energies, so that the uncertainty in mismatch in general is much larger.

3. Search Conditioned on Source Availability

We have repeated the search now with the restriction that the initial excited state has the possibility of being produced with a source commercially available from Eckert and Ziegler's list of available isotopes. Results are once again shown graphically in Figure 2.

A list of the top candidates with mismatches below 10 eV is given in Table 2. In this table, we have the same issue as before in connection with a large uncertainty in the associated Q-value when there are insufficient digits listed in the NUDAT2 database for the excited state energy. Also, we see some of the transitions in gas atoms, as well as in naturally occurring but unstable isotopes, such as ^{40}K and ^{235}U, which would complicate a subdivision experiment. There is also the headache that for some of the initial excited states the associated yield from a radioactive source is low.

This suggests that we would like to trim down the list to focus on candidates which would have the best chance of leading to an experiment that would be simplest to execute, where we require the different transitions to occur in stable metal nuclei, and where a radioactive source is available that can produce the initial excited state efficiently. The trimmed down list is given in Table 3, where we have added an additional candidate with a higher energy mismatch.

The subdivision in the case of the 136 keV state in ^{57}Fe is illustrated in Figure 3. We have worked with the 136 keV transition in ^{57}Fe, so we have some confidence that phonon-mediated nuclear excitation transfer is possible. The various transitions listed in the table are all either E1, E2, or M1+E2, so this leads to confidence that the transitions should be able to participate in phonon–nuclear interactions.

4. Energy Mismatch

In all cases listed in Table 3, we expect an energy mismatch on the order of 4–15 eV. The question is what might be done about it.

If we consider phonon-mediated nuclear excitation transfer, then the energy mismatch in all cases is more than what might be expected from multiple phonon absorption or emission. Energy mismatches would be expected in the case of subdivision in an energy-producing Fleischmann–Pons experiment, but in our view, under conditions where

Table 2. Subdivision resonances with the smallest mismatches. Note that the mismatch listed assumed exact energies to all digits, under conditions where the energies were reported to only a few digits. While the mismatch reported for the ^{195}Pt transition at 99.880 keV is 0.0023 keV, the associated uncertainty is at least 0.05 keV.

$\|Q\|$(keV)	^AZ_i	E_i(keV)	$^AZ_{f1}$	E_{f1}(keV)	$^AZ_{f2}$	E_{f2}(keV)
0.0020	^{131}Xe	80.1854	^{157}Gd	54.536	^{161}Dy	25.6514
0.0021	^{147}Sm	121.212	^{40}K	29.8299	^{164}Er	91.380
0.0023	^{95}Mo	204.1163	^{176}Lu	194.358	^{187}Os	9.756
0.0026	^{195}Pt	98.880	^{95}Mo	59.3	^{129}Xe	39.5774
0.0029	^{195}Pt	199.532	^{183}W	99.0791	^{187}Os	100.45
0.0030	^{195}Pt	211.406	^{109}Ag	132.762	^{173}Yb	78.647
0.0033	^{75}As	198.6063	^{165}Ho	94.700	^{235}U	103.903
0.0040	^{131}Xe	163.930	^{99}Ru	89.57	^{187}Os	74.356
0.0040	^{188}Os	155.043	^{127}I	57.608	^{153}Eu	97.43098
0.0046	^{123}Te	159.024	^{158}Gd	79.5143	^{158}Gd	79.5143
0.0055	^{155}Gd	105.3106	^{181}Ta	6.237	^{183}W	99.0791
0.0061	^{55}Mn	125.949	^{161}Dy	43.8201	^{176}Yb	82.135
0.0073	^{57}Fe	136.4743	^{155}Gd	60.0106	^{174}Yb	76.471
0.0076	^{192}Os	205.7944	^{181}Ta	136.262	^{189}Os	69.54
0.0076	^{109}Ag	88.0337	^{83}Kr	41.5575	^{183}W	46.4834
0.0084	^{133}Cs	160.6121	^{109}Ag	88.0337	^{138}La	72.57
0.0085	^{129}Xe	39.5774	^{40}K	29.8299	^{187}Os	9.756
0.0086	^{155}Gd	146.0696	^{61}Ni	67.414	^{173}Yb	78.647
0.0089	^{155}Gd	117.9981	^{155}Gd	60.0106	^{159}Tb	57.9964
0.0092	^{125}Te	144.775	^{159}Tb	57.9964	^{160}Dy	86.7878

Table 3. Reduced version of Table 2 (augmented with a candidate with a higher mismatch) including candidates with available sources that produce the initial excited state efficiently, where all ground states correspond to stable metal atoms. In this table, after the transition energy, we have added the transition multi polarity.

Q (keV)	^AZ_i	E_i (keV)		$^AZ_{f1}$	E_{f1} (keV)		$^AZ_{f2}$	E_{f2} (keV)	
-0.0046	^{123}Te	159.024	M1+E2	^{158}Gd	79.5143	E2	^{158}Gd	79.5143	E2
-0.0055	^{155}Gd	105.3106	E1	^{181}Ta	6.237	E1	^{183}W	99.0791	E2
-0.0073	^{57}Fe	136.4743	E2	^{155}Gd	60.0106	M1+E2	^{174}Yb	76.471	E2
0.0153	^{85}Rb	151.192	M1 + E2	^{159}Tb	57.9964	M1+E2	^{178}Hf	93.1803	E2

excess heat occurs there is an energy exchange between the nuclear system and the vibrational system. In this case, our models indicate that an (anomalous) energy substantially greater than that of a single phonon can be exchanged in connection with each phonon exchange. However, in an experiment, similar to our ^{57}Co/^{57}Fe excitation transfer experiment (where the number of THz phonons is thought to be much less than in an excess heat experiment), we would not expect this kind of anomalous energy exchange to occur on the 136-keV transition.

One approach might be to make use of laser stimulation, where a substantial mixing of the plasmon and phonon degrees of freedom are expected in metal. In this case, the laser could be used to drive plasmon excitation at a given frequency (much higher than the phonon frequency), but because the vibrational and electron plasmonic degrees of freedom are coupled, we would expect plasmon–phonon–nuclear-mediated excitation transfer to occur. The key issue here is that the energy mismatch could be made up by the absorption of a few photons. In this case on resonance, we

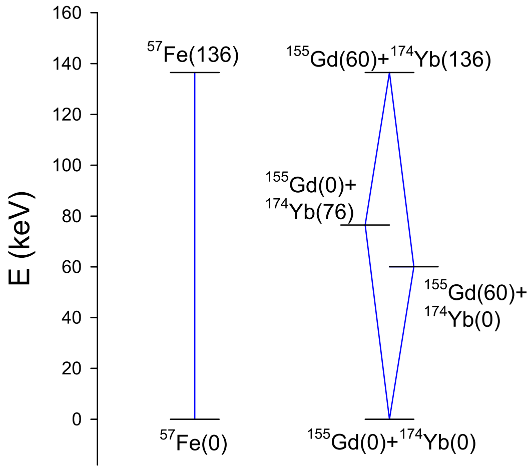

Figure 3. Level scheme associated with the subdivision of the ^{57}Fe 136-keV state.

Table 4. Candidate photon energies around which to scan under the assumption that different numbers of photons are absorbed.

^AZ_i	E_i (keV)	$^AZ_{f1}$	E_{f1} (keV)	$^AZ_{f2}$	E_{f2} (keV)	$\hbar\omega_0$ $\Delta n = \pm 2$	$\hbar\omega_0$ $\Delta n = \pm 4$	$\hbar\omega_0$ $\Delta n = \pm 6$
^{123}Te	159.024	^{158}Gd	79.5143	^{158}Gd	79.5143	2.30 eV	1.15 eV	0.77 eV
^{155}Gd	105.3106	^{181}Ta	6.237	^{183}W	99.0791	2.75 eV	1.37 eV	–
^{57}Fe	136.4743	^{155}Gd	60.0106	^{174}Yb	76.471	3.65 eV	1.82 eV	1.22 eV
^{85}Rb	151.192	^{159}Tb	57.9964	^{178}Hf	93.1803	7.65 eV	3.82 eV	2.55 eV

would have

$$E_i \; = \; E_{f1} + E_{f2} + \Delta n \hbar\omega_0 \tag{2}$$

where Δn is the (net) number of photons absorbed.

Since the mismatch in the nuclear energy levels is not known precisely, this kind of experiment would likely require some ability to scan over a range of photon energies, seeking a resonance condition—which could be detected through the emission of new gammas from the subdivided nuclear transitions. Photon energies around which to scan are listed in Table 4 for the four most interesting candidates. We see for the subdivision of the 136-keV transition in ^{57}Fe that subdivision with four-photon absorption would require a tunable laser centered at 1.82 eV, which is in the red part of the spectrum. This is depicted in Figure 4.

In the case of the phonon–nuclear interaction for individual E2 and M1 transitions, one would expect two-phonon exchange transitions to be dominant (over four-phonon or six-phonon exchange interactions) in connection with an internal nuclear transition. However, it is possible in principle that such a transition could occur through single-phonon exchange if a strong magnetic field is present (note the presence of terms involving the vector potential showing up in the same way as phonon–nuclear interaction terms in the transformed Hamiltonians in [1]). In a subdivision experiment where the absorption or emission of laser photons (which excite plasmons that mix with phonons) makes up the energy difference, then a violation of the associated photon/phonon selection rule could occur—which would tell us that

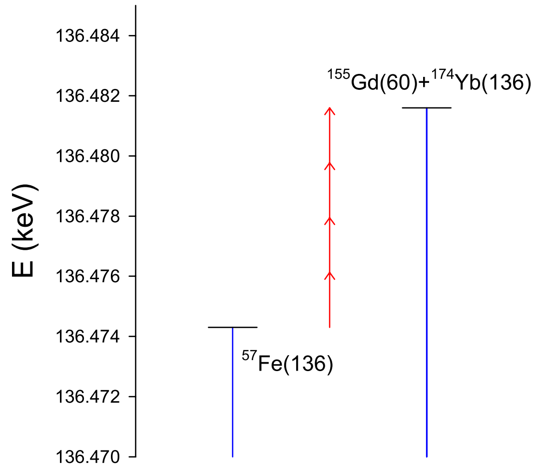

Figure 4. Level scheme illustrating the absorption of four photons to make up the mismatch in the case of the ^{57}Fe 136-keV subdivision candidate.

single-phonon exchange can occur for an E2 or M1 (or mixed M1+E2) transition, and could provide information as to the relative strength of one-phonon versus two-phonon interactions.

5. Discussion and Conclusion

A successful subdivision experiment of the kind under discussion in this paper would be important in the context of the models under consideration for accounting for excess heat in the Fleischmann–Pons experiment. This in part because such a demonstration would provide assurance that the effect is real, and in part would have the potential to provide an experiment against which a quantitative model could be tested.

Since there are only a modest number of suitable low-energy transitions, a precise match in energy between the initial transition energy and the sum of the final transitions energies does not seem to be possible. The energy mismatch in the best cases appears to be substantially larger than what could be made up through phonon exchange, although uncertainties in the excited state energies at present do not mean that this can be ruled out in general for nuclear transitions below 250 keV.

On the other hand, the energy mismatch in the candidates identified in Table 4 is sufficiently low that there is the possibility of making up the energy difference through multi photon absorption or emission, where a tunable laser couples to plasmons in the metal, where plasmons mix with phonons, and where the phonon admixture can produce internal nuclear transitions based on the relativistic phonon–nuclear interaction.

Note that the development of such a subdivision experiment would have applications outside of condensed matter nuclear science. A successful subdivision experiment would allow for the determination of high-precision energy differences between energy levels. However, in this context, a more important experiment would be one involving simple excitation transfer between levels of different isotopes. Candidates from the list of excited state energies we have assembled are given in Table 5. The candidates with the lowest energy mismatches do not have associated radioisotopes available from commercial sources but have mismatches sufficiently low to be accessible with lasers. In this table, the energy mismatch is determined from

$$E_i = E_f + Q. \tag{3}$$

Table 5. Candidate transitions for non resonant nuclear excitation transfer between transitions in different isotopes.

Q (keV)	$^{A}Z_i$	E_i (keV)	$^{A}Z_f$	E_f (keV)
0.007	^{171}Yb	66.732	^{73}Ge	66.725
0.008	^{193}Ir	138.941	^{169}Tm	138.93315
0.008	^{117}Sn	158.562	^{181}Ta	158.554
0.012	^{155}Gd	214.3515	^{179}Hf	214.3395
0.012	^{171}Yb	95.282	^{189}Os	95.27
0.012	^{180}Hf	93.324	^{67}Zn	93.312
0.038	^{158}Dy	98.918	^{195}Pt	98.880
0.039	^{99}Ru	89.57	^{119}Sn	89.531
0.047	^{187}Os	100.45	^{161}Dy	100.4033
0.050	^{151}Eu	216.72	^{189}Os	216.67

If non-resonant nuclear excitation transfer becomes important in the future in nuclear physics, then it would be possible to make use of bright narrow band tunable light sources in the UV and EUV for this kind of study. In the event that anomalous energy exchange occurs, as in the case of excess heat production, then non-resonant excitation transfer or non-resonant subdivision could be used to show anomalous energy exchange and to quantify how much (anomalous) energy can be exchanged.

A successful non resonant excitation transfer experiment between transitions in different isotopes, or a successful subdivision experiment, would in both cases provide for a new kind of gamma source where the presence (or absence) of specific gamma would be controlled by the incident light source. Note that there is the possibility of tunability under conditions where gamma emission is driven away from the nuclear resonance condition.

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