IN-BEAM NUCLEAR MAGNETIC RESONANCE OF \( \beta \)-ACTIVE NUCLEI PRODUCED BY CAPTURE OF POLARIZED NEUTRONS - SOME NEW APPLICATIONS

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To cite this version:

H. Ackermann, B. Bader, P. Freiländer, P. Heitjans, G. Kiese, et al.. IN-BEAM NUCLEAR MAGNETIC RESONANCE OF \( \beta \)-ACTIVE NUCLEI PRODUCED BY CAPTURE OF POLARIZED NEUTRONS - SOME NEW APPLICATIONS. Journal de Physique Colloques, 1982, 43 (C7), pp.C7-305-C7-308. <10.1051/jphyscol:1982744>. <jpa-00222351>

HAL Id: jpa-00222351
https://hal.archives-ouvertes.fr/jpa-00222351
Submitted on 1 Jan 1982

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IN-BEAM NUCLEAR MAGNETIC RESONANCE OF β-ACTIVE NUCLEI PRODUCED BY CAPTURE OF POLARIZED NEUTRONS - SOME NEW APPLICATIONS


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Abstract. - By capture of polarized thermal neutrons in matter spin polarized, β-active nuclei were produced. The directional asymmetry of their β-radiation was used to detect their nuclear polarization, spin-lattice relaxation and nuclear magnetic resonance (NMR) signals. The peculiarities of the method compared to conventional NMR and some new developments and applications are described.

Polarized neutrons are customarily used in scattering experiments in order to investigate condensed matter properties. It is the purpose of this paper to demonstrate the capacity of another method based on the capture of polarized neutrons /1,2/.

By capture of polarized neutrons sample nuclei $^{20}\text{F}$ can be transmuted to polarized nuclei $^{20}_{20}\text{F}$ of the same element. In practice, the number of the produced nuclei $^{20}_{20}\text{F}$ is vanishingly small and their use as probe nuclei is only possible if a subsequent β-decay $^{20}_{20}\text{F} \rightarrow ^{20}_{21}\text{F}$ occurs which can be used as sensitive means of detection. For some nuclides $^{20}_{20}\text{F}$ the β-radiation distribution has a considerable directional asymmetry $a_0$ with respect to the nuclear polarization. $a_0$ thus reflects directly the degree of the nuclear polarization and can be used to detect any changes of it due to spin-lattice relaxation (SLR), reorientation in crystal fields or NMR transitions. Examples of well-suited nuclides are $^{6}\text{Li}(T_{1/2}=7.84 \text{ s}), ^{12}\text{B}(20 \text{ ms}), ^{20}_{20}\text{F}(11 \text{ s}), ^{110}_{109}\text{Ag}(24.6 \text{ s})$ and $^{116}_{15}\text{In}(14 \text{ s})$. The β-decay lifetimes are in the region ms...min and SLR times $T_1$ must be in the same range or longer that a nuclear polarization can be detected. Typical sample volumes are in the range of 1 to 5 cm$^3$.

The initial degree of polarization of the probe nuclei $^{7}\text{Li}$ is solely determined by properties of the capture process and hence independent of the Boltzmann factor, i.e. of magnetic induction B and temperature T. Thus, low B fields and high T values may be accessible in cases where conventional NMR encounters severe difficulties. Further, SLR times can be measured via transients of the asymmetry $a_0$ after activation pulses without irradiation of rf fields. This avoids skin effect problems and allows the investigation of aggressive materials in sealed metallic containers. Another peculiarity to be mentioned here is the fact that the probe nuclides $^{20}_{20}\text{F}$ and $^{116}_{109}\text{Ag}$ possess nuclear quadrupole...
moments contrary to the stable fluorine and silver nuclei and the observation of crystal electric gradients becomes possible.

Neutron capture is a "soft" process compared to nuclear reactions with fast particle beams. Nevertheless, the prompt capture-γ radiation imparts to the activated nuclei a mechanical recoil or ionizes their electronic shell which leads to the production of point defects. If they live sufficiently long to interact with their nearby probe nuclei the defects can be microscopically studied.

In the following some new applications are presented which essentially use the just listed peculiarities.

Fig. 1. Field dependence of \( T_1(\delta) \) in \((\text{SiO}_2)_{0.67}(\text{Li}_2\text{O})_{0.33}\) glass for various temperatures. The lines are fits assuming \( T_1 \propto B^\beta \), yielding \( \beta \approx 1 \).

The possibility to measure SLR times \( T_1 \) at low B fields was a precondition to observe the B dependence of \( T_1(\delta) \) in Li silicate glass (Fig. 1). \( T_1 \) was found to be approximately proportional to B in the range 14...830 mT. This result, together with a linear dependence of \( T_1^{-1/4} \) in the range 6...170 K, was tentatively explained by the assumption that SLR in the low temperature regime is caused by quadrupolar coupling of Li to a nearby two-level system /3/.

The observation of SLR in liquid Li-Bi alloys requires high temperatures. To this end the very reactive material was sealed in Nb containers. In Fig. 2 \( T_1 \) results at \( T = 1500 \) K, plotted as \( (T_1)^{-1/2} \) versus the Bi concentration are shown.

Near the composition \( \text{Li}_0.75\text{Bi}_{0.25} \) a marked minimum (maximum of \( T_1 \)) occurs. It can be explained by incipient electron localization and compound formation /4/. The effect is stronger than in the melt \( \text{Li}_{0.8}\text{Pb}_{0.2} \) studied earlier /5/.

The two following examples make use of a recent refinement of the method allowing the separate observation of different classes of the same activated nuclide. Differently behaving classes may be caused by different defect configurations near the probe nuclei or by diffe-

Fig. 2. Concentration dependence of \( (T_1)^{-1/2} \) of \( \delta \) Li in liquid Li-Bi alloy.
rent crystal lattice sites being occupied by the activated probes. The distinct observation is based on the possibility to selectively depolarize one class by a strong rf field. So its contribution to $a_\beta$ is suppressed, it becomes "invisible" in the measurement /6,7/.

In the silver halides AgF, AgCl and AgBr we used $^{110}\text{Ag}$ as activated probe nucleus. Due to effects of the prompt capture-\(\gamma\) radiation the neutron activation process can create point defects in the vicinity of the $^{110}\text{Ag}$ nuclei.

One observes two classes: $^{110}\text{Ag}$ nuclei on undisturbed lattice sites corresponding to a NMR Larmor frequency $\omega_L$, and $^{110}\text{Ag}$ nuclei with nearby defects disturbing the resonance at $\omega_L$. The relative number of the defect disturbed $^{110}\text{Ag}$ spins as a function of $T$ is shown in Fig. 3 for AgCl and AgBr. From the annealing stages migration enthalpies can be derived.

![Fig. 3: Defect annealing stages in AgCl and AgBr crystals](image)

The superionic conductor Li$_3$N represents another example where two spin sorts with different behaviour occur. The Li$_3$N crystal consists of alternating Li$_2$N and Li planes whose Li ions are labelled Li(2) and Li(1), respectively. In the range $200 \, \text{K} \leq T \leq 300 \, \text{K}$ the dominant relaxation mechanism is due to intralayer diffusion of the Li(2) ions. One observes two $\delta$Li relaxation times differing by typically one order of magnitude (Fig. 4).

The short $T_1$ may be attributed to the Li(2) nuclei and should allow the study of low-dimensional diffusion.

This work is sponsored by the Bundesministerium für Forschung und Technologie.
Fig. 4. Transients of the asymmetry $a_0$ of $^8$Li in Li$_3$N. The solid line represents a two-exponential fit yielding two relaxation times. ($T = 239$ K, $B = 300$ mT)

References

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