# Pore Size from Multimodal Features of Relaxation Times

A. Afrough[1,3], S. Vashaee[1], L. Romero-Zerón[2], F. Marica[1], B.J. Balcom[1]
[1]MRI Research Centre, University of New Brunswick, Fredericton, Canada,
[2]Department of Chemical Engineering, University of New Brunswick, Fredericton, Canada,
[3]Centre for Oil and Gas – DTU, Technical University of Denmark, Kgs. Lyngby 2800, Denmark

**Introduction:** $T_1$ and $T_2$ measurement methods cannot directly determine pore size. The exact relationship is problematic because of the sample-dependent proportionality constant between $T_1$ and $T_2$ and pore size. We establish that nonground eigenmodes contribute to relaxation in common measurements and exploit multimodal features of relaxation to extract average pore size in bulk and spatially-resolved magnetic resonance measurements.

**Methods:** $T_1 - T_2$ measurements [1] were undertaken for seven rock samples and four glass-bead packs. In addition to bulk measurements, 1D profiles were acquired by Inversion Recovery-prepared Spin Echo Single Point Imaging (IR-SESPI) as a new imaging method. IR-SESPI is composed of two encoding segments of (a) inversion recovery and (b) CPMG echo train, where phase-encoding gradients are applied between the 90° pulse and the first 180° radiofrequency pulse of the CPMG segment. The measured signal $m_+(\tau_1, \tau_2)$ was transformed into a relaxation correlation function $I(T_{1,p}, T_{2,q})$ from which diffusion-relaxation modes were identified. The regularization parameter $\alpha$ in the inversion method of [2] was varied to aid the detection of nonground modes [3]. A direct search optimization method [4] found the average pore size $l$ and surface relaxivities, $\rho_1$ and $\rho_2$, by reproducing eigenmodes detected in $I(T_{1,p}, T_{2,q})$ according to the Brownstein-Tarr solution [5].

**Results and Discussion:** By logarithmically reducing $\alpha$, higher eigenmodes of large $L11$ and small $S11$ pores of Indiana limestone appear at $\alpha = 0.1$, as shown in Fig. 1.The estimated average pore size for large and small pores was respectively 39.6 $\mu$m and 10.0 $\mu$m versus SEM sizes of 50 $\mu$m and 10.1 $\mu$m.

Imbibition of NaCl solution in air-saturated Berea was measured by the IR-SESPI pulse sequence with 16 $k$-space points at $B_0 = 0.05$ T. Analysis for each point in the image space demonstrated a reduction in the pore size from 30 $\mu$m at the inlet end of the sample to 19 $\mu$m at the outlet end. The reduced apparent pore size is due to partially liquid-filled pores in the core plug. Similar analysis was successfully extended to bulk and spatially-resolved measurements in other samples and processes.

**Conclusion:** Nonground eigenmodes are commonly disregarded in the data analysis of magnetic resonance in porous media, even though they have been described for decades. This work clearly demonstrates that nonground eigenmodes contribute to magnetic resonance relaxation measurements. Multimodal features of $T_1$ and $T_2$ were employed to estimate the average pore size. This finding enables reprocessing of a large body of extant experimental data and permits the development of new imaging methods that directly measure pore size.

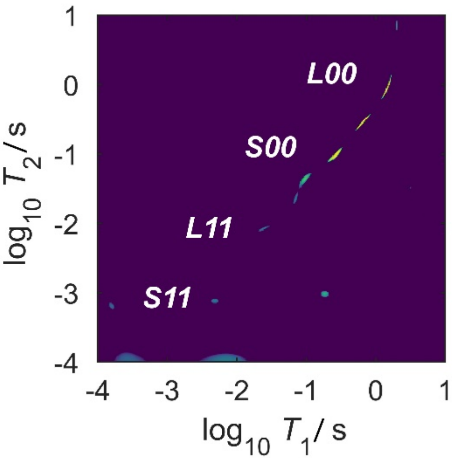


Fig. 1: Nonground relaxation eigenmodes for large $L11$ and small $S11$ pores appear by reducing the regularization parameter to 0.1.

**References:** [1] Song, Venkataramanan, Hürlimann, et al. J. Magn. Reson. (2002). [2] Venkataramanan, Song, Hürlimann, IEEE Trans. Signal Process (2002). [3] Afrough, Vashaee, Romero-Zerón, Balcom, Phys. Rev. Appl. (2019). [4] Kolda, Lewis, Torczon, SIAM Rev. (2003). [5] Brownstein, Tarr, Phys. Rev. A (1979).