$^{80m}$Br/$^{80}$Br - A new electron-gamma PAC Probe

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Conversion electron - gamma PAC measurements of the 49 keV - 37 keV cascade in $^{80}$Br through the intermediate $2^-$ state with $T_{1/2} = 7.4$ ns were performed with a system of two magnetic lens spectrometers and two BaF$_2$ scintillation detectors. The parent $^{80m}$Br activity with half-life of 4.4 hrs was implanted into Ni, Zn and graphite at the ISOLDE separator at CERN. The observed interaction frequency in the nickel matrix is in good agreement with the known value of the hyperfine field for Br in Ni and the magnetic moment of the $2^-$ state. From the measured quadrupole interaction in Zn and graphite the electric field gradients at Br were obtained.

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Introduction

Gamma – gamma perturbed angular correlation (PAC) spectroscopy has over the last decades been widely applied to studies of impurities in metals, semiconductors, superconductors, biomolecules, surfaces and various other materials. The use of this technique is limited, however, by the available fairly small number of isotope with suitable decay characteristics and sufficiently long parent halflife. On-line isotope implantation experiments can, in principle, give access to many new source isotopes of very short halflife. For a widespread application in solid state research these are, however, generally not well adapted.

The use of conversion electrons in PAC spectroscopy has opened already a number of further probe elements with reasonably long parent halflifes for this technique [Cor00]. When coupled to isotope separator implantation, in particular, the study of several previously unused isotopes with low energy highly converted transitions is feasible in this way. We have tested another such case that shows considerable promise for applications in condensed matter research, $^{80m}$Br/$^{80}$Br.

The 49 keV - 37 keV cascade through the intermediate $2^-$ state with $T_{1/2} = 7.4$ ns (see insert in Fig. 1) has already once been used in courageous effort for a gamma-gamma PAC experiment in solid Br$_2$ in order to measure the nuclear quadrupole moment [Taq78]. Due to the high conversion coefficient of the 49 keV transition the measurement had only rather poor statistical accuracy, in spite of the several weeks of counting time.

Experimental

In our experiments the $^{80m}$Br activity with halflife of 4.4 hrs was obtained from the ISOLDE separator at CERN by irradiation of a heated Nb or ZrO$_2$ target coupled to a high-temperature plasma ion source. The beam of $^{80m}$Br was generally accompanied by $^{80}$Br ($T_{1/2} = 18$ m), $^{80}$Rb ($T_{1/2} = 30$ s), $^{80}$Kr (stable) and a small amount of $^{80}$Sr ($T_{1/2} = 1.8$ h). This mixed isotope beam was implanted at 60 keV into the properly cleaned solids at room temperature. After a few minutes the pure $^{80m}$Br activity, in decay equilibrium with its daughter $^{80}$Br, could be used for the experiments.
For measuring the conversion electron - gamma PAC spectra we have used a system of two magnetic lens spectrometers and two BaF$_2$ scintillation detectors [Cor00] in square planar geometry. The electron spectrum in Fig. 1a recorded with the magnetic lens set to high energy resolution shows a clear peak for the K - conversion of the 49 keV transition. The cleanliness of the PAC spectra obtainable with this instrument can be appreciated from the halflife curve for the intermediate state in Fig. 1b, that extends over three decades. The time resolution of the setup was 2.3 ns, limited by the BaF$_2$ detector of the 37 keV gamma ray. By fitting the decay curve we obtained an intermediate state halflife of $T_{1/2} = 7.5(1)$ ns, in perfect agreement with the previously reported value.

Results

a) Nickel

The perturbation pattern observed in a nickel matrix is shown in Fig. 2. In the Fourier transform one clearly sees the two modulation frequencies with a ratio of 2 to 1, as required for magnetic perturbation. The fitted interaction frequency is

\[ \omega_L = 250 (20) \text{ MHz}. \]
The hyperfine field for Br in Ni is known from a PAC measurement with $^{77}\text{Br}$ [3] and with improved accuracy from a recent nuclear orientation experiment [4] as 7.4 (1) T. The magnetic moment of the 2$^-$ state [5] has been obtained previously by PAD as $-1.67 (12) \mu_B$. Combining these two numbers one calculates an expected Larmor frequency of 293 (20) MHz, in quite good agreement with the one measured here.

It must be noted, however, that only a fraction of about 25% of the implanted Br nuclei see this field. The others apparently come to rest in defective environments that lead to a large spread of high interaction frequencies.

b) Graphite

The perturbation pattern observed following implantation into a highly ordered pyrolytic graphite (HOPG) sample, measured with the cleavage plane in the diagonal of the detector setup, is shown in Fig. 3. Obviously the interaction frequencies due to the quadrupole interaction in this matrix are quite high. The data can be fitted with the assumption of a single unique site taken up by the probe atoms. The pattern is consistent with an axially symmetric electric field gradient (EFG) ($\eta$ less than 0.1) with the z-axis perpendicular to the graphite planes. The fitted quadrupole coupling constant is

$$\nu_Q = 257 (5) \text{ MHz}$$

with a spread $\delta = 8\%$.

The quadrupole moment of the 2$^-$ state has been determined earlier [2]. With a recent recalibration of the reference value for $^{79}\text{Br}$ [6] one gets $Q = 15.9 (5) \text{ fm}^2$.

The identification of the specific lattice site taken up by Br in the hexagonal matrix is not yet possible. The calculated electric field gradient $V_{zz} = 670 \text{ V/Å}^2$, however, is in a region typical for bromine atoms covalently bonded to carbon.

![Fig. 3: PAC spectra for $^{80}\text{Br}$ as implanted into graphite and Zn.](image)

c) Zinc

After implantation into a polycrystalline zinc foil the quadrupole interaction for Br in this matrix leads to the perturbation pattern of Fig. 3. This pattern cannot be due to an unperturbed substitutional site after implantation. Obviously the size and valence misfit leads to a strong trapping of defects at Br. Assuming a distribution of the interaction strength and also a non-vanishing asymmetry parameter the fit shown in the figure can be obtained. The parameters are:

$$\nu_Q = 45 (5) \text{ MHz}, \ \eta = 0.9, \ \delta = 31\%.$$
With this value a tentative number for the EFG at Br in Zn can be quoted as 115 V/Å². From the systematic trend [7] one expects the sign to be negative.

**Outlook**

With the new e-gamma PAC probe tested here several interesting possibilities for applications in solid state research can be envisaged. Bromine is an important impurity in II-VI semiconductors, and the use of PAC has already been demonstrated to give clear information on the local environment in such materials.

The possibility to measure electric field gradients at bromine in simple non-cubic solids opens the possibility to determine also the nuclear quadrupole moments of isomeric states in other Br isotopes. The difficulties encountered in the present work in obtaining a unique site on implantation into metals will require a careful analysis, however.

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**References**