Antiferromagnetic structure and electronic properties of BaCr$_2$As$_2$ and BaCrFeAs$_2$

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The chromium arsenides BaCr$_2$As$_2$ and BaCrFeAs$_2$ with ThCr$_2$Si$_2$ type structure (space group $I4/mmm$; also adopted by ‘122’ iron arsenide superconductors) have been suggested as mother compounds for possible new superconductors. DFT-based calculations of the electronic structure evidence metallic antiferromagnetic ground states for both compounds. By powder neutron diffraction we confirm for BaCr$_2$As$_2$ a robust ordering in the antiferromagnetic $G$-type structure at $T_N = 580$ K with $\mu_{Cr} = 1.9 \mu_B$ at $T = 2$ K. Anomalies in the lattice parameters point to magneto-structural coupling effects. In BaCrFeAs$_2$ the Cr and Fe atoms randomly occupy the transition-metal site and $G$-type order is found below 265 K with $\mu_{Cr/Fe} = 1.1 \mu_B$. $^{57}$Fe Mössbauer spectroscopy demonstrates that only a small ordered moment is associated with the Fe atoms, in agreement with electronic structure calculations with $\mu_{Fe} \approx 0$. The temperature dependence of the hyperfine field does not follow that of the total moments. Both compounds are metallic but show large enhancements of the linear specific heat coefficient $\gamma$ with respect to the band structure values. The metallic state and the electrical transport in BaCrFeAs$_2$ is dominated by the atomic disorder of Cr and Fe and partial magnetic disorder of Fe. Our results indicate that Néel-type order is unfavorable for the Fe moments and thus it is destabilized with increasing iron content.

I. INTRODUCTION

The discovery of high-$T_c$ superconductivity in iron-based pnictides and chalcogenides has initiated intense efforts to investigate and theoretically model the magnetic states adopted by the non-superconducting relatives of these compounds. Similar as for the oxocuprate superconductors, there is a subtle interplay between magnetism and superconductivity, and spin-fluctuations are considered as the mechanism enabling the formation of Cooper pairs. The possible coexistence of specific types (spin-density wave, SDW) of magnetic order and superconductivity on the microscale in the Fe-based systems is an ongoing topic of research.

The antiferromagnetic (afm) parent compounds of cuprate superconductors are Mott (charge transfer) insulators. The situation is less clear for their Fe-based counterparts. For instance, non-superconducting pnictides like LaOFeAs or BaFe$_2$As$_2$ are metallic, itinerant antiferromagnets with low ordered moments at the iron sites ($< 1 \mu_B$), whereas chalcogenides like K$_{0.8}$Fe$_{1.6}$Se$_2$ are insulators with large Fe moments of $\approx 3 \mu_B$. Strictly, however, half-filled systems with $d^5$ configuration have to be regarded as the Mott-type parent compounds, which is confirmed by the semiconducting properties of e.g. BaMn$_2$As$_2$ as well as of LaOMnAs and LiMnAs.

There is an ongoing debate about the proper description of the electronic structure of Fe-based pnictides and chalcogenides, in particular about the appearance of electron correlation and the degree of electron itinerancy. Since the basic Fe-As layers with formally Fe$^{2+}$ ions in the parent compounds constitute a multi-orbital system, orbital ordering is also believed to be of importance. Two opposing views have been adopted: On the one hand, the iron pnictides have been considered as weakly correlated metals where a SDW magnetic state is formed due to Fermi surface nesting. On the other hand, in particular the more strongly correlated chalcogenides have been discussed as Mott-type insulators and the magnetism was modeled in terms of Heisenberg-type exchange interactions between localized moments. However, none of the limiting views can describe the many facets of magnetism which have emerged from experimental studies and actually it is believed that the Fe-based pnictides and chalcogenides are in between these extremes. For instance, even itinerant electronic systems may show pronounced correlation effects arising from Hund’s rule coupling (Hund’s metals) or by high pressure, which rationalizes the existence of large magnetic moments on short timescales of the order of femtoseconds, as derived from photoemission experiments.

An important prototype system is BaFe$_2$As$_2$ which adopts the tetragonal ThCr$_2$Si$_2$-type crystal structure at room temperature and features a concomitant structural and magnetic transition at $T_N = 132$ K. Below $T_N$ a stripe-like afm order occurs with saturated Fe moments of about 0.9$\mu_B$ being aligned along the $a$ axis of the low-temperature orthorhombic crystal structure. BaFe$_2$As$_2$ can be converted into a high-$T_c$ superconductor by hole or electron doping or by high pressure. While substitution of Fe by some transition metals like Co, Ni or even Ru induces superconductivity, substitution by others like Mn does not lead to superconducting states. In contrast to BaFe$_2$As$_2$, the half-filled Mn-analogue BaMn$_2$As$_2$ remains tetrag-
nal down to low temperatures and adopts a G-type afm spin structure with a high ordered moment (3.9 μB) and a high ordering temperature of 625 K [7] and [8]. Similarly high Néel temperatures (692–758 K) and G-type afm have been observed for the Cr species in the isostructural silicides RCr₆Si₂ (R = Tb, Ho, Er) [22].

Superconductivity in manganese and chromium compounds is very rare and only recently representatives have been found. The first, binary CrAs, has been long known for its structural and helimagnetic ordering transition at 240–190 K with sizable Cr moments of 1.67 μB [25]. The ordering temperature decreases dramatically to zero for pressures of 0.7–0.8 GPa and superconductivity with critical temperature up to 2.2 K appears [26] and [27]. At ambient pressure superconductivity has been investigated in the new A₂Cr₃As₂ (A = K, Rb, Cs) compounds featuring quasi onedimensional Cr₃As₃ tubes [28] and [29].

The Mott scenario for the transition-metal arsenides [30] considers a mirror-symmetry in the many-body physics arising when the half-filled d⁵ configuration is either doped by electrons or by holes. The Cr compounds formally have a d⁵ configuration and in this sense are the hole-doped analogues to the electron-doped d⁵ system BaFe₂As₂. Recently, some theoretical studies explored the possibilities to find superconductivity for BaM₂As₂ and LaOMAs with transition-metals M (or mixtures) with less than 5 electrons [31] and [32]. Emphasis in these works is put on the strength of correlations in dependence with less than 5 electrons [31 and 32].

II. EXPERIMENTAL & CALCULATION DETAILS

Here, we focus on the system Ba(Fe₁₋ₓCrₓ)₂As₂, where no superconducting compositions have been found so far [23, 33, and 34]. Theoretical calculations predicted an afm checkerboard (G-type) ordering in the end member BaCr₂As₂ [33] and a ferromagnetic (fm) ground state in atomically ordered BaCrFeAs [7]. Another electronic structure calculation predicted ordered BaCrFeAs₂ as a fully compensated antiferromagnet with an iron moment of 2.6 μB [36]. Such a material could be relevant for spintronics applications. Neutron diffraction studies on iron-rich BaFe₂₋ₓCrₓAs₂ single crystals with 0 < x < 0.94 indicated that near x = 0.6 the SDW ground state is replaced by a G-type afm state [34], but spin structure and ordering temperature of the end member BaCr₂As₂ have not been studied experimentally yet. Also electronic structure calculations of EuCr₂As₂ suggested a stable G-type afm order of the Cr sublattice (in addition, the Eu²⁺ ions show fm ordering below 21 K) [37]. A recent experimental study confirmed these predictions [38].

We investigated the detailed crystal and magnetic structures of BaCr₂As₂ and BaCrFeAs₂ by temperature dependent powder neutron diffraction. Magnetic susceptibility, electrical transport, specific heat, and ⁵⁷Fe Mössbauer spectroscopy measurements complement the study. Our theoretical studies predict a random occupation of Cr and Fe on the transition-metal site for BaCrFeAs₂ and metallic afm G-type ordered ground states for both compounds. Experimentally, it is shown that both compounds in fact feature G-type afm order, where the Néel temperature T_N = 580 K of BaCr₂As₂ is nearly as high as that of BaMn₂As₂, although the magnetic moment is only half as large. Both compounds are metallic conductors. BaCrFeAs₂ turns out to be atomically disordered, and thus only average magnetic moments are obtained from neutron diffraction. Most interestingly, the Fe Mössbauer spectra indicate that the Fe magnetic moments are much smaller than those of Cr and of similar size as in BaFe₂As₂. T_N decreases with increasing iron content, thus the G-type order is unfavorable for the Fe moments. The itinerant character of the magnetism persists in the whole stability range of the G-type order, whereas BaMn₂As₂ with the same nominal d electron count as BaCrFeAs₂ is a semiconductor.

BaCr₂As₂ and BaCrFeAs₂ were synthesized by reacting CrAs and FeAs with Ba in an alumina crucible. The binaries were synthesized according to Singh et al. [33] using Cr (chemPUR, 99.99 %), Fe (chemPUR, 99.9 %), and As (Alfa Aesar, 99.999 %). To control the harsh reaction between the binaries and Ba (Alfa Aesar, 99.999 %), only 1/3 of the barium was added initially. The mixture was heated to 1423 K and held for 12 h. Then the prod-

FIG. 1. a.) BaCr₂As₂ crystallizes in the ThCr₂Si₂ structure (space group I4/mmm). b.) Crystals form as shiny black platelets. c.) HAADF image and diffraction pattern. d.) Zoom of the HAADF image, the inset shows the theoretical atom positions (Ba red, Cr green, As yellow).
uct was ground and additional Ba was added. These steps were repeated until the powder x-ray diffraction pattern (PXRD) did not show any CrAs or FeAs impurities. In both cases an excess of ≈5% Ba was added to react all of the strongly magnetic CrAs or FeAs. Single crystals were grown using the Bridgman technique with alumina crucibles under argon atmosphere. The crucible was heated to 1823 K and held for 24 h, then it was moved with 1 mm h⁻¹ out of the hot zone of the furnace. Single crystals (Figure 1b) up to 10 mm × 5 × 4 mm could be grown. For the neutron diffraction experiments ≈ 4 g of polycrystalline sample was prepared.

The crystal structure (ThCr₂Si₂ type, tI10, space group (SG) I4/mmm, No. 139, Ba on 2a, Cr on 4d, As on 4e) was confirmed by PXRD using Cu-Kα radiation (λ = 1.54056 Å), with a Huber G670 camera (Guinier technique). The refined lattice parameters are a = 3.9667 and c = 13.6214 Å for BaCr₂As₂ and a = 3.986 and c = 13.2939 Å for BaCrFeAs₂. Additional reflexes suggest the presence of traces of BaAl₂O₄ in some samples. High-resolution transmission electron microscopy (HR-TEM) microstructure studies were performed using a FEI Titan resolution transmission electron microscopy (HR-TEM) microscope. In both cases an excess of CrAs or FeAs. Single crystals (Figure 1c and d) on 4 as shown in Figures 1c and d for BaCr₂As₂ could be found. In agreement with the PXRD patterns (PXRD) did not show any CrAs or FeAs impurities. In both cases an excess of CrAs or FeAs. Single crystals (Figure 1b) up to 10 mm × 5 × 4 mm could be grown. For the neutron diffraction experiments ≈ 4 g of polycrystalline sample was prepared. The crystal structure (ThCr₂Si₂ type, tI10, space group (SG) I4/mmm, No. 139, Ba on 2a, Cr on 4d, As on 4e) was confirmed by PXRD using Cu-Kα radiation (λ = 1.54056 Å), with a Huber G670 camera (Guinier technique). The refined lattice parameters are a = 3.9667 and c = 13.6214 Å for BaCr₂As₂ and a = 3.986 and c = 13.2939 Å for BaCrFeAs₂. Additional reflexes suggest the presence of traces of BaAl₂O₄ in some samples. High-resolution transmission electron microscopy (HR-TEM) microstructure studies were performed using a FEI Titan 80-300. In the high-angle annular dark field (HAADF) images (shown in Figures 1c and d for BaCr₂As₂; not shown for BaCrFeAs₂) no signs of disorder on the Ba 2a(0,0,0), Cr/(CrFe) 4d (1/4, 1/4, 1/4) or As 4e (0,0,0) sites could be found. In agreement with the PXRD pattern, segregates of BaAl₂O₄ were seen on the surface for some BaCrFeAs₂ crystals. The average composition of the crystals was found to be Ba₀.₀₃(4)Cr₀.₅₂(5)As₂₀.₃(5) and Ba₁₀.₀₁(6)Cr₀.₉₆(8)Fe₁₀.₀₈(2)As₂₁₀(1) by chemical analysis with inductively coupled plasma optical emission spectroscopy (ICP-OES).

Powder neutron diffraction experiments on BaCr₂As₂ and BaCrFeAs₂ have been carried out on the instruments E2, E6, and E9 at the BER II reactor of the Helmholtz-Zentrum Berlin. The instrument E9 uses a Ge-monochromator selecting the neutron wavelength (0,0,0), Cr/(CrFe) 4d (1/4, 1/4, 1/4) or As 4e (0,0,0) sites could be found. In agreement with the PXRD pattern, segregates of BaAl₂O₄ were seen on the surface for some BaCrFeAs₂ crystals. The average composition of the crystals was found to be Ba₀.₀₃(4)Cr₀.₅₂(5)As₂₀.₃(5) and Ba₁₀.₀₁(6)Cr₀.₉₆(8)Fe₁₀.₀₈(2)As₂₁₀(1) by chemical analysis with inductively coupled plasma optical emission spectroscopy (ICP-OES).

For BaCr₂As₂ the calculations were started with the values a = 3.96, c = 13.6 Å, and z = 0.361 [40]. A G-type aß order was assumed and the lattice was set up in SG I4/m2 (119) and the Cr atoms were located on the split 2c and 2d sites to allow for the anti-parallel orientations of their magnetization. This space group concerns the atomic positions, the final magnetic symmetry depends on the direction of the quantization axis and is described by a Shubnikov color group (here P4'/nmm (123.344)). A full structural optimization showed that the above given parameters are nearly relaxed, in agreement with previous observations [35].

In the calculations of the electronic structure for BaCrFeAs₂ the same basic atomic and magnetic structures were used. Two cases were assumed, an ordered and an alloyed structure. In the ordered structure, the initial 4d position of the Cr atom was split and half of the new positions was occupied by Fe. This results in SG I42m (119) with Ba 2a, Cr 2c, Fe 2d, and As 4e. Starting from the experimental lattice parameters, an optimization of the ordered structure resulted in aₜ = 4.012 Å, cₜ = 13.3819 Å, and zₜ = 0.357. The strong deviations of these optimized parameters from the experimental ones suggest that the ordered case is not realized, i.e. in the actual material Cr and Fe are disordered. For the
The different atoms were constrained to be equal. The isotopic temperature factors of the different atoms were constrained to be equal.

### Table I. Results of the crystal structure refinements for BaCr$_2$As$_2$ and BaCrFeAs$_2$

<table>
<thead>
<tr>
<th>Structure</th>
<th>R$_{N}$</th>
<th>(a) (Å)</th>
<th>(c) (Å)</th>
<th>(Z)</th>
<th>(V) (Å$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BaCr$_2$As$_2$ at 2 K</td>
<td>0.0480</td>
<td>3.9503(2)</td>
<td>13.6047(10)</td>
<td>2</td>
<td>212.30(3)</td>
</tr>
<tr>
<td>atom site</td>
<td>(x)</td>
<td>(y)</td>
<td>(z)</td>
<td>(B) (Å$^2$)</td>
<td></td>
</tr>
<tr>
<td>Ba</td>
<td>2a</td>
<td>0</td>
<td>0</td>
<td>0.32(3)</td>
<td></td>
</tr>
<tr>
<td>Cr</td>
<td>4d</td>
<td>0</td>
<td>0.19(2)</td>
<td>0.32(3)</td>
<td></td>
</tr>
<tr>
<td>As</td>
<td>4e</td>
<td>0</td>
<td>0.35779(10)</td>
<td>0.19(2)</td>
<td></td>
</tr>
<tr>
<td>BaCrFeAs$_2$ at 2 K</td>
<td>0.0402</td>
<td>3.9793(1)</td>
<td>13.2532(4)</td>
<td>2</td>
<td>209.86(1)</td>
</tr>
<tr>
<td>atom site</td>
<td>(x)</td>
<td>(y)</td>
<td>(z)</td>
<td>(B) (Å$^2$)</td>
<td></td>
</tr>
<tr>
<td>Ba</td>
<td>2a</td>
<td>0</td>
<td>0</td>
<td>0.19(2)</td>
<td></td>
</tr>
<tr>
<td>Cr</td>
<td>4d</td>
<td>0</td>
<td>0.19(2)</td>
<td>0.19(2)</td>
<td></td>
</tr>
<tr>
<td>Fe</td>
<td>4d</td>
<td>0</td>
<td>0.35779(10)</td>
<td>0.19(2)</td>
<td></td>
</tr>
</tbody>
</table>
| As     | 4e     | 0   | 0.35

alloyed structure it was assumed that Fe and Cr occupy both the 2c and 2d position in a 50:50 ratio.

## III. RESULTS

### A. Crystal structures

The crystal structures of BaCr$_2$As$_2$ and BaCrFeAs$_2$ were investigated by powder neutron diffraction. Note that below \(T_N = 580\) K, respectively 265 K, the patterns also included magnetic Bragg intensity (see Section III). Both compounds crystallize in the tetragonal SG \(I4/mmm\) (No. 139), where the Ba, Cr(Fe), and As atoms occupy the Wyckoff positions \(2a(0,0,0)\), \(4d(0,\frac{1}{2},\frac{1}{2})\), and \(4e(0,0,z)\), respectively. The same SG was reported earlier for BaMn$_2$As$_2$. From the data sets collected on the fine-resolution powder diffractometer E9 we could not find any additional peak splitting indicating a lower crystal structure symmetry. The refinements of the crystal structure of BaCr$_2$As$_2$ from data sets recorded in the temperature range from 2 up to 750 K resulted in residuals between \(R_N = 0.048\) and 0.088 [defined as \(R_N = \langle |F_{\text{obs}}|-|F_{\text{calc}}|/|F_{\text{obs}}| \rangle\). These values are somewhat larger than expected. This can be ascribed to the fact, that the investigated sample contained an impurity, which could not be characterized so far (see Figure 2). Further, additional impurity peaks of the sample container were observed in the diffraction patterns using the high temperature furnace on E9. Nevertheless, the lattice parameters, as well as the positional parameters of BaCr$_2$As$_2$ could be refined with good accuracy. In the case of BaCrFeAs$_2$ the crystal structure was investigated in the temperature range between 2 and 275 K. Due to the higher purity of this sample the refinements resulted in smaller residuals between \(R_N = 0.035\) and 0.043. The results of the Rietveld refinements of the data sets collected at 2 K are given in Table I. It is emphasized that there are no indications of superstructure reflections which would point to atomic order of Cr and Fe atoms.

Figure 2a shows the temperature dependence of the cell parameters as well as the cell volume. For BaCrFeAs$_2$ the lattice parameters \(a\) and \(c\) show a continuous increase from 2 up to 750 K, which is above the magnetic ordering temperature \(T_N = 265(5)\) K. A similar trend was found for BaMn$_2$As$_2$. A continuous increase of \(a\) and \(b\) was also observed for BaCr$_2$As$_2$ but only in the range from 2 K up to about 300 K. Further heating up to 700 K leads to a decrease of the \(c\) parameter, while the increase of the \(a\)-parameter becomes somewhat more pronounced (see Figure 3). As a consequence, the ratio \(c/a\) decreases from 3.43 at 300 K to 3.34 at 750 K. The former value is in agreement with literature data [49]. These results indicate that the magnetic transition in BaCr$_2$As$_2$ is accompanied by subtle structural modifications, in contrast to BaMn$_2$As$_2$. The anomaly in the \(c\) parameter is reflected in the change of the distance between the arsenic atoms lying along the \(c\) direction. Namely, one observes a decrease of the distance \(d(\text{As-As})\) between...
The evolution of the DOS with increasing Coulomb parameter $U$ in the LDA+$U$ calculation is given in Figure 6. Note that the unoccupied minority states of one of the Cr atoms correspond to the unoccupied majority states of the other, and vice versa for the occupied states due to the anti-symmetric spin densities of an antiferromagnet. The increased $U$ results in an increase of the magnetic moment at the Cr atoms (cf. Table I). Their values are in the range 2.4-3.5 $\mu_B$.

The “bare” coefficient of the electron specific heat $\gamma_0 = \pi^2 k_B^2 n(\epsilon_F)/3$ for BaCr$_2$As$_2$ is $\approx 8$ mJ mol$^{-1}$ K$^{-2}$. For the various calculation schemes the results are also given in Table I. The inclusion of SO interaction has only a weak effect on $\gamma_0$. For LDA+$U$, it is found that $n(\epsilon_F)$ – and thus $\gamma_0$ – increases slightly and has a maximum at $U \approx 1$ eV, but then decreases with further increase of $U$. Using SPRKKR and the mean field approximation a Néel temperature $T_N,\text{calc} \approx 880$ K can be calculated.
twice as high as the one calculated for BaCr$_2$As$_2$. It arises from flat bands around $\varepsilon_F$. A detailed analysis of the DOS reveals that those states are localized at the Fe atoms. In many cases, compounds with such a peaked DOS at $\varepsilon_F$ are not stable.

The electronic structure and the DOS of the alloy variant of BaCrFeAs$_2$ are shown in Fig. 7. The result of the chemical disorder scattering are strongly broadened electronic states, in particular close to $\varepsilon_F$. The broadening causes a reduction of the maximum of the DOS just above $\varepsilon_F$ to about 5 eV$^{-1}$, which is still higher compared to BaCr$_2$As$_2$.

The magnetic properties of ordered and alloyed BaCrFeAs$_2$ are compared in Table III. The moment for the atomically ordered phase compares well with 2.6 $\mu_B$ reported in Ref. 38. The moments in the ordered case are not completely the same, the vanishing total moment is guaranteed by the polarization of the interstitial and the atoms in the vicinity of the magnetic Cr and Fe atoms. The orbital magnetic moments are very small, in the order of 0.002 $\mu_B$ or 0.06 $\mu_B$.

Interestingly, for the random distribution of Fe and Cr, a stable solution is found with vanishing moments at the Fe atoms at the same site. The calculation was started with a starting moment at the Cr atoms (4 $\mu_B$) but zero moment at Fe. No magnetic moment was induced during the self consistent cycles. The result is an average moment of 1.38 $\mu_B$ for the 2c/2d positions.

Also for BaCrFeAs$_2$ the Néel temperature can be calculated in the mean field approximation using SPRKKR. The value for the atomically ordered structure is very high, however, a much lower Néel temperature of about 260 K is obtained for the disordered version.
TABLE III. Magnetic properties of BaCrFeAs$_2$. Tabulated are the DOS just above $E_F$ ($n_{\text{max}}$), the absolute values of the magnetic moments at Cr and Fe species ($m_{\text{Cr/Fe}}$), and the calculated Néel temperatures ($T_{\text{N,calc}}$).

<table>
<thead>
<tr>
<th></th>
<th>ordered</th>
<th>disordered</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n_{\text{max}}$</td>
<td>6.92</td>
<td>4.99 (eV$^{-1}$)</td>
</tr>
<tr>
<td>$m_{\text{Cr}}$</td>
<td>2.74</td>
<td>2.76 ($\mu_B$)</td>
</tr>
<tr>
<td>$m_{\text{Fe}}$</td>
<td>2.53</td>
<td>0.00 ($\mu_B$)</td>
</tr>
<tr>
<td>$T_{\text{N,calc}}$</td>
<td>965</td>
<td>260 (K)</td>
</tr>
</tbody>
</table>

FIG. 8. Magnetic susceptibility of a BaCr$_2$As$_2$ crystal in a field $\mu_0 H = 1$ T parallel (red circles) to the crystallographic $c$ axis. Minor adjustments of the magnetometer oven data sets ($T > 400$ K) were made to match with the data below 400 K. The inset shows the magnetic moment from an isothermal magnetization loop measured at a temperature $T = 1.8$ K.

The temperature dependence of the magnetic susceptibility, $\chi = M/H$, at $\mu_0 H = 1$ T of a BaCr$_2$As$_2$ crystal platelet ($ab$ plane) was measured with the magnetic field parallel and perpendicular to the $c$ axis (Fig. 8). The small difference between the directions above 600 K suggests a rather weak anisotropy in the paramagnetic regime. However, no Curie-Weiss behavior could be observed up to $T = 800$ K. For $H \parallel c$ a clear kink is visible, indicating the afm ordering of the Cr sub-lattice at $T_N = 575(10)$ K, as determined from the peak in the derivative $d(\chi(T))/dT$. The decrease of $\chi(T)$ for $H \parallel c$ towards low temperatures is much stronger than for $H \perp c$, eventually suggesting an afm order with magnetic moments aligned along the $c$ axis. The behavior of $\chi(T)$ and the ordering temperature is very similar to that of BaMn$_2$As$_2$ 25. The nearly isotropic but non-Curie-Weiss behavior above $T_N$ is observed for several afm compounds with ThCr$_2$Si$_2$-type structure. It is typical for the somewhat twodimensional character of the magnetic interactions and has been treated in detail theoretically for BaMn$_2$As$_2$. For BaCr$_2$As$_2$ the smooth maximum of $\chi(T)$ may be anticipated for temperatures around 900 K.

A small upturn of $\chi(T)$ in both directions for temperatures below $\approx 50$ K suggests the presence of paramagnetic impurities, e.g. from point defects. Magnetization loops taken at $T = 1.8$ K (Fig. 8 inset) show a very small fm-like component of $\lesssim 5 \times 10^{-5} \mu_B$ for both field along or perpendicular to the $c$ axis. Also, in measurements of $M(T)$ at $\mu_0 H = 0.01$ T, a small sharp transition from a fm impurity phase becomes visible at $T_{\text{imp}} \approx 76$ K. We assign this transition and the fm-like signals to the structural and helimagnetic ordering transition of CrAs 25. The ordering temperature of CrAs is known to decrease dramatically to zero for pressures of 0.7-0.8 GPa 26 and 27. We speculate that CrAs on the crystal surface is strained and its ordering temperature is therefore reduced to $T_{\text{imp}}$.

The magnetic susceptibility of sintered BaCrFeAs$_2$ (Fig. 9) displays a broadened cusp at $T_N \approx 269(2)$ K (midpoint of step in $d(\chi(T))/dT$), but there is only a slight decrease of the $\chi(T)$ curve below this temperature. Instead, with decreasing temperature the susceptibility increases again, indicating a strong paramagnetic contribution following a Curie law. Above the Néel temperature (range 300-400 K) the data are well fitted by a Curie-Weiss law with effective moment $\mu_{\text{eff}} = 3.70 \mu_B$ and Weiss temperature $\theta_W = -273$ K. The BaCrFeAs$_2$ crystal shows a similar cusp, however at $\approx 225$ K. The lower $T_N$ of the single crystal is probably due to a slightly lower Fe content compared to the sinter sample. The decrease of $\chi(T)$ is more pronounced for $H \parallel c$, suggesting an afm ordered
structure with the magnetic moments lying in the crystallographic c direction. The paramagnetic contribution in the magnetically ordered state of BaCrFeAs$_2$ is discussed in connection with the Mössbauer results (Sec. III E).

The electrical resistivity, $\rho(T)$, of the BaCr$_2$As$_2$ crystal measured for current in the $ab$ plane (Fig. 11) increases almost linearly with temperature and indicates metallic behavior of the compound ($\rho_{300\,K} = 136\,\mu\Omega\,cm$). The residual resistance ratio $\text{RRR} \approx 3.8$ indicates a fair quality of the specimen and the residual resistance is already reached at $\approx 13\,K$. Interestingly, below this temperature $\rho(T)$ increase very slightly (by $\approx 0.1\%$ of $\rho_0$). The magnetoresistance (MR, Fig. 11 inset) is very small and positive for high temperatures. Surprisingly, for $T = 2.0\,K$ it is negative and quite strong (-1.7\% at $\mu_0 H = 9\,T$). This might indicate the damping of an additional scattering mechanism at very low temperatures compared to the $T_N$. The origin of both the upturn of $\rho(T)$ below 13\,K and of the negative MR might be due to a Kondo-hole effect. Non-magnetic atoms replacing magnetic Cr in the antiferromagnetically ordered lattice can give rise to a Kondo-like upturn of resistivity at low temperatures. This scattering is weakened by the application of a magnetic field resulting in a negative MR proportional to the field. The Hall resistivity curves $\rho_{xy}(H)$ are linear, the Hall constants are positive and do almost not vary with temperature. This observation is consistent with the hole pocket around the $\Gamma$ point (cf. Fig. 6). Within a one-band model the Hall constant corresponds to a hole density $n_h \approx 1.5 \times 10^{22}\,cm^{-3}$ and low mobility ($b_h = 11\,cm^2\,V^{-1}\,s^{-1}$ at $T = 2\,K$).

For polycrystalline BaCrFeAs$_2$ (Fig. 10) as well as for a single crystal (not shown) the electrical resistivity is about five times higher. Interestingly, it displays only a weak temperature dependence and increases continuously with decreasing temperature. Similar to BaCr$_2$As$_2$ there is an upturn below a certain temperature (here, $\approx 40\,K$). The absence of a typical metallic resistivity behavior is probably due to scattering of charge carriers on the disordered Cr/Fe species of the 4$d$ Wyckoff site. The order of magnitude suggests however that BaCrFeAs$_2$ is still a metal. Nominally iso-electronic BaMn$_2$As$_2$ crystals grown in MnAs flux show an about 100\,times higher resistivity [6]. The magnetoresistance of BaCrFeAs$_2$ is small ($<0.15\%$) for all temperatures, indicating that magnetic scattering due to the atomic Cr/Fe disorder is unimportant. Also for BaCr$_2$As$_2$ the Hall isotherms $\rho_{xy}(H)$ are linear, however Hall constants are negative and vary with temperature. They correspond to electron densities $n_e = \varepsilon \times 10^{23}\,cm^{-3}$ at $T = 300\,K$ and only $1.5 \times 10^{21}\,cm^{-3}$ at 2\,K with $b_h = 6\,cm^2\,V^{-1}\,s^{-1}$.

The specific heat, $c_p(T)$, of the two compounds is presented in Fig. 11. For BaCr$_2$As$_2$ no anomalies from transitions are visible up to 320\,K. However, $c_p(T)$ for BaCrFeAs$_2$ is larger than that of BaCr$_2$As$_2$ in the covered temperature range which might also be due to the Cr/Fe disorder. A very small step-like anomaly can be seen at $\approx 260\,K$ (barely standing out of the noise). The transition temperature is in agreement with our magnetization and neutron diffraction data (see Section III E). The small entropy change connected with this magnetic ordering is due to the low ordered moments of Cr/Fe and the predominantly itinerant character of the magnetic system. The Dulong-Petit limit $c_p = 3nR$ ($R$ = molar gas constant, $n$ = number of atoms) is reached by both compounds at around room temperature.

At low temperatures the specific heats (see Fig. 11 inset) are well described by $c_p(T) = \gamma T + \beta T^3 + \delta T^5$ where $\gamma$ is the coefficient of the linear term $\gamma T$ (usually assigned to conduction electrons) and $\beta T^3$ and $\delta T^5$ are the first
two terms due to the harmonic theory of lattice specific heat. For BaCr$_2$As$_2$ (BaCrFeAs$_2$) least-squares fits in the range 1.9–7K result in $\gamma = 18.8$ (64.9) mJ mol$^{-1}$ K$^{-1}$, $\beta = 0.51$ (0.56) mJ mol$^{-1}$ K$^{-4}$ corresponding to an initial Debye temperature of 268 (259) K, and $\delta = 0.6$ (0.0) $\mu$J mol$^{-1}$ K$^{-6}$. The $\gamma$ value obtained for BaCr$_2$As$_2$ is close to the value deduced by Singh et al. [35], however the linear term of BaCrFeAs$_2$ is very large. The $\gamma$ value for BaCrFeAs$_2$ is confirmed through measurements on the single crystal for which we show the susceptibility in Fig. 9. The lattice properties (Debye temperatures) of the two compounds are similar, as expected from the small atomic mass difference of Cr and Fe. Also, afm spin waves do not play a role due to the high Néel temperatures.

The linear specific heat contribution is insensitive to magnetic fields (cf. Fig. 11 inset). For BaCr$_2$As$_2$ in a field $\mu_0 H = 9$ T the linear coefficient $\gamma$ is not changed at all. For BaCrFeAs$_2$ the specific heat increases slightly in $\mu_0 H = 9$ T for $T < 5$ K (by maximally 1.8 % at 3.3 K), which might be due to a Schottky-type anomaly due to minor impurities. Thus, the enhanced $\gamma$ values should either not be due to spin fluctuations at all or the spin fluctuations are of too high in energy. Especially BaCr$_2$As$_2$ has a very high Néel temperature and the fluctuations might not be quenchable by such a small field.

### E. Magnetic structures

![FIG. 12. Temperature dependence of the magnetic moments per transition-metal atom in BaCr$_2$As$_2$ and BaCrFeAs$_2$ as obtained from powder neutron diffraction data (instruments E2, E6, and E9). Magnetic intensity of Bragg reflections disappears at the Néel temperatures $T_N = 580(10)$ K and $T_N = 265(5)$ K respectively.](image)

In order to investigate the magnetic structure of BaCr$_2$As$_2$ we have collected a powder neutron pattern at 2K. In comparison to the data collected at 750K, well above the Néel temperature $T_N = 580$ K, it was shown that magnetic intensities appear at the positions of nuclear Bragg reflections indicating a magnetic structure, which can be described with the propagation vector $k = 0$. This shows that the translation $t = (\frac{1}{2}, \frac{1}{2}, \frac{1}{2})$ associated with the $I$ cell is not lost. In Figure 2 it can be seen that the strongest magnetic intensity is observed at 2$\theta = 27.4^\circ$, which is the position of the Bragg reflection 101. Strong intensity could be generated at this position using a magnetic structure model, where the chromium atoms in the Wyckoff positions 4$d$, located at $(0, \frac{1}{2}, \frac{1}{2})$ and $(\frac{1}{2}, 0, \frac{1}{2})$, are coupled antiparallel. Due to the $I$ centering the operation $t = (\frac{1}{2}, \frac{1}{2}, \frac{1}{2})$ does not change the direction of the spin. Therefore one finds the spin sequence $+ + - -$ for the Cr atoms in the positions $(0, \frac{1}{2}, \frac{1}{2})$, $(\frac{1}{2}, 0, \frac{1}{2})$, $(\frac{1}{2}, \frac{1}{2}, 0)$, and $(0, \frac{1}{2}, \frac{3}{2})$.

Using this structure model the magnetic structure could be successfully refined, when the magnetic moments are aligned parallel to the c axis. The same type of magnetic ordering is found for BaMn$_2$As$_2$ and also for the Cr sublattice in EuCr$_2$As$_2$ [38]. Assuming an additional magnetic component within the $ab$ plane, magnetic intensity should appear at the position of the reflection 002. Magnetic intensity could not be easily determined from the difference patterns collected at 2 and 750 K, in the fully ordered and the paramagnetic state, because the strong structural changes lead to a change of the nuclear intensity of the reflection 002. Therefore we have refined simultaneously the crystal and the magnetic structure at 2K. The calculated nuclear intensity of the 002 reflection is even slightly larger than the observed one. This clearly indicates the absence of an additional magnetic component within the $ab$ plane, i.e. the absence of any spin canting to the $c$ axis. From the data set collected at 2K on instrument E9 we finally found for the Cr atoms a magnetic moment of $\mu_{\text{exp}} = 1.88(2)\mu_B$ resulting in a residual $R_M = 0.0268$ [defined as $R_M = (\Sigma|I_{\text{obs}} - |I_{\text{calc}}|)/\Sigma|I_{\text{obs}}|$. From the data set collected on instrument E2 the magnetic moment $\mu_{\text{exp}} = 1.80(2)\mu_B$ was found to be slightly smaller (residual $R_M = 0.118$). It has to be mentioned that the moment value determined from the E9 data is more reliable, since the overall scale factor could be determined with higher accuracy (a much larger number of nuclear Bragg reflections was available). From the data collected on E2, E6, and E9 we are able to determine the temperature dependence of the magnetic moment up to the Néel temperature $T_N = 580(10)$ K (see Figure 12). The results from the neutron diffraction experiments compare well with those from magnetization data of the BaCr$_2$As$_2$ single crystal (Fig. 3). The experimental magnetic Cr moments at 2 K compare reasonably well with the values obtained from our (cf. Table I and previous [35] electronic structure calculations. The experimental Cr moment is even slightly smaller than the calculated moments. This shows that electronic correlation effects reflected in the parameter $U$ of the LDA+$U$ calculations do not play a role as increasing $U$ lead to larger Cr magnetic moments.

Accordingly we have determined the magnetic struc-
ture of BaCrFeAs$_2$. As it can be seen in Figure 2 the strongest magnetic intensity could also be observed at the position of the reflection 101. The magnetic intensities of BaCrFeAs$_2$ are found to be much weaker than those in BaCr$_2$As$_2$ indicating that the averaged magnetic moments of the Cr and Fe atoms are strongly reduced. A moment $\mu_{\text{exp}} = 1.09(3) \mu_B$ was refined resulting in a residual $R_M = 0.068$. The Néel temperature $T_N = 265(5)$ K compares well with our magnetic susceptibility data (Fig. 9).

FIG. 13. Mössbauer spectra of BaCrFeAs$_2$ at the indicated temperatures. Dots correspond to the experimental data, solid lines to the best fits.

F. Mössbauer spectroscopy on BaCrFeAs$_2$

Representative $^{57}$Fe Mössbauer spectra of BaCrFeAs$_2$ are shown in Figure 13. The room temperature spectrum appears as a broadened line which can be fitted by a quadrupole doublet with an isomer shift $IS$ of 0.44 mm m s$^{-1}$ and a quadrupole splitting $QS$ of 0.13 mm m s$^{-1}$. By contrast, the spectrum at 5 K features a complex broad pattern which evidences the presence of magnetic hyperfine splitting. The spectrum was fitted by assuming a distribution of hyperfine fields, yielding $IS = 0.59$ mm m s$^{-1}$ and a peak hyperfine field $B_{hf} = 5.4$ T. The isomer shifts are slightly larger than those of BaFe$_2$As$_2$ [50] which adopts the SDW phase below the magnetic ordering temperature. Nevertheless the local electronic structure is quite similar in the two compounds. Most remarkably, the peak $B_{hf}$ of about 5 T in BaCrFeAs$_2$ is nearly the same as the $B_{hf}$ in the magnetically ordered phases of BaFe$_2$As$_2$ [50] and LaOFeAs [51]. From the neutron diffraction study we obtained an average magnetic moment of 1.09 $\mu_B$ per magnetic ion. Assuming that the Cr moment is the same as in BaCr$_2$As$_2$ (1.8 $\mu_B$) we estimate the iron moment as 0.4 $\mu_B$.

It has been pointed out that a direct estimation of Fe moments from $B_{hf}$ is questionable due to spin-orbit induced contributions to $B_{hf}$ in the iron pnictides [52]. Nevertheless, a small iron moment is in qualitative agreement with the small $B_{hf}$ for BaCrFeAs$_2$. A similarly small iron moment of 0.4 $\mu_B$ was reported for LaOFeAs [52], whereas a larger moment of 0.9 $\mu_B$ was derived for BaFe$_2$As$_2$ [10]. The spectra of BaCrFeAs$_2$ are, however, much less resolved than those of BaFe$_2$As$_2$ and LaOFeAs which reflects the Fe-Cr disorder in the present material giving rise to a broad $B_{hf}$ distribution. Both, neutron diffraction and Mössbauer data confirm that Fe and Cr atoms are disordered, while some previous electronic structure calculations assumed an ordered arrangement [4] and [30]. A large ordered Fe moment of 2.5–2.6 $\mu_B$ predicted from the electronic structure calculations for atomically ordered BaCrFeAs$_2$ (Ref. 30 and Table III) is incompatible with the neutron diffraction and the Mössbauer data.

FIG. 14. Hyperfine field distributions in the low-temperature range which were extracted from Mössbauer spectra of BaCrFeAs$_2$. The dashed lines indicate the positions of the peak hyperfine fields given in the Figure.

Indications for an unusual behavior of the Fe moments is obtained from the temperature dependence of $B_{hf}$. With increasing temperature a pronounced decrease in hyperfine splitting is apparent even in the temperature region 5-100 K (Figure 14), which is unexpected as the Néel temperature is much higher (265 K). At 100 K the $B_{hf}$ distribution even extends down to 0 T (Figure 14) indicating that a fraction of the iron atoms is already
non-magnetic. These observations are in contrast to the behavior of BaFe$_2$As$_2$ where in this temperature range only a minor reduction of $B_{hf}$ was observed although $T_N$ is considerably smaller ($\approx 140$ K) \cite{50}. The strong decrease of the peak $B_{hf}$ from 5.4 T at 5 K to 2.4 T at 100 K is also in sharp contrast to the temperature dependence of the total magnetic moments derived from neutron diffraction (Figure 12).

A possible scenario is that the Fe moments do not participate in the $G$-type afm structure and rather freeze in the low temperature range which is consistent with the fact that no anomaly is apparent in the temperature dependence of the moments between 2 and 100 K. The formation of the $G$-type afm order then is still driven by the large Cr moments. Further on, the upturn in the susceptibility $\chi(T)$ below $T_N = 265$ K (Fig. 9), which is in contrast to the behavior of BaCr$_2$As$_2$, is a further indication that the iron moments are at least partially disordered. As demonstrated above electronic structure calculations of atomically disordered BaCrFeAs$_2$ starting with zero Fe moment result in a stable solution with $\mu_{Fe} \approx 0$ and $\mu_{Cr} = 2.76 \mu_B$. The resulting average moment of 1.38 $\mu_B$ per formula unit of BaCrFeAs$_2$ is not too far from the experimental moment of 1.09 $\mu_B$. The mismatch of the Fe moments with $G$-type antiferromagnetism explains why $T_N$ in Fe-substituted BaCr$_2$As$_2$ decreases drastically from 580 K in the parent compound to $\approx 50$ K for an iron content of about 70% where finally the $G$-type order becomes unstable and is replaced by the SDW structure \cite{34}. At higher temperature the hyperfine splitting further decreases and for $T \geq 200$ K essentially a broad unstructured line is found. In this temperature range the Fe atoms are possibly polarized by the Cr moments. Above 260 K only minor changes in line broadening occur which compares well with $T_N = 265$ K obtained from neutron diffraction and susceptibility data.

IV. CONCLUSIONS

We have studied in detail the structural, electronic, and magnetic properties of BaCr$_2$As$_2$ and BaCrFeAs$_2$. BaCr$_2$As$_2$ as well as LaOCrAs \cite{31} and \cite{32} have been discussed recently in connection with the Mott scenario (see Section I) of transition-metal arsenide superconductivity. Our powder neutron diffraction studies verify that BaCr$_2$As$_2$ adopts the theoretically predicted $G$-type afm order at $T_N = 580$ K and an ordered moment $\mu_{Cr} = 1.9 \mu_B$ at 2 K. Evidence for magneto-structural coupling effects is to be clarified and this remains to be clarified whether this reflects some type of electronic instability. The experimental magnetic Cr moment agrees well with LDA electronic structure calculations whereas incorporation of electron correlation within the LDA+$U$ scheme leads to Cr moments which are too high. $T_N$ is 1/3 lower than the ordering temperature calculated within mean-field approximation, underlining the somewhat two-dimensional character of the magnetic system.

BaCrFeAs$_2$ still adopts this $G$-type afm structure but the ordering temperature is less than half of that of BaCr$_2$As$_2$. The small average moment $\mu_{Cr/Fe} \approx 1.1 \mu_B$ in connection with the small hyperfine field from Mössbauer spectra is in agreement with the results of our calculations for atomically disordered BaCrFeAs$_2$ and an Fe moment $\mu_{Fe} \approx 0$. The Néel temperature calculated within mean-field approximation is in good agreement with the experimental value (260 K and 265 K, respectively). Also the average Cr/Fe moment is in fair agreement with the calculation ($2.76 \mu_B$, distributed on two atoms). These findings, together with an anomalous temperature dependence of the hyperfine field, indicate that the small Fe moments are not incorporated into the $G$-type afm order. Thus it may be conjectured that Fe favors the stripe-type and Cr the checkerboard-type spin fluctuations, the latter being considered to be detrimental to superconductivity \cite{4}. In case of electron pairing mediated by spin-fluctuations this finding would be in agreement with the fact that so far no superconductivity was observed for BaCr$_2$As$_2$ or Cr-substituted BaFe$_2$As$_2$. Similarly, no superconductivity was found in Mn-substituted BaFe$_2$As$_2$, where the pure Mn compound BaMn$_2$As$_2$ adopts a stable $G$-type afm order as well. Accordingly not only the doping level but also the type of spin fluctuations has to be considered for predictions of new superconducting compositions.

Both BaCr$_2$As$_2$ and BaCrFeAs$_2$ are metals. The linear specific heat (Sommerfeld) coefficients $\gamma$ are much larger than expected from band theory, by a factor of 2.4 for BaCr$_2$As$_2$ and a huge factor of 5.5 for BaCrFeAs$_2$. The discrepancies for both compounds cannot be resolved by reasonable strengths of correlations. However it seems that for BaCrFeAs$_2$ the disorder of the magnetic Cr and Fe atoms to some extent additionally boosts the $\gamma$ value.

Our findings may be compared with results for the better investigated Mn 122 system. In contrast to BaCr$_2$As$_2$ BaMn$_2$As$_2$ is semiconducting \cite{5,6}. The nominal 3d$^5$ compound has a Néel temperature which is slightly higher than that of BaCr$_2$As$_2$. It is possible to induce a metallic state in BaMn$_2$As$_2$ by application of pressure \cite{44} or by hole-doping with as little as 1.6 % of K \cite{55}. In this metallic state Ba$_{1-x}$K$_x$Mn$_2$As$_2$ is still $G$-type ordered \cite{56} and is thus similar to BaCr$_2$As$_2$. But there is one important difference, the Sommerfeld $\gamma$ in the metallic Mn system is much smaller (8.4 mJ mol$^{-1}$ K$^{-1}$ for $x = 0.05$ \cite{52}) than in BaCr$_2$As$_2$. This suggests that electronic correlations are weak in the BaMn$_2$As$_2$ materials. A recent photoemission (ARPES) study corroborates that there is almost no band renormalization with respect to the DFT-based band structure in BaMn$_2$As$_2$ \cite{7}. An ARPES study on BaCr$_2$As$_2$ would therefore be highly welcome in order to shed more light on the development of electronic correlations in the 122 family of transition-metal arsenides.

For Ba$_{1-x}$K$_x$Mn$_2$As$_2$ the Néel temperature and the ordered Mn moment remain almost constant up to high substitution levels ($x \leq 0.4$) \cite{52}. In contrast, in
the substitution series BaFe$_{2-x}$Mn$_x$As$_2$ for a low Mn substitution level $x = 0.15$ a clear competition between stripe-type and checkerboard-type spin fluctuations could be observed by inelastic neutron scattering [57], quite similar to the BaCr$_{2-x}$Fe$_x$As$_2$ series [34]. For BaFe$_{2-x}$Mn$_x$As$_2$ a miscibility gap prevents the synthesis of single-phase material for Mn contents $x > 0.24$ [58].

Although both modified BaMn$_2$As$_2$-based (3$d^5$) materials [54, 57] as well as BaCr$_2$As$_2$ are afm-ordered metals, until now there are no ways known to obtain superconductors based on these materials. The partial substitution of Ba by K in BaCr$_2$As$_2$ (hole doping) showed to be unsuccessful, but surprisingly resulted in the discovery of superconducting K$_2$Cr$_3$As$_3$ [28 and 29]. Another way to possibly generate superconductivity in Mn or Cr-based 122 or 1111-type arsenides is the application of high pressure. With high pressure, in transition-metal arsenides structural instabilities come into play. We have now undertaken a structural and electrical transport study on one of our BaCr$_2$As$_2$ crystals under high pressure, the results of which will be reported elsewhere [54].

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10. A. Beleau et al., Large resistivity change and phase transition in the antiferromagnetic semiconductors LiMnAs and LaOMnAs, Phys. Rev. B 88, 184429 (2013), URL https://doi.org/10.1103/PhysRevB.88.184429


S. Medvedev et al., unpublished.