Institution: King's College London (KCL)

Unit of Assessment: 9 (Physics)

Title of case study: Harnessing Nuclear Quadrupole Resonance (NQR) for explosives detection and medicines authentication

1. Summary of the impact (indicative maximum 100 words)

Nuclear Quadrupole Resonance (NQR) methods developed by researchers at King's College London have been applied to the creation of systems to:

1) Authenticate pharmaceuticals with the potential to thwart a global black market of counterfeit medicine and thereby saving lives. As a result of its interaction with KCL researchers, Italian instrument manufacturer Stelar s.r.l. has etablished a capability in NQR spectroscopy, and developed a new NQR-based prototype product for portable medicine authentication.

2) Detect explosives and narcotics, for the improvement of security and public safety levels. KCL researchers have had a major impact and enabling influence for companies in the USA and UK working in this field, and have transferred know-how to the China Institute of Atomic Energy, for the development of NQR explosives detection systems.

2. Underpinning research (indicative maximum 500 words)

Nuclear Quadrupole Resonance (NQR) is a branch of Magnetic Resonance spectroscopy in which the signal arises from the interaction of the electric quadrupole moment of the quadrupolar nuclei in the sample with the electric field gradient surrounding the nuclei. Radio-frequency radiation excites transitions between the energy levels induced by this interaction at frequencies that are characteristic of a given material and can be used, therefore, not only to identify it but also to estimate quantity. Unlike the closely related technique of nuclear magnetic resonance (NMR), no static magnetic field is necessary, so remote materials and large volumes can be examined. Whereas the nuclear quadrupole moment is an intrinsic property of the element, the electrostatic field distribution is governed by the nature of the chemical bonds of the quadrupolar nucleus within the molecule's structure. As a consequence, the NQR spectrum is specific to each molecule and thus provides a unique fingerprint. NQR can be used to analyse a broad range of solid materials and, in particular, it is ideally suited for the analysis of ^{14}N, a spin-1 nucleus, which is the most commonly distributed quadrupolar nucleus found in explosives and in pharmaceuticals. Other quadrupolar nuclei that are commonly found in medicines include ^{23}Na, ^{35}Cl, and ^{79}Br.

Professor John Smith led an active programme in NQR spectroscopy and instrumentation development at King's College London from 1985 until his death in 2013. His research was concerned with the development and application of NQR methods, in particular ^{14}N-NQR, to detect signals from many solid explosives and drugs allowing unequivocal identification and quantitative assessment. Research at KCL since 1993 led to advances in pulsed NQR methods leading to shortened detection times and enhanced sensitivity of detection of ^{14}N frequencies, and included NQR detection of explosives in vehicles, a study of the structure and NQR spectrum of heroin hydrochloride, and the characterisation of pharmaceutical materials.

Since 2003 the research focus has been concerned with integrating NQR with advanced detection and classification techniques, in a programme in collaboration with Professors Althoefer and Seneviratne in the Division of Engineering (from 2010 the Department of Informatics). Since 2008 this work was extended to new methods integrating Polarisation-Enhanced (PE) NQR and NMR with advanced detection and classification techniques. Through the development and introduction of stochastic excitation methods and appropriate model-based data processing and classification techniques, the KCL NQR group has successfully created NQR-based detectors capable of detecting different explosives and drugs with significantly reduced detection times compared to previous methods. Exploiting the low magnetic fields used for PE-NQR, the group was able to successfully integrate NQR with NMR to extend the detection from solids to liquid explosives.

The KCL NQR research programme has been supported by a range of sources including industry. EPSRC grant GR/K98285/01 "Nuclear Quadrupole Resonance in Analytical Science", held by Professor Smith, provided funding between 1997 and 1999. Since 2003 funding awards to the NQR Group include those from EU, Wellcome Trust, the Home Office Scientific Development Branch, MOD and DSTL, and the International Atomic Energy Agency.

3. References to the research (indicative maximum of six references)

[1] M. H. Palmer, M. M. P. Kurshid, T. J. Rayner & J. A.S. Smith. *Experimental and theoretical studies of the ^{14}N quadrupole tensors in 1H-1,2,3-benzotriazole*. Chemical Physics **182**, 27–37 (1994). DOI: 10.1016/0301-0104(93)E0450-A

[2]* E. Balchin, D. J. Malcolme-Lawes, M. D. Rowe, J. A. S. Smith, M.J. Bearpark, J. W. Steed, W.Wu, A. J. Horsewill and D. Stephenson. *The unusual solid state structure of heroin hydrochloride monohydrate and its selective detection using NQR spectroscopy*. New J. Chemistry **28**, 1309-1314 (2004). DOI: 10.1039/b401797h

[3]* E. Balchin, D. J. Malcolme-Lawes, I. J. F. Poplett, M. D. Rowe, J. A. S. Smith, G. E. S. Pearce, and S. A. C. Wren, *Potential of Nuclear Quadrupole Resonance in Pharmaceutical Analysis.* Anal. Chem. **77**, 3925-3930 (2005). DOI: 10.1021/ac0503658

[4] S. D. Somasundaram, A. Jakobsson, M. D. Rowe, J. A. S. Smith, N. R. Butt, and K. Althoefer, *Robust Detection of Stochastic Nuclear Quadrupole Resonance Signals*, IEEE Transaction on Signal Processing **56**, 4221–4229 (2008). DOI: 10.1109/TSP.2008.923809

[5] E. Tate, K. Althoefer, J. Barras, M. D. Rowe, J. A. S. Smith, G. E. S.Pearce and S. A. C. Wren, *Quantitative ^{35}Cl Nuclear Quadrupole Resonance in Tablets of the Anti-Diabetic Drug Diabinese*. Anal. Chem. **81**, 5574 – 5576 (2009). DOI: 10.1021/ac900656e

[6]* J.A.S Smith, T.J. Rayner, M.D. Rowe, J. Barras, N.F. Peirson, A.D. Stevens and K. Althoefer, *Magnetic field-cycling NMR and ^{14}N, ^{17}O quadrupole resonance in the explosive pentaerythritol tetranitrate (PETN)*. Journal of Magnetic Resonance **204**, 139-144 (2010). DOI: 10.1016/j.jmr.2010.02.019

*** Publications that best indicate the quality of the underpinning research**

4. Details of the impact (indicative maximum 750 words)

The application of NQR for the improved detection and classification of explosives, drugs and pharmaceuticals, has a worldwide impact with applications in security, military and humanitarian sectors:

- detection of landmines in post war countries
- detection of improvised explosive devices (IEDs) in regions of conflict
- scanning of luggage and detection of explosives at borders, airports and other check points
- forensic analysis of explosives to determine the origin of explosives used for mines and IEDs
- authentication of medicine
- detection and identification of illicit drugs, such as narcotics.

Much of the NQR technology development within KCL was performed within programmes for military/security and drug authentication applications where the requirement was for explosives, narcotics or pharmaceutical detectors to be small enough and rugged enough for deployment on the battlefield, at border check points or pharmacies, simple enough in operation for use by untrained users, easily maintainable in a range of environments, resistant to radio frequency interference and robust enough to deal with a range of threats under a range of ambient conditions.

Research and consultancy projects funded by Her Majesty's Revenue and Customs (HMRC), the Defence, Science and Technology Laboratory (DSTL), the Ministry of Defence (MoD), the Home Office Scientific Development Branch (HOSDB), the International Atomic Energy Agency (IAEA) and, the China Institute of Atomic Energy (CIAE) demonstrate the direct applicability of KCL's intelligent sensing and detection methods in a homeland security, military and humanitarian context; the outcomes impact on the important topics of security and the public's health in the UK and internationally. The work has been published widely; patents protecting intelligent explosive detection techniques and fake drug detection methods were filed and granted.[1]

In the field of medicine authentification, the KCL NQR Group has worked closely with the Italian NMR instrument manufacturer Stelar S.r.l. to develop a prototype for a commercial product, opening up a potential new market for the company. The relationship between KCL and Stelar began within the framework of a Wellcome Trust Translational Award[2] (2010–13) to KCL to create a system capable of distinguishing between genuine and counterfeit pharmaceuticals. Through a tendering process within this programme, Stelar was identified as the industrial partner to take the technology forward, with the EU Framework 7 Project 'Counterfeit Pharmaceuticals Interception using Radiofrequency Methods in Realtime' (CONPHIRMER, 2011–present) providing further support for this project. Stelar have produced a prototype medicine authentication device based on KCL underpinning research.[3]

In low-to-middle income countries, 10-30 per cent of medicines are fake, placing patients at extreme risk. The system developed by Stelar uses the NQR signal from medicines (or their imposters), even through packaging. It provides a portable, cheap solution to medicine authentication with virtually no radiation hazard in personnel inspection, improved sensitivity, shortened inspection times and reduced false alarm rates.

In addition to a new medicine authentication product, as a result of the interaction with the KCL NQR Group, Stelar has developed a capability in NQR, with its existing marketed product lines allowing NQR spectroscopy.[4] While the company had theoretical knowledge of NQR before collaborating with King's, it had no practically applicable NQR knowledge/expertise. The KCL NQR group provided expertise and know-how to Stelar on how to use the Stelar systems for practical NQR applications including: pulse sequence methods to optimise the signal to noise ratio; approaches to radiofrequency interference reduction/cancellation; simplifying, automating, deskilling the NQR process for specific application; algorithms for signal processing, classification and decision making, to distinguish between different materials.[3]

The NQR technology developed by the KCL NQR Group also has application in the field of explosives detection. Technology development for such applications has been pursued in a project "Laboratory RF spectrometer construction and NQR sensor integration" funded by the CIAE (coordinated by IAEA, TC Project CPR/1/006), for the creation of a functional explosives detection system capable of scanning hand luggage. This included training of CIAE staff by the KCL NQR Group. The KCL expertise and acquired know-how from the underpinning research was incorporated by the CIAE into a prototype airport security system.[5]

More broadly in the field of security, as noted by the President and Founder of Bagtronics Ltd. (previously R&D Director EU Rapiscan Systems, USA, formerly also of Quantum Magnetics Inc., USA, InVision Technologies Inc., USA, and QR Sciences Ltd.): "The work of the KCL NQR Group on the detection of NQR signals from explosives and narcotics ... has had a major impact and influence on my own activities, for example on instrumental methods and the choice of the optimum conditions for detection such signals".[6]

Bagtronics is a UK based SME with extensive experience in developing security equipment and in particular equipment based on NQR. Similarly, the Chief Technology Officer of Quasar Federal Systems Inc., USA, notes, "the importance of [Smith's] pioneering work in nuclear magnetic resonance (NMR) and nuclear quadrupole resonance (NQR)" and comments that, "at my previous company, Quantum Magnetics,... [Smith] kept us on the right path by demonstrating that a particular application was feasible, no matter how improbable it seemed at first."[7] One example of this was the KCL NQR Group's work on the detection of explosives in vehicles, i.e., large vehicle bombs of the kind used in terrorist attacks. "For those of us working in the field, [Barras et al. 'Detection of ammonium nitrate inside vehicles by nuclear quadrupole resonance' *Applied Magnetic Resonance* **25**,411-437 (2004), DOI:10.1007/BF03166538] included an invaluable discussion of the NQR parameters of ammonium nitrate detection.... Just the knowledge that such a vehicle scanning system is possible was enabling and very important".[7]

5. Sources to corroborate the impact (indicative maximum of 10 references)

1. Information on the NQR patent portfolio currently held by KCL.
2. Wellcome Trust website: Announcement of Award, 27-07-2010 http://www.wellcome.ac.uk/News/2010/News/WTX060296.htm
3. Email from the DIrector of Stelar s.r.l., for confirmation of the development of a medicine authentication product and use of KCL know-how, and of the transfer of NQR expertise from KCL to Stelar.
4. Product specification for Stelar PC-NMR, indicating NQR capability. http://www.stelar.it/2010/download/free/datasheet/PC-NMR%20depliant.pdf
5. Email from Chinese Institute of Atomic Energy (CIAE) confirming King’s input to development of NQR explosives detection systems and training of staff at CIAE.
6. Letter from President and Founder of Bagtronics Ltd. (previously R&D Director EY, Rapiscan Systems) describing the impact of KCL research on the development of NQR based systems and associated signal processing for the detection of narcotics and explosives.
7. Email from Chief Technology Officer of Quasar Federal Systems (previously CEO at Quantum Magnetics Inc) confirming the impact of KCL research for the detection of explosives in vehicles.