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AN INTRODUCTION TO THE INTERACTION OF THE IMMUNE SYSTEM WITH ELECTROMAGNETIC FIELDS.

Vincent Lauer*

Abstract:

The present paper is a synthesis of a recently published model of the interaction of the immune system with electromagnetic waves. It is limited to the interaction of the immune system with electromagnetic waves below 3 GHz, suitable for the interpretation of interactions of the immune system with radiofrequency waves commonly used in radio-communications. Three states (Cognate antigen Recognized CR, Antigen Not Recognized ANR, and Neutral State) of T lymphocytes are introduced, which facilitates the understanding of the model. The intrinsic consistency of the model is made more apparent by first presenting the physical model of antigen recognition and non-recognition, after which the interaction of T lymphocytes with electromagnetic waves appears as an unavoidable consequence of this physical model. The power dependency of the interaction and the power thresholds are also discussed.

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1- INTRODUCTION:

A model of the interaction of the immune system with radiofrequency electromagnetic fields was first proposed in (Lauer 2013) and was then improved and applied for interpreting experimental results on animal models in (Lauer 2014a). The present paper is a synthesis of this model, limited to the interaction of the immune system with electromagnetic waves below 3 GHz, suitable for the interpretation of interactions of the immune system with radiofrequency waves commonly used in radio-communications. Three states (Cognate antigen Recognized CR, Antigen Not Recognized ANR, and Neutral State) of T lymphocytes are introduced, which facilitates the understanding of the model. The intrinsic consistency of the model is made more apparent by first presenting the physical model of antigen recognition and non-recognition, after which the interaction of T lymphocytes with electromagnetic waves appears as an unavoidable consequence of this physical model. The power dependency of the interaction and the power thresholds are also discussed.

2- STATES OF T LYMPHOCYTES.

Following an interaction with an Antigen Presenting Cell (APC) a T lymphocyte can enter either of the following states, which can be inferred from but were not explicitly disclosed in (Lauer 2014a) (see figure 1):

a) a "cognate antigen recognized" state (CR). Transitions to state CR result in elimination of the T lymphocyte by negative selection (in the negative selection portion of the thymus), proliferation (in lymph nodes), or destruction of the APC (in the diseased organ).

b) an "antigen not recognized" state (ANR). Transitions to state ANR result in elimination by positive selection (in the positive selection portion of the thymus) and in temporary inactivation (elsewhere). Temporarily inactivated T lymphocytes stop searching their cognate antigen and are evacuated from infected organs, leaving better access for other T lymphocytes likely to recognize corresponding non-self antigens.



Figure 1: lifecycle of T cells and its interaction with electromagnetic waves.

State CR is entered when the affinity of the T lymphocyte for the presented antigen on the Antigen Presenting Cell (APC) is higher than a Recognition Threshold. State ANR is entered when the affinity is lower than a Non-Recognition Threshold. The affinity of the T lymphocyte for a number of antigens is between the Recognition Threshold and the Non-Recognition Threshold, in which case the T lymphocyte remains essentially undisturbed in a Neutral State, i.e. it keeps searching for antigens. A lymphocyte which has survived positive and negative selection is expected to remain in the neutral state when interacting with self antigens, but enter either the CR or the ANR state when interacting with non-self antigens.

An individual antigen on an APC is recognized by an individual T Cell Receptor (TCR) on a T lymphocyte. However at lymphocyte level the overall affinity of the T lymphocyte for the antigen on the APC depends on the antigen but also on the number of copies of the antigen which are presented by the APC. Some T lymphocytes have inhibitory receptors and may be able to enter state CR only if the number of TCRs having recognized their cognate antigen overcomes a weighted number of activated inhibitory receptors, yielding a strong dependency on the number of copies of the antigen. The dependency of the overall affinity on the number of presented copies of the antigen allows T cells to recognize not only abnormal antigens but also normal antigens presented in abnormal numbers.

3 - UNDERLYING PHYSICAL MODEL.

3.1. ANTIGEN RECOGNITION

The basic unit involved in antigen recognition comprises the T Cell Receptor, antigen(p) and Major Histocompatibility Complex (TCR-pMHC)) and can be represented in a multidimensional space representing coordinates of the atoms of the TCR-pMHC. Figure 2 shows only two coordinates *x*, *y* as it is not possible to represent the full multi-dimensional reality, and a conformational energy E depends on *x* and *y*, thus defining a surface. As an analogy, the TCR-pMHC behaves like a ball on this (virtual) surface, so that it tends to stabilize in valleys or wells corresponding to distinct conformations (i.e. distinct spatial arrangements, without changes in chemical bounds). Well (a) is the initial conformation, wells (c) and (d) respectively trigger states CR and ANR of the lymphocyte (if inhibitory receptors are present, a sufficient number of TCR-pMHCs entering well (c) may be necessary to trigger state CR), and well (b) is an intermediate conformation. Figure 3 shows energy as a function of the coordinate *s* along the minimum energy path linking wells (a) (b) and (c). In quantum mechanics, the energy of the TCR-pMHC in each well can take discrete values represented as horizontal lines of figure 3, corresponding to vibrational energy levels. The TCR-pMHC having such quantized energy is said to be in a corresponding "quantum state".



Figure 2: Projection in the x,y plane of the energy surface of	Figure 3: energy profile along minimum energy path showing
the TCR-pMHC.	quantum wells (a), (b) and (c). This is a section of Figure 2 along
	line (a) (b) (c) and assumes that the T lymphocyte has survived
	positive and negative selection. Frequency difference $\Delta F1$ [resp.
	$\pmb{\Delta F2}$] is the frequency of the electromagnetic wave adapted to
	cause transition T1 [resp. T2] between the quantum states
	states $ a\rangle$ and $ b\rangle$ [resp. $ b\rangle$ and $ c\rangle$].

Figures 2 and 3: The Rabi frequency Ω_{ab} [resp. Ω_{bc}] is the frequency of quantum oscillations of the system between quantum states $|a\rangle$ and $|b\rangle$ in wells (a) and (b) [resp. $|b\rangle$ and $|c\rangle$ in wells (b) and (c)].

Transitions between wells are stimulated by the thermal background electromagnetic field ("thermal noise") in a manner comparable to the stimulation of similar transitions by artificial waves (see appendix). Considering only one quantum state in each well, the evolution of the state vector is described by (adapted from Scully and Zubairy 1997):

$$\begin{split} |\phi(t)\rangle &= \\ \left[\frac{\Omega_{bc}^{2}}{\Omega_{ab}^{2}+\Omega_{bc}^{2}} + \frac{\Omega_{ab}^{2}}{\Omega_{ab}^{2}+\Omega_{bc}^{2}}\cos\left(\frac{t}{2}\sqrt{\Omega_{ab}^{2}+\Omega_{bc}^{2}}\right)\right]|a\rangle + i\frac{\Omega_{ab}}{\sqrt{\Omega_{ab}^{2}+\Omega_{bc}^{2}}}\sin\left(\frac{t}{2}\sqrt{\Omega_{ab}^{2}+\Omega_{bc}^{2}}\right)|b\rangle - \frac{\Omega_{ab}\Omega_{bc}}{\Omega_{ab}^{2}+\Omega_{bc}^{2}}\left[1 - \cos\left(\frac{t}{2}\sqrt{\Omega_{ab}^{2}+\Omega_{bc}^{2}}\right)\right]|c\rangle (1) \end{split}$$

wherein Ω_{ab} [resp. Ω_{bc}] is the Rabi frequency of the direct transition between the quantum states $|a\rangle$ and $|b\rangle$ in wells (a) and (b) [resp. $|b\rangle$ and $|c\rangle$ in wells (b) and (c)]. Under this equation the overall transition probability from (a) to (c) is maximized when the Rabi frequencies Ω_{ab} and Ω_{bc} are equal (as an analogy, the oscillations of a string are better transmitted to another string having the same oscillation frequency). Likewise, the overall transition probability from (a) to (d) is maximized if Ω_{ab} equals the Rabi frequency Ω_{bd} of the (b) to (d) transition.

The height of the barrier between wells (a) and (b) and therefore the Rabi frequency Ω_{ab} of the (a) to (b) transition depends on the antigen and is intermediate between a lower Rabi frequency Ω_{bc} of the (b) to (c) transition and a higher Rabi frequency Ω_{bd} of the (b) to (d) transition ($\Omega_{bc} < \Omega_{ab} < \Omega_{bd}$). Positive [resp.negative] thymus selection eliminates lymphocytes that make transitions to well (d) [resp.(c)] in the presence of self antigens so that lymphocytes having survived thymus selection normally make a transition to well (d) or (c) only upon an encounter with a non-self antigen. Where the non-self antigen blocks the path from (a) to (b) by increasing the energy barrier as shown on Figure 3, it opposes (a) to (b) oscillations yielding a low Ω_{ab} (near to Ω_{bc}) and causing a transition to well (c) triggering state CR. When the non-self antigen yields a high Ω_{ab} (near to Ω_{bd}) then it causes a transition to well (d) triggering state ANR.

Figure 4 is a three-dimensional view representing the blocking of the (a) to (b) minimum energy path by an antigen (a reduced number of dimensions out of a multi-dimensional reality is represented). To efficiently block the (a) to (b) path, the antigen must have precisely the right shape, otherwise low energy pathes subsist between the energy barriers. Thus, path obstruction by the antigen is an extremely selective mechanism, as is expected for the recognition of a cognate antigen.



Figure 4: three-dimensional view representing the blocking of the (a) to (b) minimum energy path by an antigen (a reduced number of dimensions out of a multi-dimensional reality is represented).

3.2. INTERACTION OF ELECTROMAGNETIC WAVES WITH ANTIGEN RECOGNITION.

Stimulation of (a) to (b) [resp. (b) to (c)] transitions by an artificial electromagnetic wave in addition to the thermal electromagnetic field increases the Rabi frequency Ω_{ab} [resp. Ω_{bc}] which is proportional to field strength.

Quantum states in wells (a) and (b) have comparable energies, and transitions between these states can be stimulated by electromagnetic waves having frequencies of less than 3 GHz (figure 3) resulting in an increased value of Ω_{ab} ,

bringing Ω_{ab} farther from Ω_{bc} and thus inhibiting (a) to (c) [i.e. state CR] transfers (mechanism INH), and

bringing Ω_{ab} nearer to Ω_{bd} and favoring (a) to (d) [i.e. state ANR] transfers (mechanism INA).

Whilst using only one quantum state in each quantum well simplifies the equations, in the real world there are a multiplicity of quantum states in each quantum well, which has an impact on mechanisms INA and INH. Generally, a large exposure bandwidth favors both mechanisms because it results in more (a) to (b) transitions being simultaneously stimulated. In order to substantially inhibit all transitions from well (a) to well (c) under mechanism INH, the bandwidth of the electromagnetic wave must be larger than a typical separation Δ_b between quantum states in well (b) (see Figure 5). But under mechanism

INA, if a direct path to well (b) from an initial state A0 in well (a) is not stimulated, then this state may still make indirect transitions to well (b) through intermediate states in well (a) or elsewhere and through at least one stimulated (a) to (b) transition, and these indirect transitions will contribute to the overall transitions to wells (b) and (d). Therefore, a large bandwidth is not an absolute requirement for mechanism INA. An analogy is as follows: if various pathes connect place A to place B, it is necessary to block them all in order to stop people going from A to B. But if no path yields from A to B, it is sufficient to open one to allow people to go from A to B. In short, INH requires a bandwidth above a certain threshold Δ_b (this is the "bandwidth condition") but INA does not have such an absolute bandwidth condition so that where INH and INA compete, <u>a large bandwidth favors INH over INA</u>.



Figure 5: Transitions from state A0 to eigenstates in well (b) cannot be stimulated due to insufficient bandwidth. Therefore transitions from quantum state A0 to well (c) are not inhibited.

Both mechanisms INH and INA also depend on a frequency condition. Frequencies must be within a certain range corresponding to existing (a) to (b) transitions.

Under equation (1), substituting well (d) to well (c), the probability of transfer to well (d) is proportional to $\left|\frac{\Omega_{ab}\Omega_{bd}}{\Omega_{ab}^2 + \Omega_{bd}^2}\right|^2$. Under mechanism INA, with $\Omega_{ab} < \Omega_{bd}$, the probability of transfer to well (d) increases with exposure power. However, if the power of the electromagnetic wave is increased so that Ω_{ab} becomes larger than Ω_{bd} , then the probability of transfer to well (d) starts decreasing. Thus mechanism INA has an optimal power value above which its efficiency diminishes.

Also, if the electromagnetic wave is a pulse, taking into account the cosine terms in equation (1) it yields a maximum transfer to well (d) when $\frac{T}{2}\sqrt{\Omega_{ab}^2 + \Omega_{bd}^2} = \pi + 2k\pi$ wherein *T* is the pulse length and *k* is an integer, and minimal transfer to well (d) when $\frac{T}{2}\sqrt{\Omega_{ab}^2 + \Omega_{bd}^2} = 2k\pi$. Therefore, as the power of the electromagnetic wave (and therefore $\frac{T}{2}\sqrt{\Omega_{ab}^2 + \Omega_{bd}^2}$ increases), the probability of transfer to well (d) has successive minimums and maximums (power windows). This behaviour affects mechanism INA and may extend to signals which are not strictly pulses but present repetitive amplitude variations.

Above 9 GHz, experimental results show that the (b) to (c) transition is stimulated rather than the (a) to (b) transition (Lauer 2014a). Between 3 and 9 GHz no experimental results are available. The 3 GHz and 9 GHz limits shown on Figure 3 are reasonable values in view of experimental results.

4. INFLUENCE OF THYMUS SELECTION.

In cancer, a "normal" cell becomes abnormal and presents antigens which are "near-self", or may even present self antigens in abnormal numbers. T lymphocytes that control cancer recognize these near-self or self antigens as their cognate antigen, so as to enter state CR yielding to destruction of the cancerous cell, but they recognize them only weakly, else they would be eliminated by negative selection when interacting with a similar antigen in the thymus. Thus these lymphocytes when interacting with their cognate antigen are near the Recognition Threshold on Figure 1. Likewise, in an auto-immune disease a self antigen is "accidentally" recognized as its cognate antigen by a T lymphocyte. It recognizes this cognate antigen only weakly, otherwise (as should ideally be the case) it would be eliminated by negative selection when interacting with a similar antigen in the thymus. Because T lymphocytes implied in cancer and auto-immune diseases are near the Recognition Threshold, they are affected soon when exposure conditions inhibit transitions to state (CR) under mechanism INH, even at very low power, yielding a direct pro-cancer (since cancerous cells are no more recognized) and anti-auto-immune effect (since "accidentally recognized" self antigens are no more recognized).

Thymus selection of T lymphocytes in exposed conditions is based on recognition of self antigens in the presence of the electromagnetic wave, so that T lymphocytes selected in exposed conditions behave normally in exposed conditions with respect to self and near-self antigens. Therefore the above-mentioned pro-cancer, anti-auto-immune effect is transient and ceases when enough T lymphocytes have been renewed and replaced by T lymphocytes selected by the thymus in the presence of the electromagnetic wave. Naive mature T lymphocytes implied in cancer and auto-immune diseases are likely short-lived due to their agressiveness towards the self, so only a pool of recent thymic emigrants needs to be replaced.

A single abnormally agressive naive T lymphocyte can suffice generate a T lymphocyte lineage controlling a cancer or causing an auto-immune disease, so alternances of exposure and non-exposure yield an anti-cancer, pro-auto-immune effect effect due to the abnormal agressiveness in non-exposed conditions of T lymphocytes selected under exposed conditions.

Infectious diseases (when the pathogen does not mimic the self) are affected by the inhibition of antigen recognition but are little affected by thymus selection because antigens presented by infected cells are not self antigens. This yields a permanent pro-pathogen effect. Yet a line of T lymphocytes recognizing a pathogen and affected by exposure may often (not necessarily always) be replaced by another one after a new primary reaction.

	А	В	C	D	E
exposure Immune	Permanent low exposure (thermal)	Permanent high exposure	Transition from Low to High exposure: period immediately after	Transition from High to Low exposure : period immediately	Alternance between low and high exposure (at least half time low
threat			transition	after transition	exposure)
cancer	standard	standard	Pro cancer	Anti cancer	Anti cancer
auto- immune disease	standard	standard	Anti-autoimmune	Pro-autoimmune	Pro-autoimmune
infectious disease	standard	pro pathogen	pro pathogen	pro pathogen	pro pathogen

These considerations are summarized in Table 1.

Table 1: Effect of low-power, high-bandwidth exposure on cancer, auto-immune and infectious diseases, under mechanism INH. These effects co-exist with effects under mechanism INA, but at low power and large bandwidth, concerning cancer and auto-immune diseases they are the dominant effects. N.B. This table is valid at constant bandwidth.

T lymphocytes involved in cancer or auto-immune diseases tend to be near to the Recognition Theshold but far from the Non-Recognition Threshold on figure 1, so that transitions of such lymphocytes to the ANR state under mechanism INA require a relatively high exposure power as compared to transitions to the CR state under mechanism INH. Thus <u>a high power favors INA over INH</u> for this class of lymphocytes.

Thymus selection also interacts with mechanism INA. Mechanism INA triggers elimination of lymphocytes by positive selection in the positive selection section of the thymus, which yields a pro-cancer effect at sufficiently high power when the number of lymphocytes surviving positive selection is significantly diminished. Mechanism INA also triggers temporary inactivation of lymphocytes in the negative selection section of the thymus, and such temporarily inactivated T lymphocytes largely escape negative selection because they cease to interact with presented antigens. Some lymphocytes that should normally have been eliminated by negative selection due to excessive aggressiveness towards self antigens escape, yielding an anti-cancer and proauto-immune effect after suppression of the artificial wave which triggered mechanism INA. This anti-cancer effect dominates at lower power values than the pro-cancer effect because it does not require a highly significant part of the lymphocytes to be affected, yet requires higher power values than effects under Table 1 because lymphocytes implied in cancer and autoimmune diseases are farther from the Non-Recognition Threshold than they are from the Recognition Threshold.

5. ORDERS OF MAGNITUDE OF POWER THRESHOLDS.

An electromagnetic wave having a power spectrum at least as high as the thermal background in the 0-3 GHz range, corresponding to an overall power of about 8 nW/m2 (Lauer 2014a), can potentially affect any lymphocyte responding to this frequency range, which seems typical. Taking an extremely conservative range of 0-9 GHz increases this value, but on the other hand any lymphocyte responding only in a reduced frequency range can potentially be affected at a much lower power. The above thresholds may be viewed as theoretical minimum thresholds.

However, the threshold above which this lymphocyte ceases to recognize its target antigen can be much higher than the theoretical minimum, depending on how strongly the antigen is recognized absent the artificial electromagnetic wave.

Upon an encounter with its cognate antigen in a cancerous cell, a lymphocyte recognizing cancerous cells is in the CR state. On Figure 1, different lymphocytes recognizing cancer are spread in an area going somewhat above the Recognition Threshold, which also implies that the practical power threshold for affecting recognition of cancerous cells (i.e. for bringing the lymphocyte below the Recognition Threshold) will be "on average" significantly higher than the theoretical minimum, and that a statistical effect on cancer will be obtained only above a threshold which is significantly higher than the theoretical minimum.

T lymphocytes selected in the presence of an artificial wave are normally in the Neutral State below the Recognition Threshold on Figure 1 upon an encounter with any self antigen in the presence of the artificial wave. Upon suppression of the artificial wave, a lymphocyte which upon an encounter with a particular self antigen was near the Recognition Threshold may cross this threshold and enter the CR state upon an encounter with the same self antigen. This can happen for a specific lymphocyte and self antigen even if the power of the artificial electromagnetic wave is near the theoretical minimum threshold. Only one lymphocyte crossing this border can cause an auto-immune disease (under Table 1 column D or E) if it is not later eliminated by regulatory systems such as regulatory T cells. Therefore, a statistical effect of exposure on an auto-immune disease can potentially appear very near to the theoretical minimum threshold, but this fact is mitigated by the existence of regulatory systems.

Pathogens carry foreign antigens which are not normally near the Recognition Threshold or the Non-Recognition Threshold, so that the necessary power for an electromagnetic wave to bring a lymphocyte normally recognizing a pathogen from the CR state to the Neutral State is generally expected to be much higher than the theoretical minimum threshold. However for a particular pathogen, being near the Recognition Threshold or near the Non-Recognition Threshold may be a survival strategy,

so that one cannot exclude the possibility of particular infectious diseases being affected by exposure to electromagnetic waves at power levels near to the theoretical minimum.

For effects under Table 1 on cancer and auto-immune diseases, it is not the power of the artificial electromagnetic wave which is essential per se, but rather the contrast between low exposure and high exposure, both of which may comprise artificial electromagnetic waves. For example in the case of a low to high exposure transition, the magnitude of the effects is determined not only by the high exposure power but also by the initial low exposure. The theoretical minimum thresholds discussed above thus apply when the low exposure state is the thermal background, but (as applied to cancer and auto-immunity) they differ when the low exposure already comprises artificial waves, which is generally the case.

6. CONCLUSION:

In the biologist's language, the recognition of its cognate antigen by a lymphocyte was generally described using a basic picture of "key and lock" but no explanation was provided for any physical effect under which the key and lock mechanism could trigger an active response by the lymphocyte. The key and lock mechanism corresponds – to a certain extent - to the blocking of the minimum energy path by the cognate antigen in the present model. However, the underlying physical model described herein also brings a reasonable explanation of how the key and lock mechanism triggers an active response. There are no known alternative proposals, and the simplicity of the present model is compatible with the limited level of complexity of implied biological molecules and with a reasonable physical approach. The key and lock mechanism, being on a microscopic scale, was unlikely to trigger an active response in a manner comparable to any known macroscopic mechanism.

The physical part of the model thus brings a reasonable answer to the essential question of how lymphocytes recognize their cognate antigens, based on the experimentally validated existence of transitions between distinct conformations stimulated by electromagnetic waves (see appendix). The existence of mechanism INA and temporary inactivation of lymphocytes was directly verified in vitro in (Lyle et al 1983), leaving only mechanism INH as somewhat hypothetical. The remainder of the biological part of the model is essentially a logical development based on pre-existing knowledge, on the physical part of the model and on the existence of temporary inactivation of lymphocytes. Therefore, the proposed model has a high level of intrinsic consistency. It implies the existence of predictable interactions of the model. Indeed, the existence of these interactions has been verified based on a number of experimental and statistical findings (Lauer 2014a,b), and these interactions lend themselves well to further experimental validations.

The physical model is qualitative rather than quantitative. Turning it into a quantitative model will require experimental work to better know the implied molecules and conceptual work to take into account stimulated transitions in simulation programs. Semi-quantitative approaches like the one proposed in (Lauer 2013) may provide an intermediate level of understanding of the underlying physics. The biological part of the model also needs further work, inter alia including a better understanding of lymphocyte selection after thymus involution and of the interaction between different TCRs on the same lymphocyte.

APPENDIX: STIMULATED TRANSITIONS BETWEEN DIFFERENT CONFORMATIONS.

Let us consider an artificial electromagnetic wave at the transition frequency between quantum states $|a\rangle$ and $|b\rangle$ in wells (a) and (b) corresponding to distinct conformations (figure 6). The artificial wave stimulates the $|a\rangle$ to $|b\rangle$ transition and the system oscillates between the two wells at a Rabi frequency Ω_{ab} which is proportional to the square root of the power of the wave (based on Scully and Zubairy 1997). If the wave is pulsed with a pulse length T, assuming the system is initially in well (a) there is a transition to well (b) yielding a biological effect if at the end of the pulse the system is left in well (b), corresponding to $T\Omega_{ab} = \pi + 2\pi k$ (k an integer), and there is no transition if at the end of the pulse the system is left in well (a), corresponding to $T\Omega_{ab} = 2\pi k$. Thus the biological effect exists only for certain values of power corresponding to $\Omega_{ab} = \frac{1}{T}(\pi + 2\pi k)$ in which the system is left in well (b) at the end of the pulse (i.e. there are "power windows"). The power dependency is simple in this case but can be more complex if there are several quantum states in each well or if the waveform has more complex amplitude variations (Figure 7).







Figure 7: typical power windows in a biological experimentation

One argument against these power windows is that due to thermal relaxation the system would quickly loose coherency. To understand why this is not the case, we can assume that from quantum state $|b\rangle$ in well (b) the system can make transitions to a further quantum state $|c\rangle$ in the same well, stimulated by the thermal background electromagnetic field, corresponding to thermal relaxation. Equation (1) applies and the probability of a transfer from (a) to (c) is proportional to $P = \left| \frac{\Omega_{ab} \Omega_{bc}}{\Omega_{ab}^2 + \Omega_{bc}^2} \right|^2$. When Ω_{ab} , which is proportional to the artificial electromagnetic field, becomes much higher than Ω_{bc} which is independent of it, then this probability P is asymptotically zero. Thus during a pulse stimulating the $|a\rangle$ to $|b\rangle$ transition, transitions to $|c\rangle$ are inhibited, i.e. if the pulse is strong enough there is no thermal relaxation. These considerations qualitatively explain why thermal relaxation does not occur, and thus not cause a loss of coherency, during the pulse.

However thermal relaxation can occur after the pulse and can empty state $|b\rangle$ (through transfer to state $|c\rangle$ and other states in the same well) and re-fill state $|a\rangle$ (through transfer from other states in the same well) so that the next pulse can against transfer probability of presence from $|a\rangle$ to $|b\rangle$, until wells (a) and (b) are at thermal equilibrium with one another and quantum states $|a\rangle$ and $|b\rangle$ are equally populated.

These power windows have been found in many biological effects of electromagnetic waves, including calcium efflux (Blackman 1989) or effects of GSM on the reproduction of flies (Panagopoulos 2010). They are not easily explainable in a "classical mechanics" picture, so that they are strong confirmation of the existence of stimulated transitions in biological systems.

When the artificial wave is continuous rather than pulsed, such power windows do not occur but system oscillations between (a) and (b) stimulated by an artificial wave can to bring these wells to thermal equilibrium faster (due to a higher Rabi frequency Ω_{ab}) than the slower thermally stimulated transitions between the same wells. This is probably what occurred in (Bohr and Bohr 2000) where exposure to microwaves caused a near instantaneous, non-thermal transition between two conformations of a protein, which otherwise required a long period of time.

The existence of transitions stimulated by artificial waves and affecting biological systems is thus a reasonable physical possibility, experimentally confirmed by observed power windows and by observed stimulated transitions between distinct conformations of a protein.

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