UNISOR NUCLEAR ORIENTATION FACILITY

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Abstract

The combination of an on-line isotope separator and a dilution refrigerator has increased the applicability of the nuclear orientation technique to a wide range of nuclei, especially those very far from stability. The UNISOR Nuclear Orientation Facility (UNISOR/NOF) is among the two (the other being NICOLE at CERN) that have recently become operational. The following is an overall view of the UNISOR system and recent results.

1. Introduction

The major developments in the low-temperature nuclear orientation field that took place during the last decade can be summarized as follows. First, the use of a dilution refrigerator to cool nuclei far from stability after production in an accelerator and electromagnetic selection, is a major extension of the method. The principal limit on the half lives $t_{1/2}$ of nuclei which can be studied by this method is due to the nuclear-spin relaxation time, T_1 , which is typically >10 s. Since the nuclei under study are produced directly by ion implantation, another advantage of this method is that the problems associated with the insolubility of impurities in the host materials by diffusion techniques are eliminated. There are now four on-line systems of this type: the KOOL at Leuven, Belgium (1); the DOLIS-COLD at Daresbury, England (2); the

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Belgium (1); the DOLIS-COLD at Daresbury, England (2); the UNISOR/NOF at Oak Ridge, USA; and, a very recent addition, NICOLE at CERN, Switzerland (3). The FOLBIS system in Bonn, Germany is not on-line to an accelerator (4). The second major development of the past decade has been, the use of the Nuclear Magnetic Resonance technique on oriented nuclei, NMR/ON, by on-line systems. The NMR/ON technique was applied up to this decade only to long-lived isotopes. (See review by Herzog (5)). Due to the need for high statistics and long search times of the resonance, this technique was considered to be incompatible with on-line systems. The success of the first NMR/ON by KOOL (6) on some of the In and Ag isotopes rightfully proved that the on-line application of the nuclear orientation method in combination with nuclear magnetic resonance provides a powerful technique for directly determining ground or isomeric state spins of short-lived isotopes. Furthermore, this technique provides a very accurate measurement of the g-factor of the implanted nuclei. The last decade has also seen the development of the ability to detect α , β (6,7) and internal Bremsstrahlung radiation in on-line systems (8,9). The occurrence of the dipole term A_1 in the angular distribution function for β particles gives a number of practical advantages, e.g., higher orientation effects at higher temperatures and measurements of spin 1/2 states. The importance of the α -detection technique in connection with oriented nuclei in on-line systems lies in the fact that the anisotropy of the α -radiation is a measure of structural changes from parent to daughter nuclei.

Traditionally, the application of the low-temperature nuclear orientation technique in the solid state field included the measurement of static hyperfine interaction (HFI) parameters (both the hyperfine field B and the electric field gradient eq), thermometry, dilute magnetism, brute force nuclear orientation, nuclear spin relaxation, and radiation damage. The recent innovations, mostly in the area of NMR/ON, include the technique of Modulated Adiabatic Passage on Oriented Nuclei (MAPON), developed (10) as a means of measuring the weak electric quadrupole splitting, Δv_Q , of the hyperfine interaction due to an electric field gradient, V_{zz} ; a novel spin echo technique that enables the measurement of the sign of g (11); and the double resonance NMR/ON method (12) which was used to study a rare-earth system, $^{160}\text{TbTb}$, for the first time and can serve as a model for studies in the rare earth region. (For a review of the NO applications in the solid state field prior to 1985, see (13)).

In the nuclear spectroscopy field, the major contribution of the nuclear orientation technique, especially on-line nuclear orientation, is in the nuclear spectroscopy of nuclei far from stability. This is due partly to the limitations of traditional techniques, such as angular correlations (low intensity of coincidence measurements) or in-beam studies (reduced population of low spin states) and partly to extensive technical developments of on-line isotope separators with accelerators which made access to nuclei far from stability possible. Thus, coupled with gamma ray and conversion-electron spectroscopy, nuclear orientation

experiments, yield ground and excited level spin values, static magnetic dipole and electric quadrupole moments of ground states and long-lived isomers, and most importantly transition multipolarities of almost all radiations emitted in radioactive decay. A detailed study on the measurements of magnetic dipole moments and electric quadrupole moments by low-temperature nuclear orientation techniques can be found in (14) and (15) respectively. The need to measure the transition moments unambiguously on the other hand deserve special attention for the reasons explained below.

The measurements of E2/M1 mixing ratios have provided very sensitive tests of different nuclear models (16). The mixing ratio, δ , may be a more sensitive parameter in many instances than a reduced transition probability, such as a B(E2) or B(M1) value. This is because a δ value contains matrix-element values, so the relative phases of the electric and magnetic multipole operators are preserved, whereas a transition probability depends on the square of a matrix element. Several things can be learned by studying the mixing ratios of nuclei:

a) Comparison of mixing ratios with the predictions of the Single Shell Model can tell us about nuclear collectivity and shell closures.

b) The sign of δ also is a good source of information especially on the shape of nuclei. For example, a transition from nuclei with a level structure characteristic of a spherical vibrator to those with a structure described in terms of a deformed rotor occurs in the A=150 region upon crossing the boundary between N=88 and N=90

where both the sign and magnitude of multipole mixing ratios change (17).

c) Shape coexistence is another instance where one needs accurate mixing ratio measurements. Existing bands of different shape within the same nucleus, for example, can be seen in the case of neutron deficient Au isotopes (18) where the sign of δ changes between these bands (19). The states of the same spin in these two bands are characterized, in some cases, by connecting transitions with E0+M1 multipolarity. Internal conversion data are unable to resolve ambiguities in possible multipole admixtures. Such E0 transitions are considered signatures (20) for transitions between differently shaped bands in the same core.

The examples above and many others require an unambiguous and precise determination of mixing ratios. The precision in these measurements is determined by how well the systematic errors are eliminated. This can be done well to a certain degree, but the certainty in the determination of δ can only be satisfied if one of the two possible solutions for δ is rejected. This is because δ is a quadratic function of the directional distribution coefficients, A_2 . In order to eliminate one of the two solutions, it is often necessary to use A_4 , and this requires measurements at an independent angle, such as 45° . The need for this extra angle can further be clarified using the arguments by Krane (21). In Fig. 2 of ref. (21), the values of the $\delta(E2/M1)$ mixing ratios, one corresponding to nearly (99%) pure E2 radiation and the other to 99% M1 radiation, give the same $W(90^\circ)/W(0^\circ)$ ratio but differ by 20% in

their 45° angular distribution. Thus only a measurement at this angle will help to distinguish these two cases unambiguously.

This fact is the main design principle behind the UNISOR/NOF. In Section 2, the basic design principles that underlie the operation of UNISOR/NOF are discussed. Section 3 contains the preliminary results recently obtained in the facility.

2. Experimental Set-up

Figure 1 shows a schematic comparison of the four fully on-line nuclear orientation systems. The common feature of three of these on-line systems is that the separated ion beam is directly ~~implanted onto the target through a side access.~~ The UNISOR/NOF, on the other hand, differs in design in that the beam access to the target is from the bottom of the refrigerator. This configuration allows up to eight detectors to view the target. Also, the construction of the heat shields enables the 8 detectors, four at 45°, to view the target with essentially the same solid angle. The external field direction, which determines the axis of symmetry, lies in the equatorial plane.

A schematic dual plane view of the UNISOR/NOF is shown in Fig. 2. The Holifield Heavy-Ion Research Facility (HHIRF) 25 MV Tandem accelerator (TM) provides the primary beam which is focused on a target in a modified FEBIAD ion source (IS). The ionized reaction products are then accelerated (typically at 50 kV) and mass separated by a 90° bending magnet. The chosen mass beam is focused (see Section 2.2) before entering the cold beam tube (CBT) which is part of the refrigerator cryostat. The ferromagnetic foil (T) on

which the activity is implanted is soldered to the cold finger of the ^3He - ^4He dilution refrigerator (DR) which should maintain the temperature at about 12 mK with the 4K baffle open. The magnetic domains in the target foils (usually Fe) are polarized by a 1.5 T superconducting magnet (SM).

2.1 The ^3He - ^4He Dilution Refrigerator

The refrigerator and the bottom access beam assembly (Fig. 3) were manufactured by Oxford Instruments (22). The refrigerator is a standard design, but, in order to allow bottom access, the tail section and the magnet have been modified. The tails are cylindrical; the outer one is 18 cm in diameter, so the closest source-to-detector distance is 9 cm. At this distance, for detectors with 5 cm crystal diameter, the magnet allows 1.65, 1.29, and 1.07 % solid angle for 0°, 45°, and 90° detectors respectively. There is also a 2.2 cm opening at the bottom of the magnet for beam entrance. The refrigerator is equipped with a "top load" facility to change target material while the refrigerator is operational. The cooling power of the refrigerator at a circulation rate of 500 $\mu\text{mol/s}$ is given by the power relation: $Q = 0.017(T^2 - 44.9) \mu\text{W}$ where T is the target base temperature.

The target foils and thermometer sources are soldered on the face of a 1.0 cm diameter cylindrical, copper sample holder which is screwed into the mixing chamber of the dilution unit by the top loading rod. The sample holder is made of high purity oxygen-free tellurium copper and lies at the center of a 1.5 T Helmholtz-type superconducting magnet which can also be run in persistent mode. The

field direction is horizontal, and the beam direction is vertical to this field. The refrigerator cryostat and the detectors are accommodated by a 6m high platform. A separate platform for detection electronics, experimentalists, and cryogenic liquid transfer surrounds the inner one.

Recent experiments have shown that when all the baffles are closed a base temperature of 7.6 mK can be reached.

2.2 The beam line

The 50 kV beam from the separator is controlled and monitored by several lenses and deflector assemblies. At first, the separated beam is focused in the dispersion chamber of the separator in which a beam profile monitor and a Faraday cup check the shape and intensity of the beam before it enters the horizontal beam line. A compressor lens at the beginning of the beam line narrows the beam; an Einzel lens at the end focuses it to the entrance of the 90° electrostatic deflector. The transmission through the horizontal beam line is checked by a removable Faraday cup. An x-y beam scanner can also be used to monitor the beam shape before it is bent up. A 90° electrostatic deflector consisting of seven equally spaced parallel plates deflects the beam. A quadrupole triplet lens just beyond the deflector provides the final focusing before the beam enters the cold beam line. The final steering of the beam is achieved by a set of x-y deflectors placed just before an iris used to control the size of the beam striking the target. The intensity of the beam at this stage is monitored by a Faraday cup mounted on the 4K baffle.

The transmission from dispersion chamber to the target ranges from 70% to 96% for different beams.

2.3 Data acquisition system

Currently the UNISOR/NOF data acquisition system is based on a Tennecomp TP 5000 system which is linked to a Concurrent mainframe computer through a CAMAC interface. The spectra can automatically be transferred to the mainframe where they are stored either on high capacity disk drives or magnetic tapes.

The software of both computers allows the collection time of the acquisition, the number and length of spectra to be transferred and the type of data storage to be controlled. A separate program accesses the data on the disk and monitors the base temperature of the refrigerator, and calculates the anisotropy of up to three peaks in the isotope of interest. Thus, the experimenters can monitor the alignment of the sample in real time.

2.4 Data Analysis

In on-line nuclear orientation experiments the number of counts observed by a detector at a given angle θ is given by:

$$N(\theta, T) = N_T f_\theta W(\theta, T) t_\theta(T) \quad (1)$$

where N_T is the beam rate at temperature T , f_θ is a function of the intrinsic efficiency of the detector at angle θ , solid angle subtended by the detector at angle θ , branching factors involved in the decay, and radiation attenuation through dewars etc. $t_\theta(T)$ is the counting time at temperature T . $W(\theta, T)$ refers to the directional distribution function for a detector at an angle θ and temperature T as defined in (23).

In off-line nuclear orientation experiments where the decay of the isotope of interest is constant, and since the nuclear orientation coefficients, B_k , go to zero at high temperature ($T \approx 1$ K), the normalization factor $N_T f_\theta$ can be determined at high temperature. In on-line experiments, the variations in the rate of ion implantation due to the fluctuations in the accelerator beam current or changes in the extraction efficiency of the isotope separator will cause variations in N_T between "warm" ($T \approx 1$ K) and "cold" ($T < 20$ mK) data. In this case, the normalization will no longer cancel from the ratio $N(\theta, T)/N(\theta, T \rightarrow \infty)$. So we will have

$$R = \frac{N(\theta, c) / t_\theta(c)}{N(\theta, w) / t_\theta(w)} = \frac{N_c f_\theta W(\theta, c)}{N_w f_\theta 1} \quad (2)$$

which will reduce to:

$$R = W(\theta, c) N_c / N_w \quad (3)$$

where c and w refer to "cold" and "warm" data respectively.

Instead we define the ratio:

$$R_\theta = R/R_0 \quad (4)$$

so that the unknown beam-rate ratio N_c/N_w is eliminated. Then, the anisotropies at different angles θ can be given with respect to 0° , as shown below:

$$A(\theta) = 1 - W(\theta, T)/W(0, T) \quad (5)$$

Experimentally it is convenient to choose the ratio of this function in the following way:

$$A(\theta) = 1 - \frac{[N(\theta, c)/t(\theta, c)] [N(0, c)/t(0, c)]}{[N(\theta, w)/t(\theta, w)] [N(0, w)/t(0, w)]} \quad (6)$$

where θ refers to six possible 45° or 90° positions and 0 means 0° or 180° . Due to differences of dead time of each detector, live times should be known quite accurately. The errors on $N(\theta, T)$ include statistical uncertainties as well as additional uncertainties introduced in background correction and peak fitting. The advantage of the present system is that, from any pair of $A(90^\circ)$, it is possible to directly obtain the values of $a_2(=B_2U_2A_2)$ and $a_4(=B_4U_4A_4)$ where A_k and U_k for $k=2$ and 4 refer for gamma radiation to directional distribution and deorientation coefficients, respectively. Furthermore, by averaging results from pairs of diametrically opposite detectors, systematic effects associated with movement of the beam are reduced. For example, averaging a_k calculated from $A(45^\circ)$ and $A(90^\circ)$ with a_k calculated from $A(45^\circ)$ and $A(270^\circ)$, we correct for movement along the line connecting the 90° and 270° detectors.

In the six-detector system now in use, it is possible to obtain a_k from 8 different combinations of detectors (0° or 180° ; 90° or 270° ; 45° or 225°). In these eight combinations, each detector is used four times, so in the final statistical average of the eight a_k values, the uncertainty is increased by $\sqrt{4}=2$. In the final analysis, if the orientation coefficients, B_k , are known from information based on the parent ground state, the main source of error on distribution coefficients, A_k , then would be due to those

of U_k coefficients.

3. The On-Line Nuclear Orientation of ^{191}Hg

The nuclide ^{191}Au , which has a $j=3/2$ ground state and lies in a region of even-even nuclei with a $O(6)$ symmetry (24) was chosen for the first UNISOR/NOF on-line experiment to determine whether its low-lying spectrum could be described by this classification scheme.

The excited states of ^{191}Au , studied by radioactive decay of the ^{191}Hg high spin isomer ($T_{1/2}=51$ min) were produced by using a 110 MeV C beam from the HHIRF Tandem on natural W target. Throughout the experiment the beam intensity was 2×10^5 ion/sec at the target. The data were collected in eight cycles. Beam was allowed on the target when the target was about 1 K and was deposited for $\approx 1/2$ h in each cycle. Then the gate valve controlling the beam access was closed and the target was cooled down to base temperature. At this temperature, cold data was collected for two hours. Data were acquired from six detectors placed at 0° , 45° , 90° , 180° , 225° , and 270° in 12-14 runs, each of 10 min duration. At the end of each cycle, the sample foil was replaced by a new iron foil in order to avoid the buildup of daughter activity. The activity was collected on the target while warm data was being taken. At the end of this period, the beam was shut off by a gate valve, and the target was allowed to cool for about 30-40 mins.

The 102 transitions observed in ^{191}Au are currently under analysis.

4. Conclusion

The UNISOR/NOF system has now successfully demonstrated a new

design for on-line nuclear orientation refrigerators whereby the beam enters the system from the bottom. The option of placing detectors at 45° angles around the target, a unique feature of the system, enables us to determine uniquely the transition moments, and reduces some of the systematic errors such as count rate fluctuations due to beam movement, changes in distance between the sample holder and the bottom 90° detector due to thermal contractions, etc. This feature also enhances the counting statistics due to the number of detectors available. The technical changes necessary to achieve this extra feature did not by any means affect the performance of the refrigerator, nor will they affect the incorporation of a NMR system and particle detectors, but unambiguous determination of multiple mixing ratios with a high degree of accuracy will enhance our understanding of nuclear structure.

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Figure Captions

Fig. 1 A schematic comparison of fully on-line systems.

Fig. 2 An overall view of the UNISOR/NOF experimental set-up.

TM; HHIRF 25MV Tandem, IS; modified FEBIAD ion source, MS; mass separator 90° bending magnet, ED; 90° electrostatic deflector, QL; quadrupole triplet lense, CBT; cold beam tube, SM; superconducting polarizing magnet, T; ferromagnetic target foil, DR; dilution refrigerator.

Fig. 3 The bottom beam access to ^3He - ^4He refrigerator.

1; mixing chamber, 2; target, 3; superconducting magnet (1.5T), 4; room temperature shield, 5; 77K shield, 6; 4K shield, 7; iris, 8; iris controller.

LEUVEN

1 - 0
3 - 90

5,6 cm

• 0.5, 1.5 T
vertical

ON-LINE SYSTEMS DARESBUY/NICOLE

NO OF DETECTORS

2 - 0
2 - 90

SOURCE TO DETECTOR DISTANCE

7 cm

MAX. MAGNETIC FIELD & DIRECTION

1.5 T
horizontal

FIRST ON-LINE IMPLANTATION

UNISOR/NOF

2 - 0
4 - 45
2 - 90

9 cm

1.5 T
horizontal

UNISOR OLNO FACILITY

ORAU 8761.1

THE BOTTOM ACCESS