The on-line low temperature nuclear orientation facility NICOLE

2017 J. Phys. G: Nucl. Part. Phys. 44 044010

(http://iopscience.iop.org/0954-3899/44/4/044010)

OPEN ACCESS
IOP Publishing

Made open access 7 August 2017
Journal of Physics G: Nuclear and Particle Physics

J. Phys. G: Nucl. Part. Phys. **44** (2017) 044010 (13pp) https://doi.org/10.1088/1361-6471/aa5f22

The on-line low temperature nuclear orientation facility NICOLE

T Ohtsubo[1], S Roccia[2], N J Stone[3,4], J R Stone[3,4], C Gaulard[2], U Köster[5], J Nikolov[6], G S Simpson[7] and M Veskovic[6]

[1] Department of Physics, Niigata University, Niigata 950–2181, Japan
[2] CSNSM, Université Paris Sud, CNRS/IN2P3, Université Paris Saclay, F-91405 Orsay, France
[3] Department of Physics and Astronomy, University of Tennessee, Knoxville, TN 37996, United States of America
[4] Department of Physics, University of Oxford, Oxford, OX1 3PU, United Kingdom
[5] Institut Laue-Langevin, F-38042 Grenoble, France
[6] University of Novi Sad, Faculty of Sciences, Department of Physics, 21000 Novi Sad, Serbia
[7] LPSC, F-38026 Grenoble, France

E-mail: jirina.stone@physics.ox.ac.uk

Received 16 November 2016, revised 31 January 2017
Accepted for publication 8 February 2017
Published 8 March 2017

CrossMark

Abstract

We review major experiments and results obtained by the on-line low temperature nuclear orientation method at the NICOLE facility at ISOLDE, CERN since the year 2000 and highlight their general physical impact. This versatile facility, providing a large degree of controlled nuclear polarization, was used for a long-standing study of magnetic moments at shell closures in the region $Z = 28$, $N = 28$–50 but also for dedicated studies in the deformed region around $A \sim 180$. Another physics program was conducted to test symmetry in the weak sector and constrain weak coupling beyond V–A. Those two programs were supported by careful measurements of the involved solid state physics parameters to attain the full sensitivity of the technique and provide interesting interdisciplinary results. Future plans for this facility include the challenging idea of measuring the beta–gamma–neutron angular distributions from polarized beta delayed neutron emitters, further test of fundamental symmetries and obtaining nuclear structure data used in medical applications. The facility will also continue to contribute to both the nuclear structure and fundamental symmetry test programs.

Keywords: nuclear orientation, magnetic moments, weak interactions, beta delayed neutrons, fundamental symmetries

(Some figures may appear in colour only in the online journal)

1. Introduction

A facility for 'Nuclear Implantation into Cold On-Line Equipment' (NICOLE) was installed at the on-line isotope separator ISOLDE 3 at CERN in 1988. The main purpose of the NICOLE facility is to implant the unique ISOLDE mass separated short-lived radioactive isotopes into a pre-cooled ferromagnetic foil. The foil is soldered to the cold finger of the ^{3}He–^{4}He dilution refrigerator and magnetized by an applied field provided by a superconducting coil. The implanted nuclei, cooled to milliKelvin (mK) temperatures in a sufficiently strong hyperfine field in the ferromagnetic foil, become polarized and emit radiation with an anisotropic spatial angular distribution with respect to the axis of the applied field. The angular distribution is determined by nuclear parameters such as ground state spin, electromagnetic moments and the multipolarity of emitted radiation, as well as by the solid state properties of the implant in the host lattice, including the hyperfine field, the electric field gradient and the spin-lattice relaxation time. Low temperature nuclear orientation experiments offer multi-faceted information on nuclear physics provided the solid state parameters are known and vice versa [1]. The NICOLE facility has yielded a wealth of results in both areas of physics over the years. In this review we discuss the main achievements since the year 2000 when the last ISOLDE Laboratory Portrait was published [2]. Results related to nuclear structure are reviewed in section 2 and results focused on solid state physics are outlined in section 3. Section 4 is dedicated to search for new physics beyond the standard model. Finally section 5 contains perspectives for a future research on the NICOLE facility.

2. Magnetic moments and nuclear structure studies

2.1. Odd-A nuclei in the vicinity of even–even (sub)shells

Magnetic dipole moments $\vec{\mu} = g^{(l)}\vec{l} + g^{(s)}\vec{s}$ provide a unique tool for probing details of nuclear wavefunctions. They are sensitive to nuclear coupling schemes because of the difference between g-factors $g^{(l)}$ and $g^{(s)}$, associated with the components of the total nuclear angular momentum $\vec{j}$, and the orbital $\vec{l}$ and spin $\vec{S}$ momenta of protons and neutrons. For odd-A nuclei at, or in the near vicinity of, major shell closures, the most extreme shell model predicts the so-called 'Schmidt limits' for the value of magnetic dipole moments. Experimentally, the majority of measured moments deviate from the Schmidt limit by 0.5–1.5 $\mu_{\rm N}$ [3]. In almost all cases these deviations place the measured moments between the $(\vec{l} - \vec{s})$ and $(\vec{l} + \vec{s})$ couplings which form the two Schmidt limits for any total nuclear spin $\vec{j}$. The average deviation of odd-proton nuclei is about 20% higher than the average deviation of odd-neutron nuclei. Of the few nuclei that deviate from the Schmidt limit by less than 0.2 $\mu_{\rm N}$, nearly all have a $p_{1/2}$ odd nucleon.

These deviations originate from the fact that the extreme shell model assumes the odd nucleon to be in a pure single-particle state. Since the change in magnetic moment is directly proportional to the amplitude of admixtures of other states, even small configuration contributions can significantly affect the measured magnetic moment. Furthermore, the form of the magnetic moment operator to be used in finite nuclei differs from that of the free nucleon, on which the Schmidt limits are based. Theory calculating the deviations from Schmidt limits has to account for the configuration mixing, as well as for some other more subtle effects included in the magnetic moment operator such as meson exchange currents and

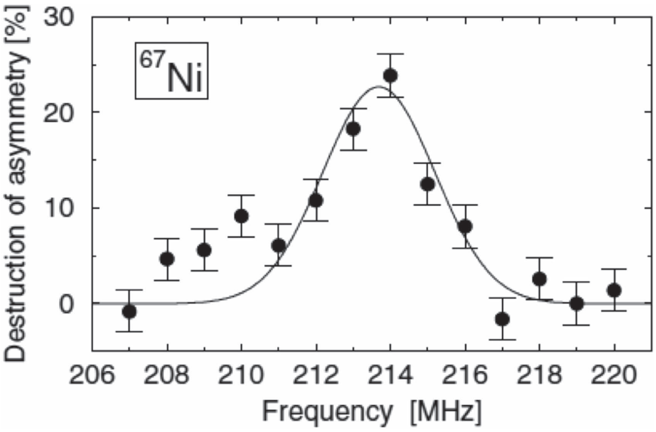

Figure 1. Beta-NMR/ON for ^{67}Ni(Fe). Reprinted figure with permission from [5]. Copyright 2000 by the American Physical Society.

electromagnetic final state corrections [3]. Accurate experimental determination of deviations from Schmidt limits provides an excellent testing ground for such a theory.

The magnetic moments of two nuclei with the $\nu p_{1/2}$ configuration accessible to experiment, (^{17}O and ^{207}Pb) are already known [4]. The magnetic moment of ^{67}Ni (one neutron outside $Z = 28$, $N = 40$ core) was measured using the beta-NMR/ON technique at the NICOLE facility for the first time. Resonant destruction of the anisotropy of the beta emission from polarized ^{67}Ni, implanted on-line into a cold Fe lattice, by an applied radio-frequency field, yielded the magnetic moment $\mu[^{67}\text{Ni}] = +0.601(5)\ \mu_N$. The result confirmed the expected small deviation from the Schmidt limit and was successfully interpreted theoretically using an effective magnetic moment operator which includes core polarization, meson exchange and relativistic effects [5]. In figure 1 we show the resonance curve used to determine the magnetic moment of ^{67}Ni, illustrating the quality of the data.

The study of deviations from the Schmidt limits has been pursued further by measurements on nuclei with simple odd-proton ground state configurations in which the deviations have been predicted to be rather significant. A wide range of Cu isotopes, with a single odd proton outside the even–even Ni cores, were opened to experiment at ISOLDE with the advent of the RILIS resonance ionization laser ion source and is suitable for nuclear orientation studies. The region spanned from the ^{56}Ni ($Z = 28$, $N = 28$) shell closure towards the ^{78}Ni ($Z = 28$, $N = 50$) shell closure and included the much studied ^{68}Ni ($Z = 28$, $N = 40$) subshell closure. The Cu isotopes provided not only an opportunity to study isotopes close to the closed shell, but also are an excellent laboratory for investigation of shell evolution in medium-heavy neutron rich nuclei.

That ^{68}Ni, $N = 40$, is a subshell closure has been suggested [6] based on results of deep inelastic reactions and remains a topic of interested to the present day [7, 8]. The magnetic moment measurement of ^{71}Cu ($N = 42$) $\mu[^{71}\text{Cu}] = +2.28(1)\ \mu_N$ [9] (later confirmed in a combination of in-source and collinear laser spectroscopy experiments [10]) contributed to the investigation in that it was significantly different from the moment of ^{67}Cu ($N = 38$) $\mu[^{67}\text{Cu}] = +2.54(2)\ \mu_N$, obtained in a nuclear orientation off-line experiment in Oxford using a ^{67}Cu(Fe) sample implanted at ISOLDE. The asymmetry between the magnetic moments of these two copper isotopes with, respectively, two particles above and two holes below the proposed closed neutron sub-shell at $N = 40$, reflects the differing neutron configurations available for mixing above and below the shell closure.

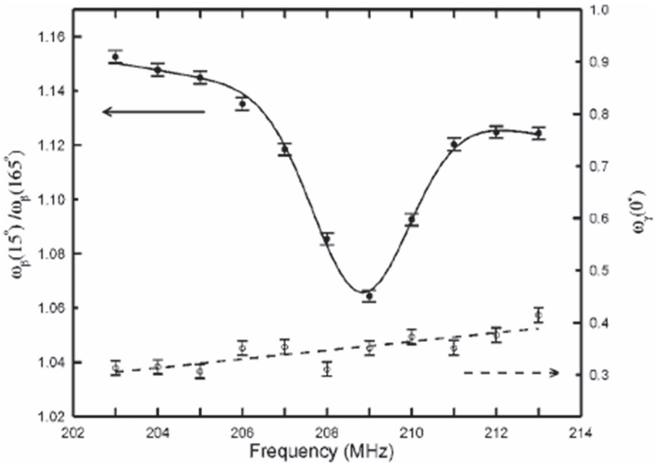

Figure 2. On-line nuclear magnetic resonance curve for ^{59}Cu. Reprinted figure with permission from [11]. See the reference for details. Copyright 2004 by the American Physical Society

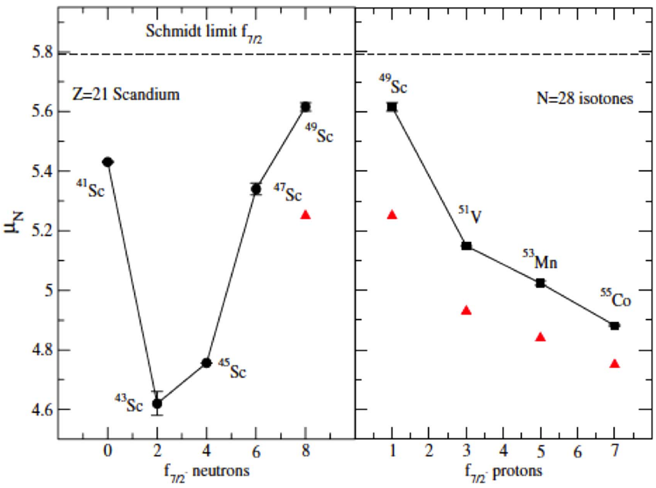

Figure 3. Measured magnetic moments (left) of odd-A Sc isotopes with one proton in the $f_{7/2}$ shell (left) and of $N = 28$ isotones (right). Results of a large-scale shell model calculation [13, 14] are depicted by (red) triangles. Reprinted figure with permission from [13]. Copyright 2012 by the American Physical Society.

The ^{56}Ni ($Z = N = 28$) shell closure was probed by measurement of the moment of ^{59}Cu ($N = 42$) $\mu[^{59}\text{Cu}] = +1.891(9)\ \mu_N$ [11] at the NICOLE facility with the beta-NMR/ON technique (for the resonance curve see figure 2). This moment was later confirmed in an in-gas-cell laser spectroscopy experiment [11]. Its low value has been seen as suggestive of a possible breaking of the ^{56}Ni closed shell. However, later measurement of the magnetic moment of ^{57}Cu ($N = 28$) $\mu[^{57}\text{Cu}] = +2.582(7)\ \mu_N$ [12] was found fully in agreement with the $Z = 28$, $N = 28$ shell closure.

Going below ^{56}Ni to the $f_{7/2}$ shell, the magnetic moment of ^{49}Sc, with a single $f_{7/2}$ proton outside the doubly magic ^{48}Ca ($Z = 20$, $N = 28$), was missing to complete the isotonic sequence of moments of Sc isotopes with even numbers of $f_{7/2}$ neutrons. Its measurement at the NICOLE facility yielding $\mu[^{49}\mathrm{Sc}] = (+)5.616(25)\ \mu_\mathrm{N}$ [13] made the Sc isotopic chain the first for which a full set of moment measurements exists between two major shells. In addition the result completes the isotonic sequence of ground-state moments of nuclei with an odd number of $f_{7/2}$ protons coupled to a closed subshell of $f_{7/2}$ neutrons. The ^{49}Sc magnetic moment was discussed in terms of the detailed theory of the structure of the magnetic moment operator showing excellent agreement with calculated departure from the $f_{7/2}$ Schmidt limit extreme single-particle value. However, as illustrated in figure 3, and discussed in [13], the systematic magnetic moments of $N = 28$ isotones provides a challenge to large-scale shell model calculations [14].

2.2. Magnetic moments of nuclei away from closed shells

Ground states of nuclei away from closed shells are rather complex with a variety of possible single-particle configurations contributing to the total wave-function. This microscopy leads to phenonema such as deformation, shape coexistence and shape transitions. Precise measurement of the ground state magnetic moments, sensitive to the wave-function make-up, helps to identify these configurations and test nuclear models.

Probing the $A = 70$ region, a precise value of the magnetic moment of the $I^\pi = 5/2^-$ deformed ground state of ^{69}As has been determined, $\mu[^{69}\mathrm{As}] = +1.6229(16)\ \mu_\mathrm{N}$, using the beta-NMR technique at the NICOLE facility [15]. Assuming the odd-proton to be in the $f_{5/2}$ shell outside a ($Z = 20$, $N = 28$) core, the moment differed considerably from the $\pi\ f_{5/2}$ single particle value obtained with g factors for a free proton. Several models, including the contribution of the deformed core and use of effective g-factors, have been applied to explain the experimental value.

In the $A = 100$ region, the beta-NMR technique was used to measure the magnetic dipole moment of the isomeric state ($I^\pi = 2^+$) in $^{104}\mathrm{Ag}^\mathrm{m}$, $\mu[^{104}\mathrm{Ag}^\mathrm{m}] = +3.691(3)\ \mu_\mathrm{N}$, which is significantly more precise than the previous value. This improvement was achieved by using a new value of the hyperfine field of Ag in iron, determined as described in section 3.1. The systematics of magnetic moments of even-A $^{102-110}$Ag was discussed in terms of mixing between the $(\pi\ g_{9/2})^{-3}_{7/2+}\ (\nu\ d_{5/2}\ \nu\ g_{7/2})_{5/2+}$ and $(\pi\ g_{9/2})^{-3}_{9/2+}\ (\nu\ d_{5/2}\ \nu\ g_{7/2})_{5/2+}$ configurations [16].

2.3. High-K isomers

Accurate measurements of the electromagnetic properties of ground states, isomers, and rotational band states in deformed nuclei yield parameters of the strong-coupling deformed model used to describe these nuclei. In the region between Yb and W ground states and isomers have close-to-constant deformation and the parameters of the strong coupling model can be explored thoroughly. In this regime the magnetic dipole moment of a band state with spin I built on a band-head with spin K depends on two g-factors, the collective g_R and the quasi-particle g_K. The magnetic dipole moment of a band-head with $I = K$, is expressed as $\mu = g_\mathrm{K}[I^2/(I + 1)] + g_\mathrm{R}[I(I + 1)]$. If the spin I is high, the magnetic moment has only weak dependence on g_R. It has been shown that for a multi-quasi-particle state for which K is a simple sum of K_i of individual components, g_K can be expressed as a weighted average of individual g_Ki (the principle of additivity). Two spectroscopic variables, the E2/M1 ratio δ in transitions from a level of spin I to a lower level of spin $I-1$ and the branching ratio of transitions from a state of spin I to lower states of spin $I-1$ and $I-2$, depend upon the difference $(g_{\mathrm{K}} - g_\mathrm{R})$ of the two (collective and quasi-particle) g factors. To separate the quasi-particle g factor g_K from the rotation g factor g_R it is necessary to have data on either

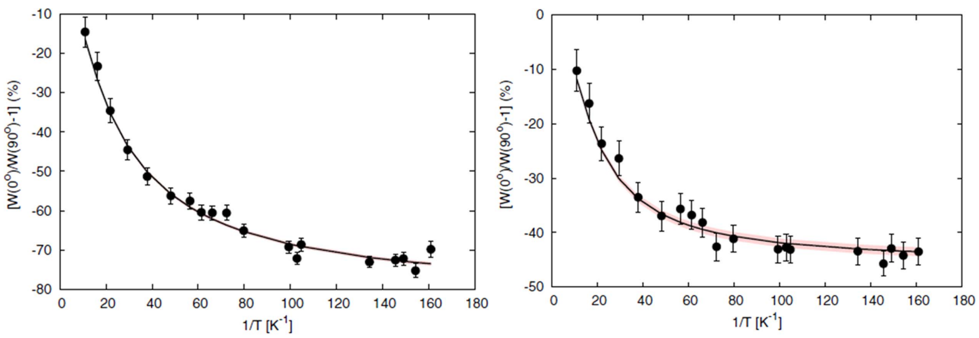

Figure 4. Anisotropy of the 228.5 keV $23/2^+ - 19/2^+$ pure E2 transition from the $23/2^+$ isomer to the band built on the $9/2^+$ [624] band (left). Anisotropy of the 277.3 keV $25/2^+ - 23/2^+$ mixed E2/M1 transition in band built on $23/2^+$ isomer. Fitted curve with shaded band is for δ [E2/M1] = +0.302(4) (right). Reprinted figure with permission from [18]. Copyright 2014 by the American Physical Society.

transition branching ratios from states in the band to lower states of spin reduced by one and two units or $M1/E2$ mixing ratios for transitions between states of spin differing by one, combined with the static magnetic dipole moment of a state of the band.

Analysis of estimations for g_K for a large number of band-heads revealed a wide, systematic, dependence of the collective g factor, g_R, upon the neutron and proton quasi-particle make-up of the band-head states, often far away from the Z/A value regularly used as an assumed value in interpretation of magnetic moments and transition properties of states in deformed nuclei. This discovery presents a new challenge to the theory of superconductivity, pairing and blocking in these nuclei [17] and gives additional reason to extend, in particular, band-head magnetic moment measurements and transition multipole mixing ratios with good accuracy.

On-line orientation measurements have been made on two high-K isomers, the $37/2^-$, 51.4 m, 2740 keV state in ^{177}Hf and the 8^-, 5.5 h, 1142 keV state in ^{180}Hf using the NMR technique and gamma-ray angular distribution measurements [18]. In ^{177}Hf these yielded high precision E2/M1 multipole mixing ratios for transitions in bands built on the $23/2^+$, 1.1 s, isomer at 1315 keV and on the $9/2^+$, 0.663 ns, isomer at 321 keV needed for extraction of g_K from experimental data. We demonstrate the quality of the fits in figure 4. The left-hand side figure shows the temperature dependence of the pure E2 transition, used to determine the fraction of implanted isotopes in good substitutional sites in the Fe lattice. The right-hand side illustrates the anisotropy of a mixed transition as a function of temperature, used to extract the mixing ratio δ. The new results provided valuable additional evidence for the validity of additivity in estimating the quasi-particle g factor g_K in these deformed nuclei as outlined above. Values of the collective g factor, g_R, obtained from detailed gamma transition anisotropy measurements, are shown to be fully consistent with the recently revealed systematic dependence of this parameter upon the quasi-particle make-up of the bands involved [17]. Further experiments on lighter K-isomers are planned to continue this interesting study.

2.4. Beyond magnetic moments: tests of fundamental symmetries

Parity, which describes reflection symmetry in the origin of a coordinate system, is one of the fundamental symmetries of physics. Establishing whether parity may be taken as a conserved quantity under a system of forces or, alternatively, determining the conditions under which, and the degree to which, parity is not conserved, form basic constraints upon physical

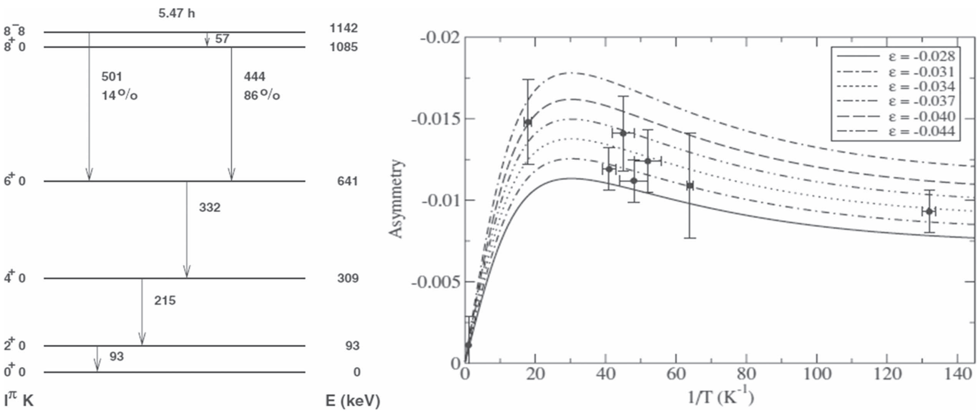

Figure 5. Decay of the 5.47 h ^{180}Hf^{m} (left). Measured asymmetry A of the 501 keV transition, as a function of inverse temperature, compared with calculations for a range of values of the E2/M2 mixing ratio ε. Reprinted figure with permission from [20]. Copyright 2007 by the American Physical Society.

theories. The demonstration of parity non-conservation (PNC) in the weak interaction, using the low temperature nuclear orientation technique [19], was one of the most important discoveries of modern physics. However, determining the extent to which parity is to be considered a conserved quantity in nuclear phenomena remains a challenge to both experiment and theory. Parity mixing in bound nuclear systems is understood as a consequence of weak (parity violating) interaction terms in the nuclear Hamiltonian, and precise calculations of this phenomenon are not yet available.

Of the many experiments aimed at detecting parity non-conservation in nuclear states, one stands out: the measurement of an irregular E2/M2 mixing in the 8^{-}– 6^{+}, highly *K*-forbidden, 501 keV gamma decay of the 5.47 h isomer of ^{180}Hf. The relevant part of the level scheme of ^{180}Hf^{m} is given in the left hand part of figure 5.

For parity conserving transitions the gamma distribution shows no forward–backward asymmetry with respect to the axis of polarization. Irregular parity admixture introduces such asymmetry. The detection of an irregular E2 admixture to the regular, mixed M2/E3 multipolarity of the 501 keV transition, deduced from the forward–backward asymmetry of its angular distribution, reported in earlier nuclear orientation studies, has for decades stood as the prime evidence for parity mixing in nuclear states. Because of some experimental uncertainties in the original measurement, the experiment was repeated at the NICOLE facility [20]. The mass-separated molecular ^{180m}HfF$_3^+$ beam from the ISOLDE mass separator [21] was implanted into an iron foil maintained at mK temperatures, producing higher degrees of polarization than were achieved in previous studies [22]. The value found for the irregular E2/M2 mixing ratio $\varepsilon = -0.0324(16)$, is in close agreement with the previous published average value $\varepsilon = -0.030(2)$ [22], in full confirmation of the presence of E2 admixture in the 501 keV transition. The temperature dependence of the forward–backward asymmetry has been measured over a more extended range of nuclear polarization than previously possible, giving further evidence for parity mixing of the 8^{-} and 8^{+} levels and the deduced E2/M2 mixing ratio. The measured forward–backward asymmetry of the 501 keV transition is shown in the right hand part of figure 5.

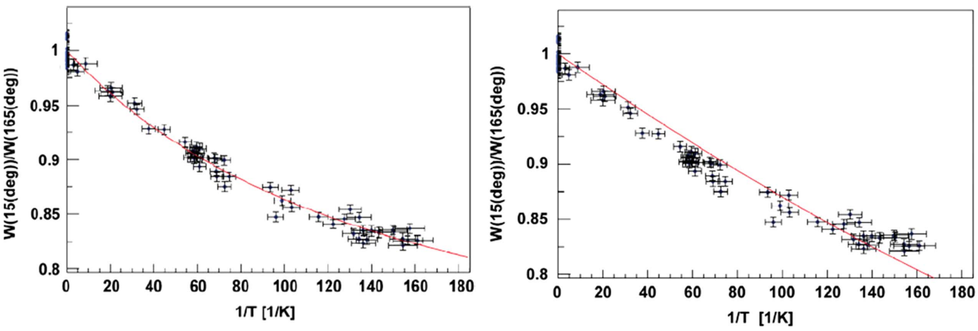

Figure 6. Temperature dependence of beta anisotropy from ^{62}Cu(Fe) fitted with (left) and without (right) a correction for the relaxation time. Reprinted figure with permission from [26]. Copyright 2006 by the American Physical Society.

3. Hyperfine fields and spin-lattice relaxation times

3.1. Hyperfine fields in Fe lattice

Nuclear orientation experiments on isotopes with known magnetic moments are an important source of information on hyperfine fields B_{hf} acting on implanted nuclei in a ferromagnetic lattice. Limited knowledge of B_{hf} is usually the main source of uncertainty in determination of magnetic moments from measured resonance frequencies in NMR experiments on oriented nuclei.

A new value for the hyperfine magnetic field experienced by copper nuclei implanted in lattice sites in iron has been obtained by combining resonance frequencies from experiments involving beta-NMR on oriented ^{59}Cu, ^{69}Cu, and ^{71}Cu nuclei with magnetic moment values obtained from collinear laser spectroscopy measurements available for $^{61–75}$Cu isotopes. The resulting value, B_{hf} (CuFe) $= -21.794(10)$ T, is in agreement with the value adopted before this work, $-21.8(1)$ T but is an order of magnitude more precise [23]. In addition, examination of differences in hyperfine field values obtained for individual Cu isotopes due to hyperfine anomalies lead to a conclusion that the anomalies are smaller than 3×10^{-3} for Cu in Fe.

To improve on the previous value of B_{hf} acting on silver implants in iron, the ground state of ^{104}Ag^{g} ($I^{\pi} = 5^{+}$) has been subject to NMR. Combining the resonance frequency with the known magnetic moment of this isotope, the hyperfine field of Ag was found to be $|B_{hf}(AgFe)| = 44.709(35)$ T [16]. Detailed analysis of other relevant data available in the literature yielded three more values for this hyperfine field. Averaging all four values, a new and precise value for the hyperfine field of Ag in Fe was found: $|B_{hf}(AgFe)| = 44.692(30)$ T. This field was used to determine the magnetic moment of ^{104}Ag^{m} as discussed in section 2.2.

3.2. Spin-lattice relaxation times

In on-line experiments when short-lived radioactive isotopes are implanted into a cooled ferromagnetic lattice at mK temperatures, the nuclei, which on implantation have random orientation and are hence at high temperature, take a finite time to cool to the lattice temperature. In the case that the nuclear lifetime is comparable with the cooling time, some fraction of the nuclei decay before reaching the lattice temperature so that the average nuclear orientation, as measured by the angular distribution of radioactive decay products from the oriented nuclei, is attenuated. Thus determination of the relaxation time, which increases at

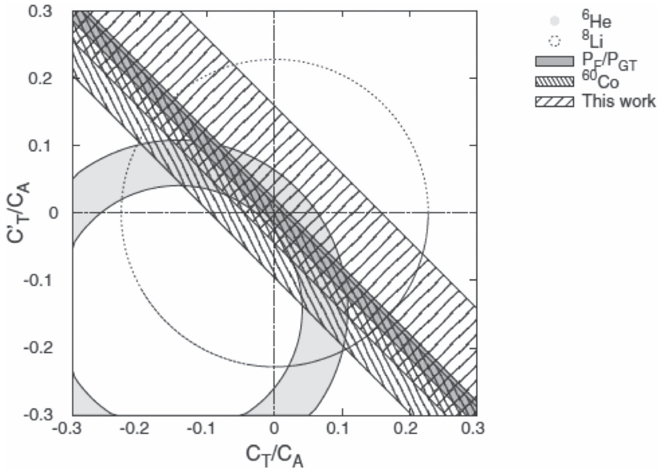

Figure 7. Limits on time-reversal invariant tensor-type coupling constants C_T and C'_T, normalized to axial-vector coupling constant C_A. Reprinted figure with permission from [28]. Copyright 2014 by the American Physical Society.

lower temperature, is of a vital importance in planning and conducting on-line orientation experiments as it limits the life-time of implanted nuclei which can be studied [24, 25]. At a more fundamental level, nuclear spin-lattice relaxation rates of implanted elements in metals permit critical test of electronic band structure theory as they depend sensitively on the local density of states near the Fermi surface. The relaxation rate is determined by a single host/nuclear parameter, the Korringa constant C_K, and the lattice temperature T_L [24, 25].

The spin-lattice relaxation times of ^{62}Cu in iron were determined from measurements of the asymmetry of beta-radiation emitted by ^{62}Cu nuclei continuously implanted into an Fe host foil and polarized at the NICOLE facility [26]. At temperatures ranging from 6.5 mK to about 100 mK and in an external magnetic field of 0.1 T, the Korringa constant for ^{62}Cu in Fe was found to be $C_K[^{62}\text{Cu}] = 4.34(25)$ sK. The effect of including the relaxation time into the analysis of the temperature dependence of the beta emission anisotropy is illustrated in figure 6, where the data are fitted by a theoretical curve with (left) and without (right) the correction for relaxation. Inclusion of the degree to which limited relaxation reduced the measured average polarization at lower temperatures led to an improved value of the extracted beta decay parameter.

4. Search for new physics

4.1. Weak Interactions study through beta decay

Precision measurements at low energy allows search for physics beyond the standard model in a way complementary to searches for new particles at colliders. In the weak sector the most general beta-decay Hamiltonian contains, besides vector and axial-vector terms, also scalar, tensor, and pseudo-scalar terms. Current limits on the scalar and tensor coupling constants from neutron and nuclear β decay are on the level of several percent. Nuclear orientation experiments are suitable to contribute to the effort to improve these limits.

An experiment to determine the beta-asymmetry parameter $\tilde{A}$ for the pure Gamow–Teller decay of ^{114}In was performed at the NICOLE facility [27]. Analysis of the data was combined with a GEANT4-based simulation code allowing, for the first time, to address in detail the effects of scattering and the magnetic field upon the measurements. The final result, $\tilde{A} = -0.994 \pm 0.010_{\mathrm{stat}} \pm 0.010_{\mathrm{syst}}$, constitutes the most accurate value for the asymmetry parameter of a nuclear transition to date. The value is in agreement with the Standard Model prediction of $\tilde{A} = -1$ and provides new limits on tensor-type charged weak currents.

In a second experiment, on the pure Gamow–Teller beta-decay of polarized ^{67}Cu, the ratio $\tilde{A}/A_{\mathrm{SM}}$ was found to be $0.980 \pm 0.14_{\mathrm{stat}} \pm 19_{\mathrm{syst}} = 0.980(23)$ [28]. This result was used to extract the C_{T}, C'_{T} and C_{A} coupling constants of the tensor and axial-vector parts of the weak interaction. The limits are comparable to limits from other correlation measurements in nuclear beta decay and contribute to further constraining tensor coupling constants. Illustration of current limits, including the result on ^{67}Cu, is given in figure 7.

4.2. Alpha decay

The half-lives of alpha- and beta-decaying nuclei have in general been considered constant, independent of their surroundings and not showing variation with temperature. However, in 2006 a sensational claim was advanced that the half-life of a radioactive isotope would change radically if the isotope were implanted in a metallic host and cooled to liquid helium temperature. The claim was based on the implausible application of the Debye plasma model to quasi-free electrons in metals. This hypothetical mechanism was proposed as a possible solution for the disposal of long-lived transuranic waste produce by fission reactors and created great media interest [29]. The claim is however contradictory to the long-time experience of low-temperature nuclear orientation groups who, in studying alpha and beta emitters embedded in metals at mK temperatures, have never observed a change in half-life of a radioactive decay.

A dedicated experiment was performed at the NICOLE facility to disprove this idea. The half-life of the α-decaying nucleus ^{221}Fr was determined in different environments, that is, embedded in Si at 4 K, and embedded in Au at 4 K and about 20 mK. No differences in half-life for these different conditions were observed within 0.1%. Furthermore, a value was obtained for the absolute half-life of ^{221}Fr, 286.1(10) s, that is in complete agreement with, and of comparable precision to, the most precise value available in the literature [30].

In a separate study further analysis was made of published nuclear orientation measurements of alpha active samples of ^{224}Ra, ^{225}Ra and ^{227}Ac. The samples were prepared at the ISOLDE isotope separator facility, CERN, the parent activities being implanted at 60 keV into iron foils. Angular distributions of alpha emission from different members of the decay chains of the ^{224}Ra, ^{225}Ra and ^{227}Ac, and their temperature dependence, between 1 K and ~25 mK, were extensively studied at the NICOLE facility. Detailed modeling including necessary correction for decay of the samples, showed no evidence for any modification of either alpha- or beta-decay half lives in the decay chains from normal accepted values [31].

5. Perspectives and future challenges

5.1. Beta-delayed neutrons from oriented ^{137,139}I and ^{87,89}Br nuclei

The NICOLE collaboration is preparing for a new experiment, for the world first study of the angular distribution of beta-delayed neutrons emitted by nuclei oriented at low temperatures [32].

Beta-delayed processes are basic to physics as the drip-lines are approached. Importantly, assuming current models of the *r*-process path, beta-delayed neutron emission is one of the important processes that has to be included in astrophysical simulations.

Conventional spectroscopy provides over-all information concerning energies, level structures and transition probabilities, but there are severe limitations in establishing details of the processes. In particular, the contribution of different partial waves to the neutron emission remains unknown. The study of the angular distribution of the beta-delayed neutrons from nuclei, with a high degree of controlled polarization, provides information on spins and parities of levels concerned and the angular momentum composition of the emitted neutron waves.

The proposed experiment is to measure the angular distribution of beta-delayed neutrons from ^{137,139}I and ^{87,89}Br nuclei, polarized at the NICOLE facility. The aim is to make direct observation of the magnitude and sign of the departure from spherical symmetry of the continuous beta-delayed neutron spectrum and establish whether the observed anisotropy of the angular distribution and its dependence upon neutron energy is consistent with theoretical predictions based on the best existing models. Neutron detection will be done using the new 'Versatile Array of Neutron Detectors at Low Energy' (VANDLE) in conjunction with high purity Ge detectors for neutron–gamma coincidence and fast beta detection to allow time-of-flight determination of neutron energy.

The experiments have a direct relevance to a recently initiated Coordinated Research Project at the International Atomic Energy Agency (IAEA) in Vienna on the development of a 'Reference Database for Beta-Delayed Neutron Emission Evaluation'.

5.2. Fundamental symmetries

We intend to pursue further testing of the parity mixing in nuclear states. As described in detail in [20], the low temperature nuclear orientation technique is well suited to study parity mixing in bound nuclear systems, which is understood as a consequence of weak (parity violating) interaction terms in the nuclear Hamiltonian. Precise calculations of this phenomenon are not yet available and any experimental input to encourage further progress in theory is valuable. We plan to extend the successful measurement of an irregular E2/M2 mixing in the 8^-– 6^+, highly *K*-forbidden, 501 keV gamma decay of the 5.47 h isomer of ^{180}Hf to analogous cases in ^{182}Hf and, possibly ^{184}Hf, taking advantage of ISOLDE beams. The 8^-– 6^+ 506.6 keV gamma-ray from the 1172.9 keV 61.5 min isomeric state in ^{182}Hf and, a still more challenging, the 8^- –6^+ 555 keV gamma-ray from the 1272.2 48 s isomer in ^{184}Hf are in principle open to experiment. A first test of ^{182m}Hf showed excessive background from 511 keV annihilation gammas that caused badly controlled background deduction for the 506.6 keV gamma ray of interest. This target had particularly strong oxyfluoride ion side-bands of ^{166}Lu causing the strong annihilation line. With a cleaner target and less oxide contamination this measurement should be feasible. ^{184m}Hf has presently too low yield and would require further target development. Extending these measurements to ^{182m}Hf and ^{184m}Hf is definitively worth pursuing, as these would provide the first data on a systematics of nuclear structure effects on PNC.

Further we will consider exploration of a possibility to launch experiments to study *T* (time) and PT (simultaneous time and parity) invariance in nuclear gamma-decay. Such experiments require detection of the linear polarization of gamma-rays from nuclei oriented by hyperfine interaction at low temperatures. Pioneering experiments were performed in 1980s [33], but the geometry and handling of the systematic errors produced by the Compton polarimeters available at that time were the main obstacle to pursuing this research. Today these experiments could be pursued exploiting clover detectors as efficient linear polarimeters [34].

5.3. Nuclear structure data on isotopes used for medical applications

Targeted radionuclide therapy is a powerful method to treat serious diseases such as cancer. Nuclides emitting short-range radiation such as α particles, low energy β, conversion or Auger electrons are linked to a biomolecule, called vector, that can selectively target cancer cells. Ultimately the best targeting could be achieved with Auger electrons due to their very short range [35]. Thus isotopes that emit conversion electrons followed by cascades of Auger electrons are of great interest. Preclinical experiments study the therapeutic effects and side effects of different radionuclides as function of activity [36, 37], but eventually this activity has to be converted into dose for direct dose/effect comparisons. This requires precise knowledge of the intensities of all conversion electrons and the resulting Auger cascades. Experimentally it is very difficult to measure precisely low-energy conversion electrons, but it might be easier to approach the problem indirectly: measure precisely the mixing ratios, then calculate the conversion electron yields. Such measurement would involve detection of rather low energy gamma-rays, requiring special detectors, to be placed inside the NICOLE cryostat.

Acknowledgments

Support of all members of the NICOLE collaboration and of the ISOLDE in-house group during our experiments and their preparation is gratefully acknowledged. The on-line low temperature orientation experiments are technically demanding and only a team effort can yield the full range of success reported in this review. Funding agencies of groups in different participation countries are listed in individual references.

References

[1] Brewer W D 1990 *Rep. Prog. Phys.* **53** 483
[2] Forkel-Wirth D and Bollen G 2000 *Hyperfine Interact.* **129** 0
[3] Castel B and Towner I S 1990 *Modern Theories of Nuclear Moments* (Oxford: Clarendon)
[4] Stone N J 2005 *At. Data Nucl. Data Tables* **90** 75
Stone N J 2014 Nuclear magnetic dipole and electric quadrupole moments *IAEA Vienna Report INDC* (NDS)-0658 (last updated)
[5] Rikovska J *et al* 2000 *Phys. Rev. Lett.* **85** 1392
[6] Broda R *et al* 1995 *Phys. Rev. Lett.* **74** 868
[7] Langanke K, Terasaki J, Nowacki F, Dean D J and Nazarewicz W 2003 *Phys. Rev.* C **67** 044314
[8] Bissell M L *et al* 2016 *Phys. Rev.* C **93** 064318
[9] Stone N J *et al* 2008 *Phys. Rev.* C **77** 014315
[10] Flanagan K T *et al* 2009 *Phys. Rev. Lett.* **103** 142501
[11] Golovko V V *et al* 2004 *Phys. Rev.* C **70** 014312
[12] Cocolios T E *et al* 2009 *Phys. Rev. Lett.* **103** 102501
[13] Ohtsubo T *et al* 2012 *Phys. Rev. Lett.* **109** 032504
[14] Honma M, Otsuka T, Brown B A and Mizusaki M 2004 *Phys. Rev.* C **69** 034335
Honma M 2004 private communication
[15] Golovko V V *et al* 2005 *Phys. Rev.* C **72** 064316
[16] Golovko V V *et al* 2010 *Phys. Rev.* C **81** 054323
[17] Stone N J, Stone J R, Walker P M and Bingham C R 2013 *Phys. Lett.* B **726** 675
[18] Muto S *et al* 2014 *Phys. Rev.* C **89** 044309
[19] Wu C S, Ambler E, Hayward R W, Hoppes D D and Hudson R P 1957 *Phys. Rev.* **105** 1413
[20] Stone J R *et al* 2007 *Phys. Rev.* C **76** 025502
[21] Köster U *et al* 2007 *Eur. Phys. J. Spec. Top.* **150** 293
[22] Chou T S, Krane K S and Shirley D A 1975 *Phys. Rev.* C **12** 286
[23] Golovko V V *et al* 2011 *Phys. Rev.* C **84** 014323

[24] Klein E 1986 *Low Temperature Nuclear Orientation* ed N J Stone and H Postma (Amsterdam: North-Holland) ch 11
[25] Shaw T L and Stone N J 1989 *At. Data Nucl. Data Tables* **42** 339
[26] Golovko V V *et al* 2006 *Phys. Rev.* C **74** 044313
[27] Wauters F *et al* 2009 *Phys. Rev.* C **80** 062501(R)
[28] Soti G *et al* 2014 *Phys. Rev.* C **90** 035502
[29] Rolfs C 2006 *Nucl. Phys. News* **16** 9
[30] Wauters F *et al* 2010 *Phys. Rev.* C **82** 064317
[31] Stone N J *et al* 2007 *Nucl. Phys.* A **793** 1
[32] Grzywacz R 2014 ISOLDE Experiment IS575: beta-delayed neutrons from oriented ^{137,139}I and ^{87,89}Br nuclei
[33] Stone J R *et al* 1988 *Hyperfine Interact.* **43** 107
[34] Jones P M *et al* 1995 *Nucl. Instrum. Methods* A **362** 556
[35] Kassis A I 2011 *Rad. Prot. Dosimetry* **143** 241
[36] Grünberg J *et al* 2014 *Eur. J. Nucl. Med. Mol. Imaging* **41** 1907
[37] Haller S *et al* 2016 *EJNMMI Res.* **6** 13