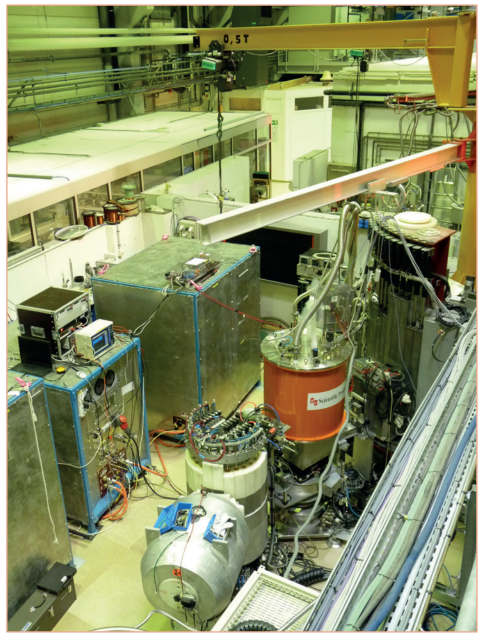
# Field-induced spin-density wave beyond hidden-order in $URu_2Si_2$

*Three-axis spectrometer IN22*

$URu_2Si_2$ is one of the most enigmatic, strongly correlated electron systems and offers a fertile testing ground for new concepts in condensed matter science [1]. In spite of more than thirty years of intense research, no consensus on the order parameter of its low-temperature hidden-order phase exists. Here, thanks to neutron diffraction under pulsed magnetic fields up to 40 T, we identify the field-induced phases of $URu_2Si_2$ as a spin-density wave state [2]. The transition to the spin-density wave represents a unique touchstone for understanding the hidden-order phase.

**Figure 1**

Three-axis spectrometer IN22 (CRG-CEA) with the 40 T cryomagnet and the 1 MJ pulsed-field generator.



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The application of extreme conditions permits the ground state of a system to be modified in order to gain new insights about it. In $URu_2Si_2$ under pressure, the hidden-order state is replaced by an antiferromagnetic phase whose order parameter is a moment aligned antiferromagnetically along **c** with the wavevector $\mathbf{k}_0$ = (0 0 1) [3]. Under a high magnetic field applied along **c**, a cascade of first-order phase transitions at the fields $\mu_0H_1$ = 35 T, $\mu_0H_2$ = 36 / 37 T (rising / falling fields), and $\mu_0H_3$ = 39 T, leads to a polarised paramagnetic regime above $H_3$. Here, thanks to a new cryomagnet (developed by the LNCMI-Toulouse, the CEA-Grenoble, and the ILL) allowing neutron diffraction up to 40 T (**figure 1**), we have determined the magnetic structure of $URu_2Si_2$ in fields between 35 and 39 T.

After testing different wavevectors, a magnetic signal has been detected at $\mathbf{k}_1$ = (0.6 0 0). **Figure 2a** shows the time profile of a magnetic field pulsed up to 38 T, as well as the time dependence of the diffracted neutron intensities recorded during 38 T pulses at the momentum transfers **Q** = (0.6 0 0) and (1.6 0 -1), which are satellites of wavevector $\mathbf{k}_1$ = **Q** − **τ** around the structural Bragg positions **τ** = (0 0 0) and (1 0 -1), respectively. **Figure 2c** emphasises, in the window 32-41 T, the field-dependence of the diffracted neutron intensities. The enhancement of the intensity at $T$ = 2 K, absent at $T$ = 18 K, shows that long-range ordering with wavevector $\mathbf{k}_1$ is established at high field and low temperature. At $T$ = 2 K, the intensity with wavevector $\mathbf{k}_1$ is enhanced in fields higher than $\mu_0H_1$ = 35 T and drops down to the background level in fields higher than $\mu_0H_3$ = 39 T. *Via* a normalisation on the nuclear Bragg peak (1 0 -1), the magnetic intensity has been associated with a Fourier component $m(\mathbf{k}_1)$ = 0.25 $\mu_B$ / U.

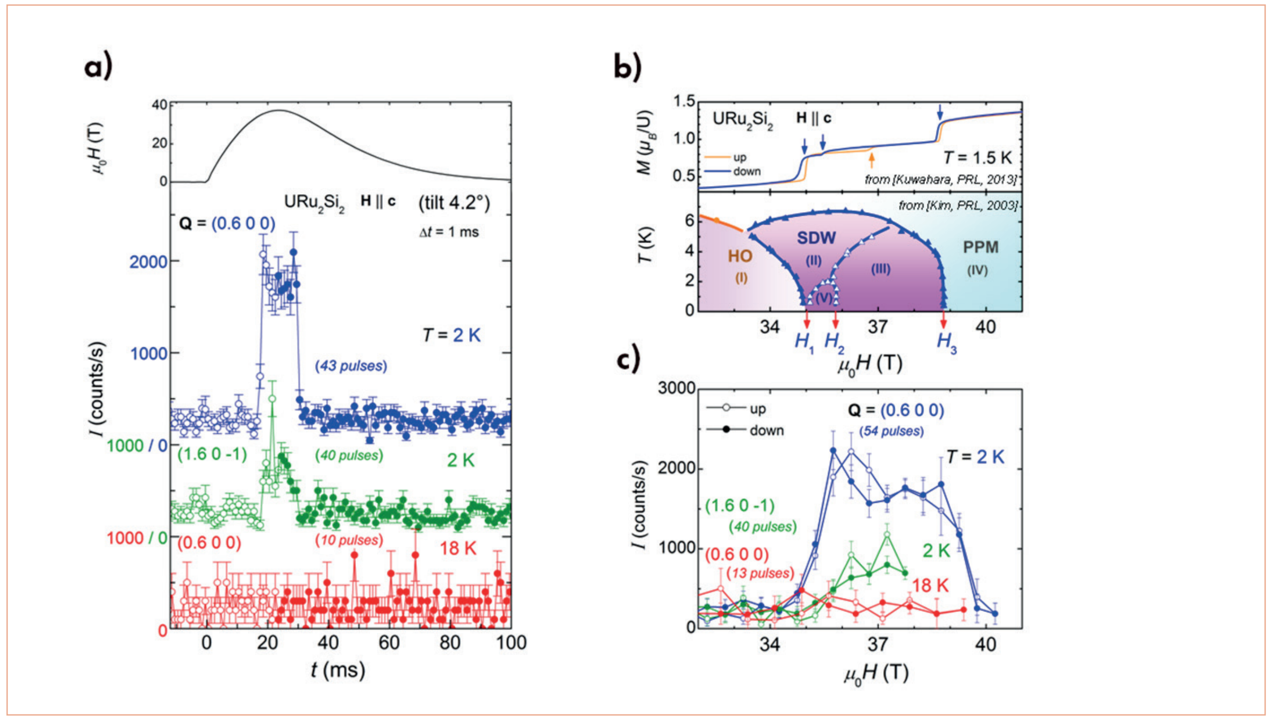
**Figure 3** presents the magnetic phase diagram of $URu_2Si_2$ under pressure and magnetic field, over a wide range of temperatures up to 75 K. In the hidden-order state, the magnetic fluctuations peaked at the hot wavevectors $\mathbf{k}_0$ and $\mathbf{k}_1$, indicating the proximity of quantum phase transitions associated with long-range ordering with the same wavevectors. With pressure [3], the disappearance of the hidden-order coincides with a transfer of weight from magnetic fluctuations with wavevector $\mathbf{k}_0$ into antiferromagnetic order with the same wavevector [4, 5].

**Figure 2**

**a)** Time profile of a magnetic field pulsed up to 38 T, and corresponding time-dependence of the neutron diffracted intensity at **Q** = (0.6 0 0) and **Q** = (1.6 0 -1).

**b)** Magnetisation versus magnetic field at $T$ = 1.5 K and magnetic-field-temperature phase diagram of $URu_2Si_2$.

**c)** Field dependence of the neutron diffracted intensities in fields up to 40.5 T.




With magnetic field, we have observed that a spin-density wave is stabilised with the wavevector $\mathbf{k}_1$, which may coincide with a loss of intersite magnetic fluctuations, as indicated by the enhanced magnetisation (**figure 2b**).

In an itinerant picture of magnetism, long-range magnetic ordering with a wavevector $\mathbf{k}_m$ can be related to a partial or complete nesting of two parts of the Fermi surface. In $URu_2Si_2$, $5f$ electrons hybridise with electrons from the conduction bands. Modifications of the Fermi surface and carrier mobility accompany the establishment of the hidden-order phase at the temperature $T_0$, and Fermi surface nestings with the wavevectors $\mathbf{k}_0$ and $\mathbf{k}_1$ can be identified [6]. However, no long-range magnetic order has been reported yet in $URu_2Si_2$ in its hidden-order phase. Resulting from the Fermi surface reconstruction at $H_1$, the nesting with $\mathbf{k}_1$ is probably reinforced, leading to the onset of the spin-density wave with the wavevector $\mathbf{k}_1$.

Our observation of a spin-density wave in magnetic fields between 35 and 39 T will certainly push to develop models incorporating on equal basis the Fermi surface topology and the magnetic interactions. With the aim of describing competing quantum instabilities between the hidden-order and long-range-ordered phases, such models will be a basis for solving the hidden order problem.

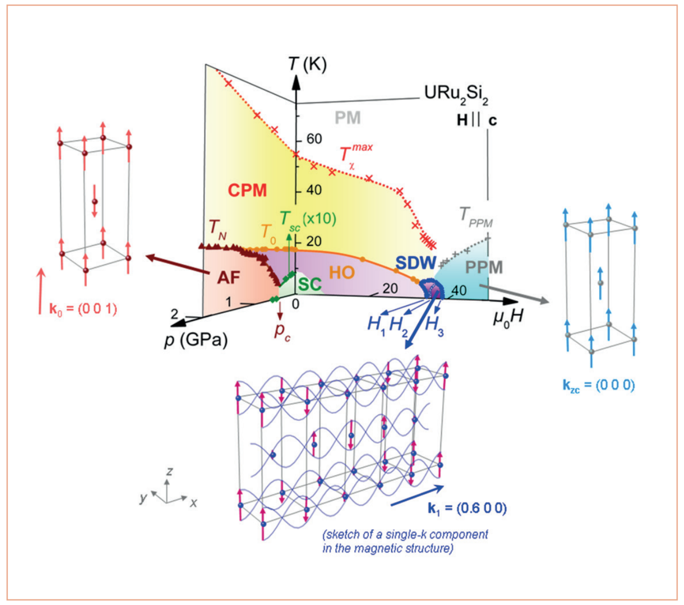



**Figure 3**

Temperature-magnetic field and temperature-pressure phase diagrams of $URu_2Si_2$.