Supplemental Materials

Spectroscopic signatures and origin of hidden order in Ba_2MgReO_6

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We present additional resonant elastic x-ray scattering data to augment the data presented in the main text.

First, to demonstrate that E_m and E_q probes different orders, we plot the azimuthal dependence of the (5,5,0) reflection at E_m (top curve in blue, at 6 K) and E_q (bottom curve in red, at 20 K) in Fig. S1. The E_m dependence has a maximum at $\psi = 0°$ and while E_q dependence has a maximum at $\psi = 90°$. Therefore, the azimuthal dependence of the (5,5,0) peak at different temperatures and energies demonstrate that the antiferromagnetic dipolar order and the antiferroic charge quadrupolar order have different symmetries.

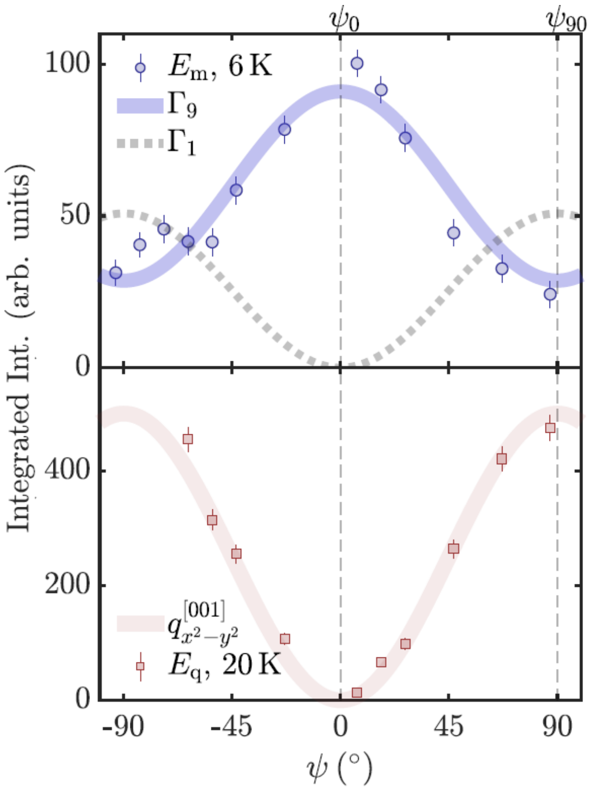

__Figure S1__. Azimuthal dependence of the (5,5,0) peak measured in the σ-π' channel at 6 K and E_m (top) and 20 K and E_q (bottom) to probe the antiferro magnetic and quadrupolar order respectively.

Next, to understand why the magnetic dipolar and charge quadrupolar resonances are so different, we plot in Figure S2 the representative energy scan associated with the magnetic dipoles (in black) and charge quadrupoles (in green). First, we note that the quadrupolar resonance contain a peak at E_m, so the ATS also couples to the Re t_{2g} states, directly. In addition, it also has a strong peak at E_q with a large tail that extends to 10.56 keV. One plausible reason why this long tail occurs is that the charge quadrupoles are more sensitive to the local crystal electric field and hybridization with the ligands which tend to broaden the ATS resonances compared to magnetic dipoles.

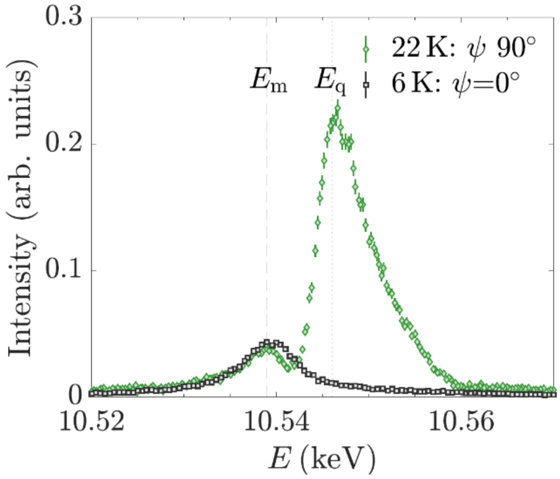

Figure S2. Energy dependence measured in the σ-π' channel at 22 K and ψ = 90° (green curve) and 6 K and ψ = 0° (black curve) for the charge quadrupolar and magnetic dipoles.

To rule out any (extrinsic) azimuthal dependence in Fig. S1 due to, for example, varying beam footprint, we plot in Figs. S3, the azimuthal dependence in the energy scans of the (5,5,0) peak at various azimuthal angles in the σ-π' channel. The low background at off-resonance energies (e.g. 10.5 keV) rules out any extrinsic azimuthal dependence due to varying beam footprint.

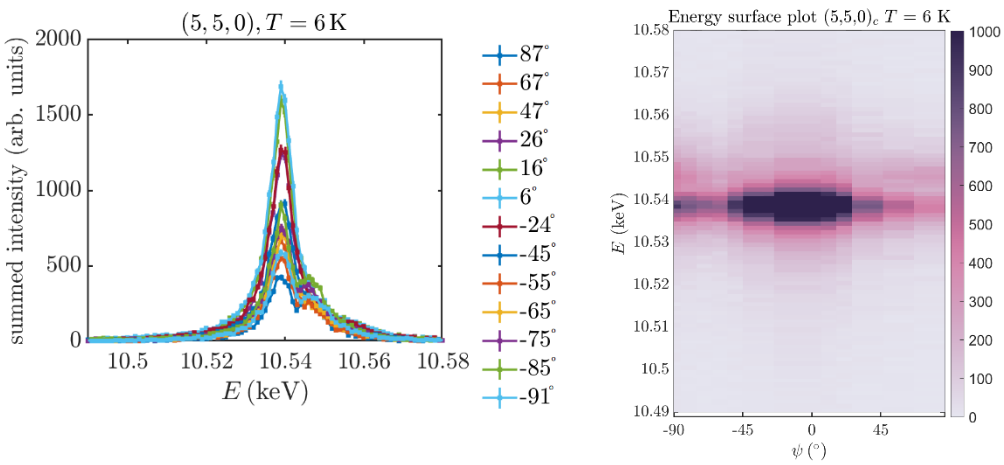

Figure S3. Energy dependence of the (5,5,0) reflection measured at various azimuthal angles at 6 K in the σ-π' channel. (left) line plot. (right) surface plot.

To rule out the leakage of the σ-σ' to the σ-π' channel, we plot the energy dependence of the (5,3,0) peak collected at 6 K in Figs. S4. The σ-σ' channel (red curve) shows a dip whereas the σ-π' channel shows a peak. This is even more apparent in the log scale, which show that the suppression of the charge contribution by at least two-orders of magnitude off resonance. As such the leakage from the σ-σ' channel can be ruled out. This is because, fortuitously the scattering angle of the analyser crystal is very close to 90° degrees.

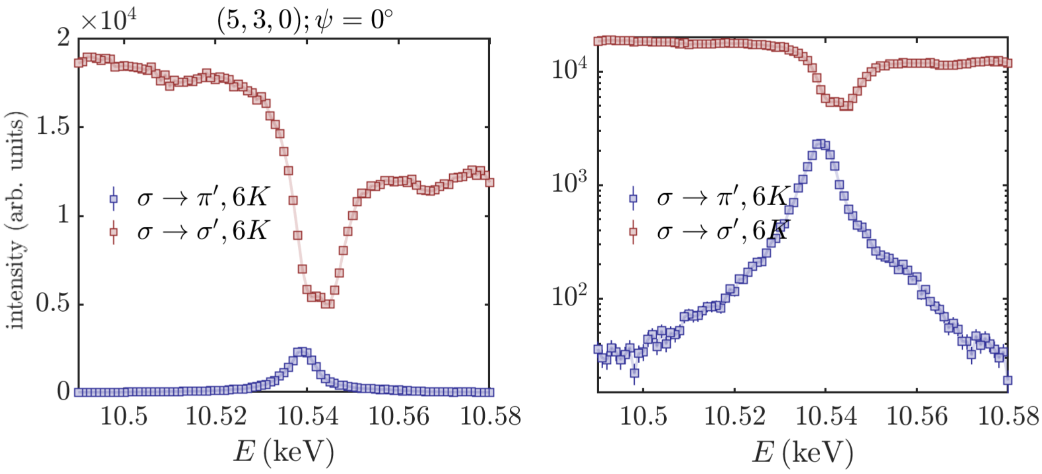

Figure S4. *Energy scan of the (5,3,0) reflection measured in the σ-σ' and σ-π' channels at 6 K. (left) linear and (right) log y scale.*

Indeed, as shown above in Figs. S4, there is a dip in the energy dependence in the σ-σ' channel and a resonant enhancement in the σ-π' channel. We also plot the energy scan of the (10,0,0) peak in the σ-π' channel [Fig. S5], which shows a peak at E_{res} and also a rejection of the leakage from the underlying charge peak at the $E_{non\text{-}res}$ energies.

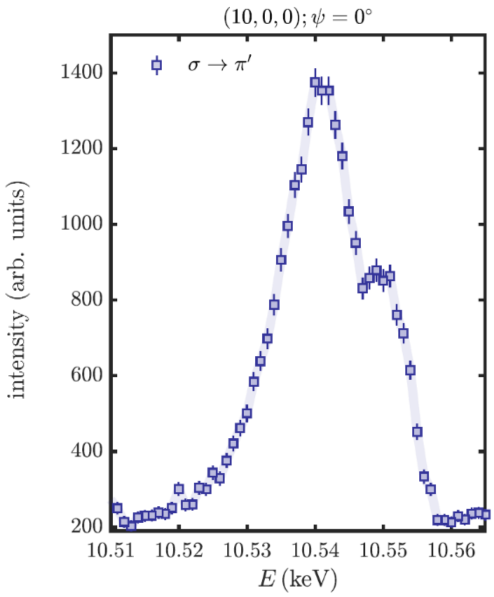

Figure S5. *Energy scan of the (10,0,0) reflection in the σ-π' channel.*

In Figure S6, we plot the temperature dependence of the (10,0,0) peak measured in the σ-σ' and the σ-π' channel, side by side. The data were collected at the same angles and energy (E_q). The red curve was collected in the σ' out-going polarization with an attenuation factor of 3 while the blue curve was measured in the π' out going polarization channel with an attenuation factor of 2. As such, the signal in the σ-σ' channel is 2 orders of magnitude stronger than that of the σ-π' channel.

First, we note that the signal in the σ-σ' channel (red data points) is flat above T_q but decreases below T_q due to the splitting of the peak. On the other hand, the signal in the σ-π' channel, increases by 50 %, just below T_q, contrary to the behaviour of the σ-σ' signal. Therefore, we can safely rule out the increase in the σ-π' channel to leakage from the σ-σ' channel, which (1) is two orders of magnitude larger in intensity, and (2) has a different temperature dependence.

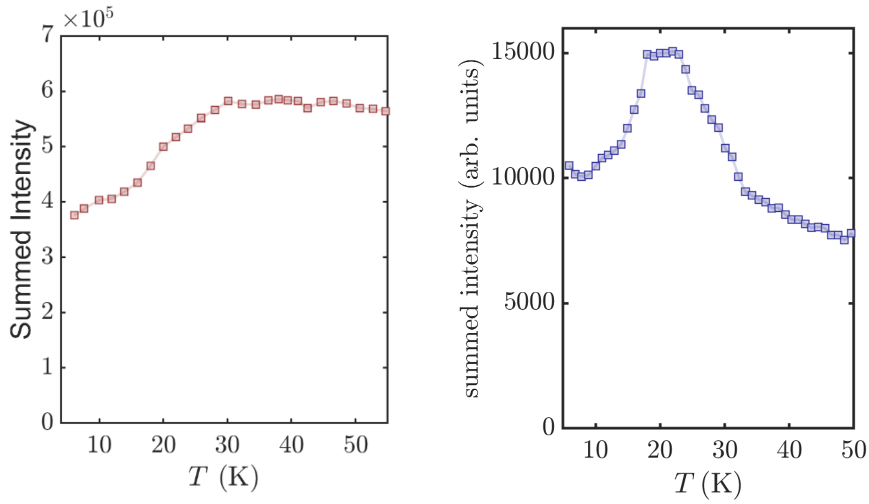

***Figure S6**. Temperature dependence of the (10,0,0) reflection measured in the (left) σ-π' and (right) σ-π' channels, respectively.*