^{23}Na, ^{27}Al, and ^{51}V Multinuclear NMR-Imaging and NMR-Spectroscopy with a 1.5 T Imager

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Nuclear magnetic resonance imaging has been performed with the nuclei ^{27}Al, ^{51}V, and ^{23}Na in some test objects with a 1.5 T imager. Encouraging signal-to-noise ratios have been obtained within reasonable measuring times in the imaging and the spectroscopy mode using a commercially available ^{23}Na headcoil.

NMR imaging with protons at magnetic fields up to 2 Tesla is now a well established method for diagnostic purposes of humans and animals [1]. Also in material research the NMR tomography with the hydrogen nucleus has been applied in some cases, e.g. [2]. The use of other nuclei has found – with the exception of ^{23}Na [3] – nearly no attention till now. The reason for this may be the low concentration of other elements in human and mammalian tissue and the smaller NMR sensitivity compared with protons. In addition the nonavailability of the hardware to the imagers for the lower frequencies of the heteronuclei plays also an important role in this context, for imaging as well as for spectroscopy with imagers.

In the following we report on some NMR investigations using the nuclei ^{23}Na, ^{27}Al and ^{51}V in the imaging and also in the spectroscopy mode of a 1.5 T imager. The NMR parameters important for the experiments are given in Table 1. An inspection of the low NMR receptivities for these nuclei compared with that of water protons reveals that it seems to be a rather hard task to obtain NMR images with these nulcei. Indeed the results for ^{23}Na of Hilal et al. [3, 4] confirm this assumption. Our experience with heteronuclear NMR spectroscopy using conventional FT-NMR spectrometers [5, 6] and also the 1.5 T imager [7] encouraged us to extend the NMR-FT imaging method to quadrupolar heteronuclei.

The experiments have been performed with a Siemens Magnetom whole body imaging system working with a superconducting magnet loaded to a magnetic induction of 1.5 Tesla. A head coil with a diameter of 25 cm which is a commercial product by Siemens, Erlangen, and which is prepared for sodium imaging has been used for the ^{23}Na measurements. It can also be tuned to the lower Larmor frequencies of ^{27}Al and ^{51}V to produce NMR images of these nuclei, too. We employed it in combination with the manufacturer supplied sodium spin echo sequence which makes use of the gradient echo refocusing technique resulting in a minimum echo time T_E of 8 ms. The spectra have been taken with the help of the usual Fourier NMR method.

In Table 2 the composition of the aqueous solutions for the imaging samples are given; they have been selected on the basis of results of earlier measurements of relaxation times and chemical shifts for ^{23}Na, ^{51}V [8] and ^{27}Al [9] to meet the requirements of imaging and large volume spectroscopy. The control and reference data presented in Table 2 have been obtained with a Bruker SXP 4-100 multinuclear FT-spectrometer and an externally stabilized iron magnet working at 2.1 Tesla [5]. T_1 and T_2 have been determined using the inversion recovery method and the multiecho Carr-Purcell-Meiboom-Gill technique, respectively.

As indicated in Table 2, the ^{51}V and ^{27}Al spectra show two signals with very different intensities and chemical shift differences of 23.8 ppm, 21.3 ppm,

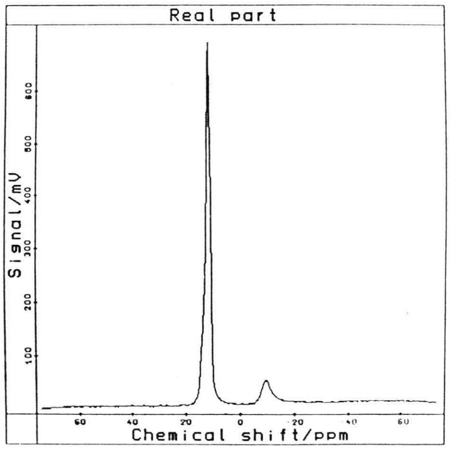

Fig. 1. ^{51}V-spectrum of sample 3 (800 ml) measured with the 1.5 T imager and a ^{23}Na headcoil. The signals arise from the VO_4^{3-} (large component) and the $V_2O_7^{4-}$ species. The chemical shift difference amounts to 21.3 ppm (see also Table 2). Experimental parameters: 32 acquisitions; measuring time: 20 sec.

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Table 1. NMR parameters for ^{23}Na, ^{27}Al, and ^{51}V; the NMR receptivity is given for 150 mmolal aqueous solutions taking the proton signal as 1 (without taking into account the relaxation times).

Nucleus	Natural abundance	Larmor frequency at 1.5 T	NMR receptivity	Spin	Quadrupole moment [10^{-28} m^2]
^{23}Na	100%	16.82 MHz	1.25×10^{-4}	3/2	+ 0.10
^{27}Al	100%	16.57 MHz	2.92×10^{-4}	5/2	+ 0.15
^{51}V	99.76%	16.71 MHz	5.15×10^{-4}	7/2	− 0.052

Table 2. The samples used in this work and some spectroscopic results obtained with the SXP-spectrometer at 2.1 T; the errors of the relaxation times amount to some percent.

Sample	Longitudinal relaxation time T_1	Transversal relaxation time T_2	Chemical shift $(a-b)$/ppm
1 NaCl 154 mmolal isotonic solution	^{23}Na: 58 ms	55 ms	–
2 $NaVO_3$ 140 mmolal in NaOH; pH = 12.4	^{23}Na: 49 ms ^{51}V: a) 14 ms b) 10 ms	39 ms – –	– 23.8
3 $NaVO_3$ 150 mmolal in 1 molar NaOH	^{23}Na: 44 ms ^{51}V: a) 41 ms b) 11 ms	28 ms – –	– 21.3
4 $Al_2(SO_4)_3$ 350 mmolal	^{27}Al: a) 39 ms b) –	32 ms –	3.6

and 3.4 ppm. Large chemical shifts are typical for heteronuclei, so the demands on the homogeneity of the magnetic field are not so strong. A typical ^{51}V NMR spectrum of sample 3 taken with the 1.5 T Magnetom imager is given in Figure 1 together with some experimental parameters. In view of the signal-to-noise ratio it is obvious that imaging must also be possible. In Figs. 2, 3, and 4 the results of NMR imaging with ^{23}Na, ^{51}V and ^{27}Al of some test objects specified in the legend are presented. The signal-to-noise ratios given have been determined by dividing the average pixel intensities of the areas in question.

From the quality of the images and the data derived it can be concluded that NMR imaging using these heteronuclei will find applications in material research as well as in biosciences.: Aluminium and vanadium are very common elements in inorganic and physical chemistry and their nuclei can be utilized for nondestructive evaluation of materials, for investigations of systems with different phases etc. As recently found, vanadium plays also a role in enzymes [10, 11] wereas aluminium is brought into connection with Alzheimer's disease [12, 13] and further has a strong impact on dialyse patients [14].

The NMR results obtained with these heteronuclei are very encouraging. Certainly the use of these NMR methods will find promising applications in the future. Further work in this field is in progress.

Acknowledgements

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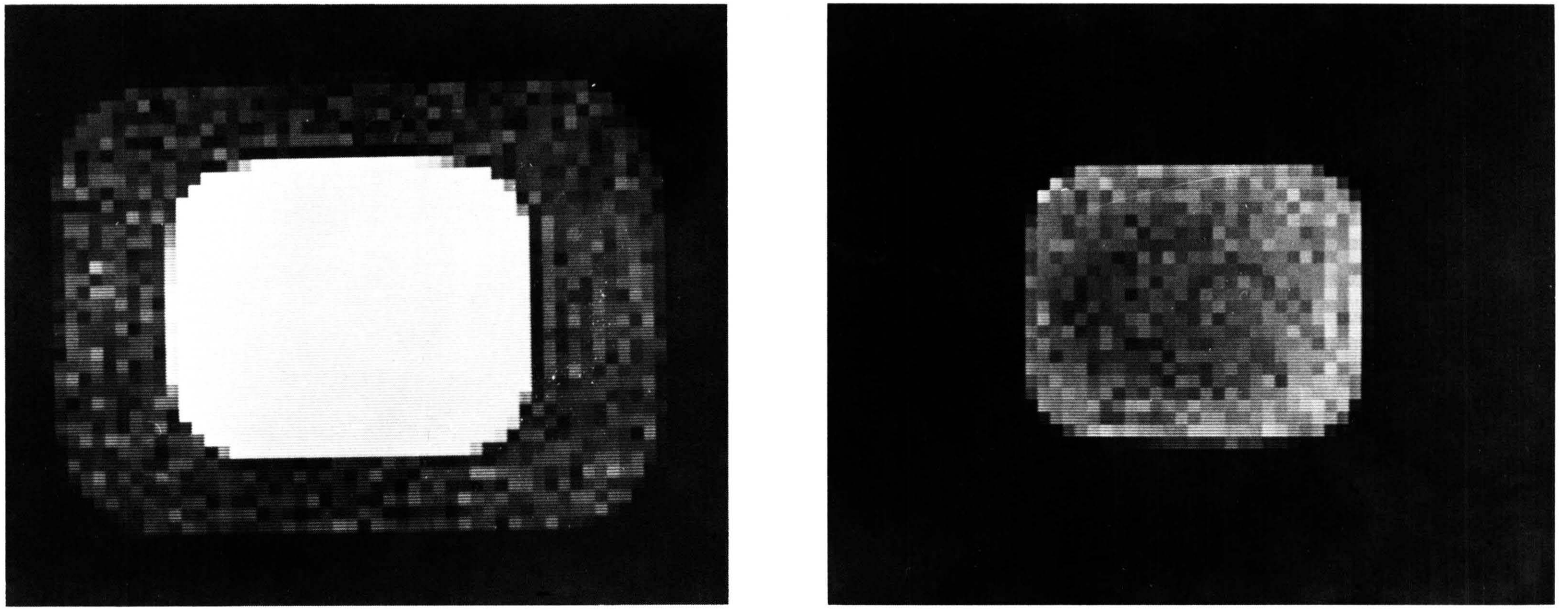

Fig. 2. NMR images using the nuclei ^{23}Na (left) and ^{51}V (right) of a rectangular bottle of sample 3 in a tub filled with sample 1. – Experimental parameters: $T_R = 100$ ms, $T_E = 8$ ms, slice thickness: 20 mm, horizontal slice orientation; 64 × 64 matrix; 192 acquisitions; total measuring time: 20 min; signal-to-noise ratios: ^{23}Na: 18:1 and 3.5:1, respectively, ^{51}V: 11:1. Note that the relaxation times in sample 2 are very short (see Table 2). This figure demonstrates the usefulness of the fast imaging method.

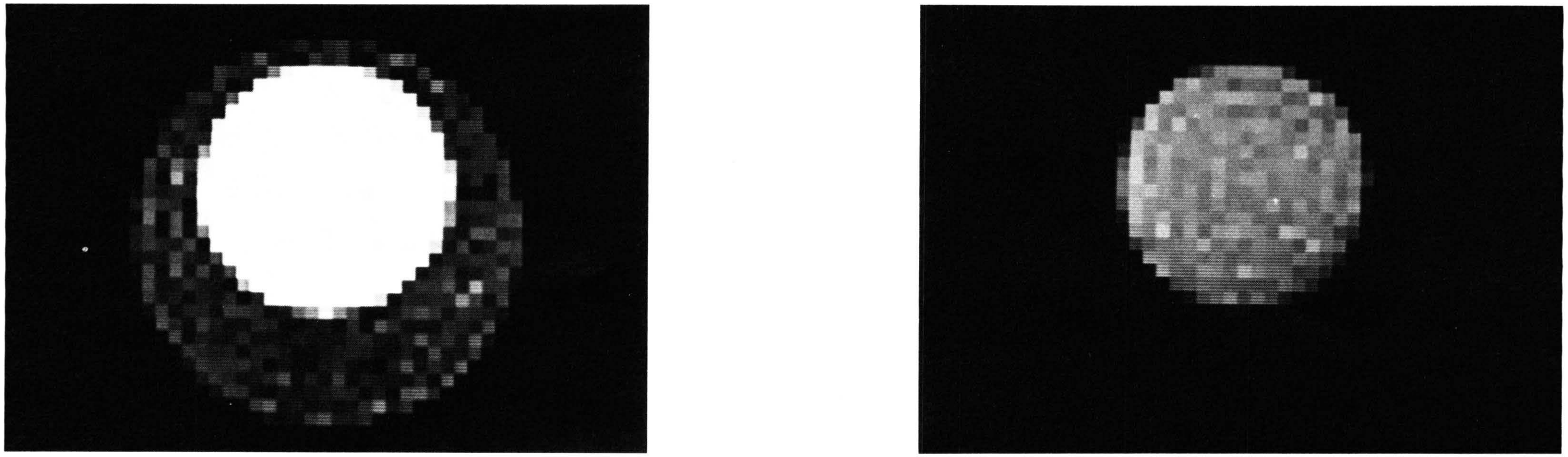

Fig. 3. NMR images using the nuclei ^{23}Na (left) and ^{51}V (right) of a 250 ml bottle (∅ 60 mm) of sample 2 in a cylinder (∅ 90 mm) filled with sample 1. Experimental parameters: $T_R = 100$ ms, $T_E = 8$ ms, slice thickness: 30 mm, horizontal slice orientation; 64 × 64 matrix;80 acquisitions; total measuring time: 8 min; signal-to-noise ratios: ^{23}Na: 10:1 and 5:1, respectively, ^{51}V: 9.5:1.

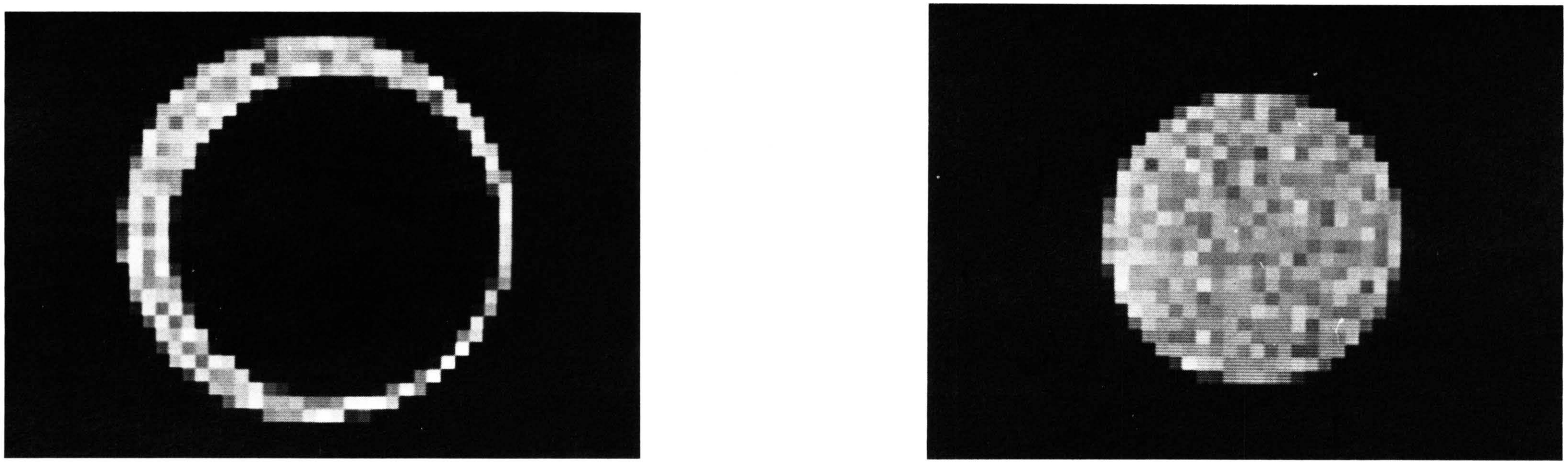

Fig. 4. NMR images using the nuclei ^{23}Na (left) and ^{27}Al (right) of a 250 ml bottle (∅ 73 mm) containing sample 4 in a cylinder filled with sample 1. Experimental parameters: $T_R = 100$ ms, $T_E = 8$ ms, slice thickness: 30 mm, horizontal slice orientation; 64 × 64 matrix; 128 acquisitions; total measuring time: 13 min; signal-to-noise rations: ^{23}Na: 6.5:1, ^{27}Al: 6.5:1.