CERN/ISC 91-11
ISC/P8
31 July 1991

Proposal to the ISOLDE Committee

Tilted-Foil Polarization and Magnetic Moments of Mirror Nuclei at ISOLDE

Rehovot[1] - CERN[2] - Oxford[3] Collaboration

C. Broude[1], G. Goldring[1], H. Haas[2], M. Hass[1], M. Lindroos[a],
P. Richards[3], J. Rikovska[3] and N. Stone[3]

Spokesman: M. Hass

Contactman: H. Haas

---

[a] Chalmers University of Technology, Goteborg, Sweden

SUMMARY

We propose a research program for measuring magnetic moments of ground states of mirror nuclei using the tilted foil nuclear polarization (TFP) method at ISOLDE. The TFP method has the potential to measure magnetic moments of nuclear ground states for all non-zero values of I. It is particularly suitable for light elements for which the polarization can easily be preserved in the catcher foil for tens of seconds and/or for nuclei with relatively short lifetimes. These are exactly the cases where low temperature nuclear orientation is not applicable because of the need for spin-lattice relaxation to take place within the nuclear lifetime and also since it has certain implant/host combination limitations imposed by the requirement of large hyperfine fields. Thus the TFP method has the potential to fill an important gap.

Our first goals are to measure the magnetic and quadrupole moments of ^{23}Mg. This experiment will allow us to determine the level of induced polarization by the TFP process and to bring the experimental set-up (300kV high voltage platform, superconducting magnet, detectors etc.) to its optimum performance.

We then plan to focus our attention on T=3/2, I=5/2 nuclei in the sd shell such as the A=19 and A=21 multiplets. The possibility also exists to carry out experiments with nuclei in the f shell, provided sufficient acceleration can be achieved. The information we expect to obtain will serve as an important test of the shell model picture for these "exotic" nuclei.

Additionally, examination of the magnitude of the polarization can be analyzed to provide information regarding ß-decay matrix elements, for example, the ratios of Gamow-Teller to Fermi matrix elements. The solid state aspect of our proposal can be very fruitful and is, to a large extent, independent of the nuclear program. We plan to commence this phase of the project once the experimental set-up is tested and the physical parameters are better established.

1. INTRODUCTION

The study of nuclei around N=Z is one of the major topics in the field of nuclear physics far-from-stability. In particular, the measurement of g-factors of ground states in pairs of mirror nuclei and the construction of sums and differences of such moments can provide direct information on the isovector and isoscalar parts of the nuclear current. The combination of a radioactive beam facility with the tilted-multifoil method allows the production of such nuclei, their subsequent polarization and then measurement of the g-factor using the β-NMR technique. An experiment on ^{33}Cl, using these ideas and low-energy nuclear reactions, was recently completed at Rochester[1].

Employing a similar technique at ISOLDE, we propose to extend such studies to other nuclei distant from the valley of stability with an experimental setup as shown schematically in Fig.1. Our first goal is to measure the magnetic moment of ^{23}Mg, the mirror nucleus of ^{23}Na. ^{23}Mg is the only nucleus in the sd shell for which there is no precise measurement of the g-factor whilst its mirror partner is well known. A determination of the electric quadrupole moment should also be possible with the proposed technique.

We want to carry out the measurement of the magnetic and quadrupole moments of ^{23}Mg ($I^{\pi} = 3/2^{+}$, $T_{1/2} = 11$ s) using the $3/2^{+}$ - $3/2^{+}$ allowed β-transition. In a second phase of the experiment, in order to explore the dependence of the magnitude of the polarization by tilted foils on lifetime and spin of the polarized nuclear state, we wish to proceed to ^{21}Mg ($I^{\pi} = 5/2^{+}$, $T_{1/2} = 123$ ms) and measure its, so far unknown, nuclear moments. We then expect to extend these measurements to other T=3/2 mirror nuclei in the sd shell and possibly to the f shell. For these cases virtually nothing is known regarding nuclear moments of ground states. The method, once well developed, can also have important applications to solid-state studies.

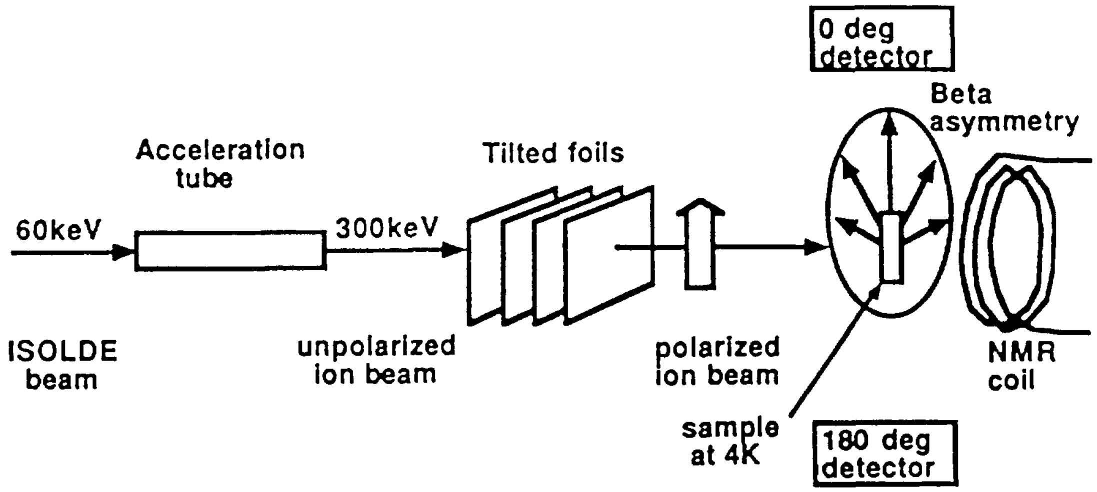

Fig.1: Scheme of experiment

2. OUTLINE OF THE EXPERIMENT

2.1 Tilted foil technique

The Tilted Foil Polarization (TFP) technique has been used successfully to induce in-beam polarization of nuclei at the several percent level [1]. The method is potentially very broadly applicable and is particularly valuable when combined with NMR destruction of the β-anisotropy for the measurement of the nuclear moments of nuclei with lifetime in the range 10^{-3} - 100 seconds.

Polarization is initially induced in ionic electrons by a surface interaction on the exit of an ion from a thin foil, tilted with respect to the ionic beam direction. The electron polarization (which is in the direction $\mathbf{n} \times \mathbf{v} = \xi$ where **n** is the unit vector perpendicular to the outgoing surface of the foil and **v** is the ion velocity vector) is transfered to the nucleus via hyperfine interaction. The effect can be enhanced by the use of several foils, spaced sufficiently apart to allow a significant nuclear precession around the total angular momentum $\mathbf{F} = \mathbf{I} + \mathbf{J}$ in flight between successive foils. Fig.2 shows this process schematically.

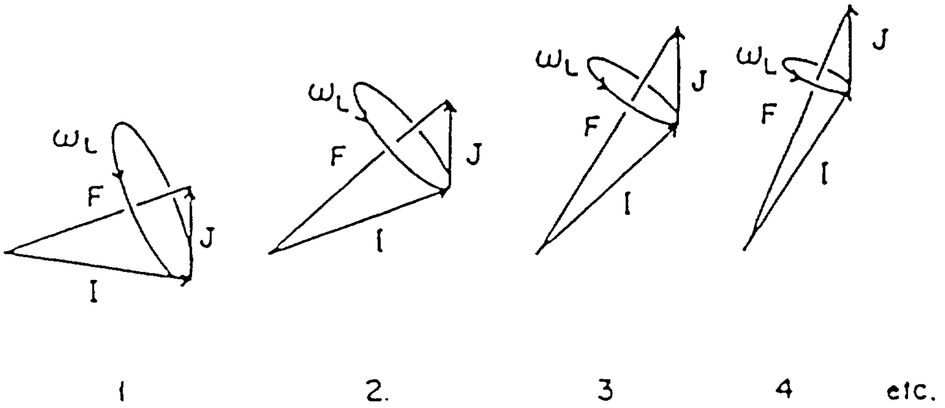

Fig.2: Transfer of electronic polarization to the nucleus in a multifoil array

Tilted foil nuclear polarization has also been used in the past for the measurement of signs of quadrupole moments of high spin isomers [2] and, recently, in a measurement of parity violation in the $17/2^-$ isomer of ^{93}Tc, again a high spin state [3]. In those experiments the ion velocity was generally in the range 0.01c - 0.03 c.

For high I and J the nuclear polarization can be derived to a good approximation in a classical limit, yielding

$$P_I(n)_{cl} = P_I(\infty)_{cl}\{1-e^{-n/n_0}\} \qquad (1)$$

where n is equal to number of foils and

$$n_0 \sim \begin{cases} 3I^2/2J^2 & I >> J \\ 2 & I = J \\ 3/2 & I << J \end{cases} \qquad (2)$$

and

$$P_I(\infty)_{cl} = P_J / \{ (1 - P_J)J/I + P_J \} \qquad (3)$$

where $P_J = <Jz>/J$ is the electronic polarization of the ions after passing one tilted foil. One of the consequences of these equations is that $P_I(n)$ increases with I, provided n is sufficiently large.

For low spins a quantum mechanical approach is needed. It will be sufficient here to consider the extreme case of I=1/2. We have obtained in this approximation

$$P_I(\infty)_{QM} = 3 / [2(J+1)] P_J \qquad (4)$$

Conditions relevant to experiments at ISOLDE differ from the earlier experiments in several important aspects:

1- lower nuclear spin I,
2- lower ion velocity,
3- smaller size, angular divergence and energy spread of the incoming beam,
4- typically higher count rates .

Lower spin will mean (i) lower expected magnitude of nuclear polarization, as P_I is expected to increase with I and (ii) smaller n_0. For the proposed cases (^{23}Mg and ^{21}Mg) it is safe to assume that I is not much larger than J. Thus three foils are all that is required and even one foil may be adequate. It has been found empirically that lower ion velocity should increase the atomic polarization P_J [4]. However, it is difficult to estimate the expected values of P_I, since neither P_J nor the average magnitude of J are known. Extrapolating from available data - not a very reliable procedure especially when data are far away in the parameter space - we estimate for ^{23}Mg:

$$P_J = 0.05\text{-}0.15$$
$$< J > = 2\text{-}3$$

and consequently

$$P_I(\infty) = 0.02 - 0.07.$$

Even at the lower end of this range, the polarization should be easily measurable with the expected counting statistics.

After passing through the last foil the ion is stopped in a catcher lattice of cubic symmetry free of internal fields cooled to a low temperature and placed in a "holding" magnetic field B_{ext} (~ 0.1T), in the direction of ξ, in order to preserve the polarization along a well defined axis during the nuclear decay. The combination of catcher temperature and holding field is chosen to make the depolarization time long compared with the nuclear lifetime.

2.2 Beta Asymmetry.

A suitable measure of the nuclear polarization is the spatial anisotropy of the emitted radiation. A general expression for the distribution from an axially symmetric nuclear ensemble is [5]

$$W(\theta) = \Sigma_\lambda B_\lambda A_\lambda P_\lambda(\cos\theta) \qquad \lambda = 0,1,2,3......... \qquad (5)$$

Generally only even terms arise for parity conserving radiations, however for polarized nuclei (e.g. by TFP) the leading term in (5) is

$$W(\theta) = 1 + B_1 A_1 \cos\theta. \qquad (6)$$

Such a distribution can be detected using (parity non-conserving) beta decay (but not e.g. gamma decay). Under certain very general simplifying assumptions concerning the beta decay Hamiltonian [5] and for allowed and most first forbidden beta transitions the distribution is as in eqn 6.

The coefficient A_1 involves angular momentum coupling coefficients and the particle parameters b_1 [5]. The orientation parameter B_1 depends upon the populations a_m of the nuclear substates I_m i.e.

$$B_1 \sim \langle I_z \rangle / I = \Sigma_m m a_m / I. \qquad (7)$$

In TFP the statistical distribution of a_m and its analytic dependence on I, μ and B_{hf} are unknown (in contrast, for example, with nuclear orientation where the a_m have a Boltzmann distribution with $E_m = -\mu B_{hf} m/I$). However, there are specific simple cases for which the A_1 coefficient is known, thus allowing extraction of B_1 from the measurement. Generally it would be very desirable to obtain A_1 coefficients from TFP experiments. Clearly, in the absence of adequate theory, this requires at least a systematic knowledge of the behaviour of B_1. It is still an open question whether, for a given spin value, $B_1(I)$ determined for one isotope can be used in analysis of data on other isotopes of the same spin in the same or neighbouring elements. This is one of the longer term points of interest and necessary investigation for the present project.

2.3 NMR observation

The implanted nuclei in a cubic environment experience a simple Zeeman splitting associated with the holding field B_{ext}. Under the influence of an applied RF field at right angles to B_{ext} resonant absorption at frequency $\nu = \mu B_{ext}/Ih$ will result in destruction of the beta asymmetry. The frequency of the NMR resonance which can be measured to high precision is a measure of the nuclear g-factor. Thus the magnetic moment of the isotope under study can be extracted without detailed interpretation of the observed asymmetry.

In a non-cubic environment the interaction with the electric field gradient will lead to a splitting of the NMR resonance line. Its measurement allows the determination of the nuclear quadrupole moment, if the electric field gradient is known. For many simple solids (e.g. Mg or F in MgF_2 [6,7]) this is the case.

3. EXPERIMENTAL DETAILS

To give to the ions from ISOLDE enough energy for transmission through the several thin foils needed for polarization, the experiment has to be mounted on a high voltage platform at typically 250 kV below ground potential. Such a platform was built and successfully tested during a first run in November 1990. Fig.3 shows the layout of the installation of such a device as it existed at ISOLDE-3. The inner platform of 1 x 1.5 x 2 m^3 was surrounded by a shielding cage of 2.6 x 3.1 x 3.6 m^3. The necessary acceleration tube, high voltage generator, and rotating shaft power generator were available at CERN. Only the mechanical construction had to be built. The experiment was controlled with the ISOLDE GOOSY system by the use of an optical coupling link in the ETHERNET. During the test run the high voltage and data taking systems worked very well after some startup problems and a beam of ^{23}Mg at 0.52MeV was transported through the acceleration tube and focused into the super-conducting magnet. Unfortunately, because of insufficient time, we had to stop at this stage. Given the novelty of working with the HV platform and the short run, we regard this preliminary test as quite successful.

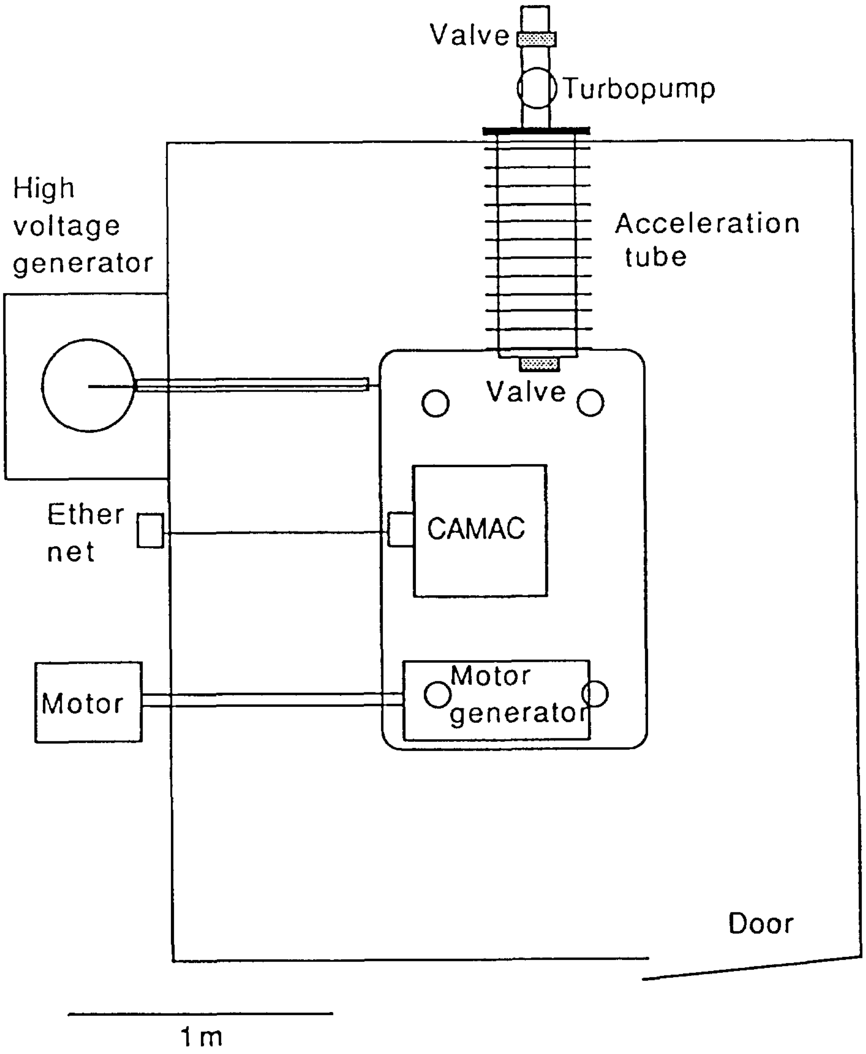

Fig.3: Layout of high voltage platform as installed at ISOLDE-3

At the entry of the foil chamber up to three 5µg/cm^2 carbon covered plastic foils are set at 70^0 to the beam axis. Such foil stacks have been produced at the Weizmann Institute, Rehovot, for many years. The foils are mounted on a carriage which allows rotation by 180^0 about the beam axis to reverse the sense of nuclear polarization. As angular straggling in the foils will lead to a spread of 5^0 of a 300 keV beam, calculated using the program TRIM for the cases to be investigated, the implantation target has to be quite close to the polarizing foils.

The first stage of the proposed experiments will be devoted to investigation of the dependence of the induced polarization on various parameters, like number of foils, tilt angle, and ion velocity. We intend to use ^{23}Mg for this purpose. The information thus obtained will make it possible to optimize the experimental conditions for the more difficult cases of ^{21}Mg and ^{21}F. The polarized nuclei will be implanted into a cubic (MgO) or non-cubic (MgF$_2$) insulator cooled to liquid helium temperature and in a magnetic holding field of ≈ 0.1 T produced by a superconducting Helmholtz coil. It is expected that the nuclear polarization can be preserved for times much longer than the halflife of ^{23}Mg. If, however, a complication due to electronic defects in these insulators were to be encountered, also semiconductors (Si) should be very suitable as implantation matrix. A small RF coil is placed around the sample to allow NMR measurement. Beta radiation will be detected using two detectors placed opposite each other perpendicular to the beam axis.

4. PROPOSED EXPERIMENTS

We intend to pursue this line of research in a project at the Booster ISOLDE facility. The platform and the whole setup will naturally have to be relocated at the new site. ^{23}Mg is the candidate for the first exploratory experiments. Beyond that, we plan a series of experiments on ^{21}Mg, ^{21}F, and other nuclei of T=3/2 in the sd shell.

Brown and Wildenthal [8] have summarized the shell model picture in the sd shell and especially compared the results for the iso-vector and iso-scalar parts of the magnetic moment operator to shell model calculations. The use of either "free-nucleon" or "effective operators" was explored in ref. 8. Our result for ^{23}Mg and, for example, pairs of T=3/2 nuclei such as ^{21}F and ^{21}Mg (I=5/2$^+$) will contribute to the understanding of the shell model structure.

Precise nuclear quadrupole moments of mirror nuclei should lead to a better knowledge of the nucleon orbitals. Up to now experimental data are extremely scarce. In the sd shell Q has been determined only for the pair ^{17}F-^{17}O. At least the pair ^{23}Na-^{23}Mg and perhaps a few others could be measured with the TFP technique in an attempt to map better the theoretical wavefunctions.

Virtually nothing is known regarding magnetic moments of T=1/2 mirror nuclei in the f shell. In our program we expect to be able to study some nuclei at the beginning of the f shell if the HV platform will reach expected voltages of about 500 kV and if one can use doubly charged ions. As a goal for the future, such measurements will be possible throughout the f shell if an additional acceleration element, such as an RFQ device, could be installed at ISOLDE.

5. FUTURE SOLID-STATE APPLICATIONS

The ß-NMR method has the potential to become a very powerful tool for the investigation of condensed matter. Until now only a few probe nuclei have been useful for this method, due to the difficulty in producing polarized nuclei. The only somewhat universal technique is capture of polarized neutrons. Experiments on ^{8}Li, ^{12}B, ^{20}F, ^{110}Ag, and ^{116}In have been successful [9]. The usefulness of this technique for solid state applications is, however, seriously limited by the fact that the samples have to contain a large amount of the element to be studied, thus forbidding the investigation of dilute impurities, otherwise characteristic for the nuclear methods. The exceptions are ^{12}N and ^{12}B, the only nuclei suitably polarized following nuclear reactions [10]. Nevertheless the few applications of the ß-NMR method have demonstrated the power of NMR coupled to nuclear detection. Pioneering studies of nuclear relaxation, diffusion, radiation defects, and glass structure have been performed.

With the development of the tilted foil technique the possibility of obtaining polarized ion beams will open up the wide spectrum of isotopes available at ISOLDE for applications of the ß-NMR technique. Clearly the strength of the method lies with the lighter elements, where spin-lattice relaxation times are sufficiently long for investigations over a wide temperature range. It is difficult, however, to predict which isotopes will be most suitable for condensed matter studies. Exploratory measurements of the beta asymmetries for several of the most interesting cases are necessary before one can discuss a solid state research program with the new technique.

Measurements of the spin-lattice relaxation or Knight shift for light elements in metals are still very scarce. Together with the hyperfine fields in the few ferromagnets they would give direct information on the conduction electron density at the impurity site, one of the few ways to test band structure calculations on a microscopic scale.

The elements of the first two periods are especially important as dopants and impurities in presently used semiconductors and even more so in diamond, one of the semiconductors of the future. ß-NMR could give direct information about electronic and lattice structure, in particular since also the nuclear quadrupole interaction can be measured with NMR accuracy. The further development of beams of the reactive light elements at ISOLDE (B,C,N,O, and Al,Si,P,S) would be of great significance in this respect.

6. CONCLUSION

The outlined TFP method has the potential to measure magnetic moments of nuclear ground states for all non-zero values of I. It is particularly suitable for light ions with short lifetimes for which the polarization can easily be preserved in the catcher foil for tens of seconds. These are exactly the cases where low temperature nuclear orientation is not applicable because of the need for spin-lattice relaxation to take place within the nuclear lifetime and also since it has certain implant/host combination limitations imposed by the requirement of large hyperfine fields. Thus TFP has the potential to fill an important gap.

Additionally the magnitude of the polarization can be analyzed to give information concerning beta decay matrix elements, their ratios and associated coupling constants.

7. BEAM TIME REQUEST

At ISOLDE the yields of ^{23}Mg from a SiC target are several times 10^7atoms/s [11], easily sufficient for the planned experiments. Actually it has been possible to have enough intensity of even the 2+ ions for ^{23}Mg in the test run. Therefore also a measurement at least up to 720 keV energy will be possible in order to learn more about the TFP process as function of energy. The intensity of ^{21}Mg has not been measured yet. From the SiC target a production in the order of 100 atoms per second may be expected. The necessary separation from the strong contaminating beam of ^{21}Na, possible with the High Resolution Separator, is essential for a measurement of this nucleus.

We intend to run the initial experiments with the SiC target coupled to the hot plasma source. This will allow to produce most of the ions necessary for the present proposal. A total of 4 runs of 9 shifts each should be sufficient for a first series of exploratory measurements. The feasibility of the ^{21}Mg measurement can only be judged after this. Naturally time for testing the high voltage platform with stable beams will be necessary several weeks before the first experiment.

8. REFERENCES

[1] W.F.Rogers, D.L.Clark, S.B.Dutta and A.G.Martin, Phys.Lett. B177 (1986)293 and references therein.

[2] E.Dafni, J.Bendahan, C.Broude, G.Goldring, M.Hass, E.Naim, M.H.Rafailovich, C.Chasman, O.C.Kistner and S.Vajda, Nucl. Phys A443(1985)135

[3] C.Broude, G.Goldring, M.Hass, N.Takahashi, S.Hoffmann, F.P.Hessberger and V.Ninov, Z. Physik A336 (1990) 134.

[4] G.Goldring, M.Hass and E.Dafni, Hyperfine Interactions 33(1987)19

[5] K.S.Krane in Low Temperature Nuclear Orientation, eds. Stone and Postma, North Holland (1986), Chapter 2, p.94 and seq.

[6] Y.Hiyama, P.M.Woyciesjes, T.L.Brown and D.A.Torchia, J. Magn. Resonance 72(1987)1

[7] F.W. Richter and D. Wiegandt, Z. Physik 269(1968)225

[8] B.A. Brown and B.H. Wildenthal, Ann. Rev. Nucl. Part. Sci. 38 (1988) 29 (1988).

[9] H.Ackermann, P.Heitjans and H.-J.Stoeckmann, Hyp. Int. 24/26 (1985) 395.

[10] T.Minamisono et al., Hyperfine Interactions 15/16 (1983) 547.

[11] E.Hagebo, P.Hoff, O.C.Jonsson, E.Kugler, H.L.Ravn, K.Steffensen and S.Sundell, in: Proc. of Workshop on Nuclei Far from Stability, Obernai (F), 1989