How quantum is bird migration: A review

B Adams[1], **I Sinayskiy**[1] **and F Petruccione**[1]
[1]Quantum Research Group, School of Chemistry and Physics, University of KwaZulu-Natal Durban, KwaZulu-Natal, 4001, South Africa and National Institute for Theoretical Physics (NITheP), KwaZulu-Natal, 4001, South Africa

E-mail: `betony@gmail.com`

Abstract. In the decades since it was first suggested as a mechanism for avian magnetoreception, the radical pair model has generated both theoretical and experimental interest. This proceedings aims to give some idea of what progress has been made and to what extent the phenomenon of bird migration can be considered an integral part of the research field of quantum biology. Evidence that birds use quantum mechanics to navigate is still not absolutely established. The radical pair mechanism is, however, strongly supported by behavioural elements of the avian compass such as the fact that it is a light dependent, inclination compass and is disrupted by radiofrequency magnetic fields. Work has also been done to show that it is structurally possible for a molecule in the eye of a bird to be influenced in a measurable way by the weak geomagnetic field. Cryptochrome, the biological molecule proposed as the site of magnetoreception, has also been investigated and found to be compatible with much of the theory. That cryptochromes might mediate magnetic responses in animals has also been documented for the case of fruit-flies. Recently, interest in the effects of radiofrequency fields has been reignited by the experimental confirmation that birds are disoriented by low intensity anthropogenic electromagnetic radiation across a broad range of radio frequencies. Current theoretical research suggests that a possible explanation for this disorientation could be a quantum needle effect which slots the avian compass more firmly into the category of quantum biology.

1. Introduction

1.1. Bird migration

Throughout recorded history there have been attempts to explain the seasonal appearance and disappearance of certain species of birds. More than 4000 years ago Egyptians exploited the extraordinary navigational skills of birds, domesticating certain species to serve as messengers. [1]. But for a long time migration was open to misinterpretation. It was only in the nineteenth century that a more rigorously scientific approach to avian migration grew out of methods such as bird-banding. Nowadays it is generally agreed that birds use a two-step process that entails first mapping their geographical position to ascertain a theoretical direction then applying a compass to locate this direction [1, 2]. Early experiments with displaced homing pigeons suggested the use of a sun compass, however this is most effective over shorter distances rather than seasonal migration [1, 3]. Experiments show that nocturnal migrants use cues related to sunset as well as a star compass, while both mature birds as well as fledglings use a magnetic compass. Although the navigational skills of mature birds differ somewhat from fledglings, with the former able to compensate for a marked displacement during autumn migration while the latter only learn to correct this displacement on their return spring migration [1, 4, 5, 6] this built-in ability to perceive the earth's magnetic field forms the base of birds' navigational system, providing a first means for navigation and homing [1, 7].

1.2. The magnetic compass

The discovery of earth's magnetic field and its use in navigation by humans, led to the belief that this field might also play a role in avian navigation. This hypothesis was given experimental heft by tests done on European robins, *Erithacus rubecula*, from the 1960s [8, 9]. There are two main theories for how birds use the geomagnetic field to orientate themselves; although the possibility of a third magnetoreceptor in the inner ear lagena of various animals is a recent development [10, 11]. The magnetite model of avian magnetoreception, first proposed by Kirschvink and Gould in 1981 [12] built on the fact that certain bacteria use magnetite to orientate themselves. Magnetite particles, a specific form of iron oxide, located in the birds' beaks align themselves in the magnetic field [13]. An alternate theory of avian magnetoreception is the radical pair model, which suggests that a light-activated molecule in the eye gives rise to a radical pair, the dynamics of which allow the bird to 'see' the magnetic field. While there is limited evidence that the magnetite model provides compass information in fields as weak as the geomagnetic field it has been suggested that birds might use a combination of both magnetite and radical pair models [14], the former to detect differences in magnetic intensity and the latter for directional information [13]. This combination could also offer a way of explaining the phenomenon of fixed responses. Fixed responses are migratory trajectories that do not follow the accepted north-south migratory direction and appear to combine elements of both models, being dependent on specific light regimes as well as being disrupted by anaesthetic applied to the beak [15]. While these responses raise interesting questions, and while it is clear that different animals seem to employ different orientation mechanisms [16, 17], it is solely with the radical pair mechanism that this review will be preoccupied [7]. It is this radical pair theory that puts avian magnetoreception into the category of quantum biology.

1.3. Quantum biology

Until fairly recently it was generally accepted that quantum effects would be unlikely to be found in the warm, wet and messy environments that characterise biological systems. However, the emerging field of quantum biology incorporates a number of mechanisms that might be understood to be quantum phenomena in processes as diverse as photosynthesis, migration, olfaction, anaesthesia and even cognition. One of these is the radical pair mechanism. The radical pair mechanism is implicated in many biological processes. In photosynthetic reaction centres it plays a role in polarisation and protection mechanisms [18, 19]. Radical pairs observed in flavoproteins such as cryptochrome might offer an explanation for the mechanism controlling the circadian clock in some organisms [20] - [22]. In addition to this, the role of radical pair mediated magnetic field effects in enzyme reactions is still being investigated [23] - [25]. This review will focus on the role that the radical pair mechanism is hypothesised to play in avian magnetoreception, it will examine the evidence for this hypothesis and how firmly it can be said that the extraordinary navigational prowess of birds can truly be called a quantum phenomenon.

2. The radical pair mechanism (RPM)

Investigation into the magnetic field modulation of chemical reactions and the formalisation of the radical pair mechanism began as long ago as the 1960s [26, 27, 28]. Application of radical pair theory to avian magnetoreception began not long after this, first proposed by Schulten *et al* in the 1970s [26]. A simple radical-pair mechanism that may be utilised as a compass is depicted in Figure 1 and can be described briefly in the following three steps. First a photon incident on the molecule in question transfers sufficient energy to excite an electron. This extra energy means that it is favourable for the electron to be transferred from donor molecule to acceptor

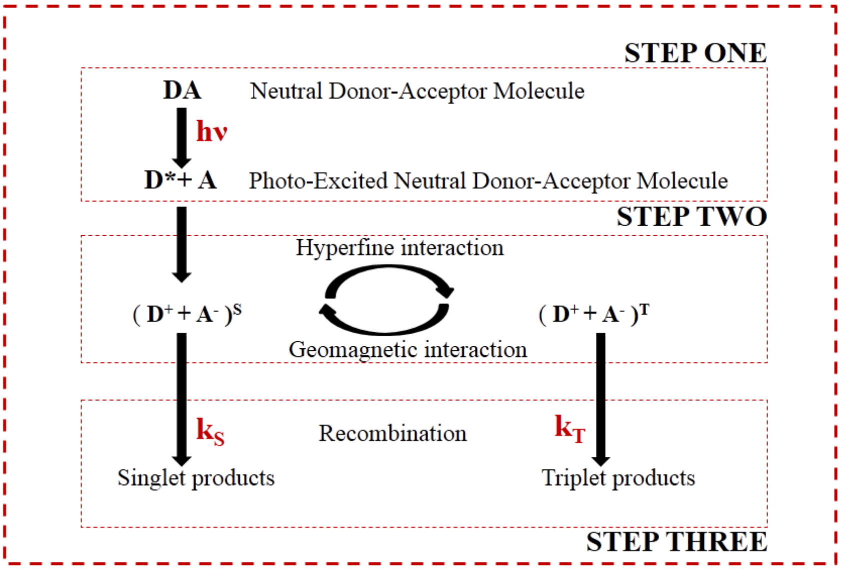

Figure 1. Radical pair schematic. A photon of energy *hv* excites an electron in the magnetoreceptor molecule causing the electron to move from donor **D** to the acceptor **A** part of the molecule. The result is a spatially separated, spin correlated electron pair: the radical pair. Hyperfine interactions between each electron and its surrounding nuclear environment cause singlet–triplet oscillations, aided by the Zeeman effect of the earth's magnetic field. On recombination singlet and triplet states give rise to different chemical products with rates $\mathrm{k_S}$ and $\mathrm{k_T}$ respectively [7].

molecule, forming a radical, or unpaired electron. The simultaneous production of two such radicals results in the spin correlated pair. Step two involves interaction with the surrounding nuclear environment and the external magnetic field, which drives interconversion of spin states between singlet and triplet states. The third and final step involves recombination by reverse electron transfer and the transformation of spin states to the specific, possibly chemical, signals which allow the bird to perceive the magnetic field [7].

2.1. Behavioural evidence

The radical pair theory of avian magnetoreception is strongly supported by the behavioural evidence of migrating birds. The avian compass is light dependent, as would be expected from the photo-activation necessary for the first stage of the mechanism. It has been demonstrated that not only are birds disoriented in darkness but their compass is also, more specifically, wavelength dependent [13]. The compass is also an inclination compass, it is not disrupted by switching poles [29]. Further evidence for the viability of the radical pair compass came in 2004 when Ritz *et al.* showed that the avian compass was disrupted by radiofrequency radiation, specifically radiation at the Larmor frequency, which led to speculation that one of the radicals in the pair had no hyperfine interaction [30]. More evidence for the radiofrequency disruption of the avian compass came in 2014. However, rather than identifying a specific frequency at which this disruption occurred the research suggested that birds were disoriented under the influence of low intensity electromagnetic radiation across a very broad range of frequencies [31]. According to a very recent study, however, the strongest evidence that the radical pair theory of avian migration is a truly quantum phenomenon is the incredible accuracy that birds achieve in their navigation. It has been shown that birds can attain a directional precision to within 5° and Hore *et al.* attribute this to the avoided crossings of the radical pair's spin energy levels. They go on to conclude that this effect, which has no classical correlation, places the avian compass firmly in the category of quantum biology [32].

2.2. Structural evidence

Progress has also been made into clarifying the structure of the avian compass and whether this might support the radical pair theory. The molecule that has been proposed as the most likely to be the site of the compass is the flavoprotein cryptochrome [33]. Four different types of cryptochrome have been confirmed in the eyes of migratory birds [34]. Plant cryptochromes have also been shown to have enhanced responses to weak magnetic fields, while the magnetic responses of fruit flies are also mediated by cryptochrome [35]. More specifically, flavin-tryptophan radical pairs in an initial singlet state have been identified in cryptochrome [36] and cryptochrome in the eye of the migratory garden warbler has been observed to form radical pairs with the long (millisecond) lifetime necessary for the dynamics of the radical pair [37].

3. Conclusion

The radical pair theory of avian magnetoreception is not a new theory, having been acknowledged as a viable one for more than a few decades. Despite this it has not yet established itself as firmly a quantum phenomenon as, for example, certain elements of photosynthetic reactions. However the recent hypothesis that the accuracy shown by birds during their migrations might be explained by avoided crossings theory could afford the mechanism a more rigorously quantum status. A good understanding of the radical pair mechanism and its possible application in the case of avian magnetoreception is important, particularly since it has been shown that birds are disoriented by weak electromagnetic radiation that is 'well below the guidelines for human exposure proposed by the International Commission on Non-Ionizing Radiation Protection (ICNIRP) and adopted by the World Health Organization' [31]. The magnetic sensitivities of chemical reactions as described by radical pair theory is a phenomenon that is not specific to birds, but implicated in a number of different processes in living systems. Indeed it has been shown that cryptochromes found in humans display light-dependent magnetosensitivity [38] and it would serve us well to know how the human body interacts with the technology that plays such an integral part in our lives.

References

[1] Wiltschko W and Wiltschko R 2003 *Animal Behaviour* **65** 257–272
[2] Collett TS and Graham P, 2004 *Current Biology* **14** R475–R477
[3] Gould JL *Current Biology*, **14:6** R221–R224
[4] Perdeck AC 1958 *Ardea* **46** 1–37
[5] Perdeck AC 1967 *Ardea* **55** 194–202
[6] Mouritsen H and Larsen ON 1998 *Journal of Experimental Biology* **201** 2927–2934
[7] B. Adams 'An open quantum systems approach to avian magnetoreception' Masters thesis 2015
[8] Wiltschko W and Merkel F 1966 *Verh. dt. zool. Ges.* **59** 362–367
[9] Wiltschko W 1968 *Zeitschrift fur Tierpsychologie* **25** 536–558
[10] Harada Y, Taniguchi M, Namatame H and Iida A 2001 *Acta Otolaryngol* **121** 590–595
[11] Wu L and Dickman JD 2011 *Current Biology* **21** 418–423
[12] Kirschvink JL and Gould JL 1981 *Biosystems* **13**, 181–201
[13] Wiltschko W and Wiltschko R 2005 *J Comp Physiol A* **191** 675–693
[14] Yan L and Tao S 2012 *Chin. Phys. B* **22: 4** 048701
[15] Wiltschko R and Wiltschko W 2009 *Communicative & Integrative Biology* **2:2** 100–103

[16] Wiltschko R, Stapput K, Ritz T, Thalau P and Wiltschko W 2007 *HFSP Journal* **1:1** 41–48

[17] Thalau P, Ritz T, Burda H, Wegner RE and Wiltschko R 2006 *J. R. Soc. Interface* **3** 583–587

[18] Kominis IK 2013 *New Journal of Physics* **15** 075017

[19] Marais A, Sinayskiy I, Petruccione F and van Grondelle R 2015 *Scientific Reports* **5**

[20] Biskup T, Schleicher E, Okafuji A, Link G, Hitomi K, Getzoff E D and Weber S 2009 *Angewandte Chemie International Edition* **48** 404–407

[21] Yoshii T, Ahmad M and Helfrich-Frster C 2009 *PLoS Biology* **7** 813–9

[22] Fedele G, Edwards MD, Bhutani S, Hares JM, Murbach M, Green EW, Dissel S, Hastings MH, Rosato E and Kyriacou CP 2014 *PLoS Genetics* **10** e1004804

[23] Buchachenko AL and Kuznetsov DA 2008 *J. Am. Chem. Soc.* **130** 12868–12869

[24] Messiha HL, Wongnate T, Chaiyen P, Jones AR and Scrutton NS 2015 *J. R. Soc. Interface* **12** 20141155

[25] Crotty D, Silkstone G, Poddar S, Ranson R, Prina-Mello A, Wilson MT and Coey JMD 2012 *Proceedings of the National Academy of Sciences* **109** 1437–1442

[26] Schulten K, Staerk H, Weller A, Werner HJ and Nickel B 1976 *Z. Phys. Chem.* **101** 371

[27] Haberkorn R and Michel-Beyerle M 1979 *Biophys. J.* **26** 489–498

[28] Steiner UE and Ulrich T 1989 *Chem. Rev.* **89** 51–147

[29] Stapput K, Thalau P, Wiltschko R and Wiltschko W 2008 *Current Biology* **18** 602-606

[30] Thalau P, Ritz T, Stapput K, Wiltschko R and Wiltschko W 2004 *Naturwissenschaften* **92** 86-90

[31] S. Engels *et al.* 2014 *Nature* **509** 353-356

[32] Hiscock HG, Worster S, Kattnig DR, Steers C, Jin Y, Manolopoulos DE, Mouritsen H and Hore PJ 2016 *PNAS* **113:17** 4634–4639

[33] Ritz T, Adem S and Schulten K 2000 *Biophysical Journal* **78** 707–718

[34] Mouritsen H and Hore PJ 2012 *Current Opinion in Neurobiology* 22 343-352

[35] Yoshii T, Ahmad M and Helfrich-Forster C 2009 *PLoS Biology* **7** 813-9

[36] Maeda K *et al.* 2012 *PNAS* **109:13** 47744779

[37] Liedvogel M *et al.* 2007 *PLoS ONE* **2:10** e1106

[38] Foley LE, Gegear RJ and Reppert SM 2011 *Nature Communications* **2** 356