$CsMn(Br_xI_{1-x})_3$: Crossover from an XY to an Ising chiral antiferromagnet

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We report on high-resolution specific-heat and magnetocaloric-effect measurements of the triangular-lattice antiferromagnets $CsMn(Br_xI_{1-x})_3$ with different x. The evolution of the magnetic phase diagrams from the easy-axis system for $x=0$ to the easy-plane system for $x=1$ was studied in detail. The specific-heat critical exponent α of the almost isotropic $x=0.19$ system agrees with the value predicted for a chiral Heisenberg scenario. In an applied magnetic field ($B=6$ T) a crossover to a weak first-order transition is detected.

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I. INTRODUCTION

The triangular-lattice antiferromagnets ABX_3 with $CsNiCl_3$ structure, where the magnetic B^{2+} ions form a triangular lattice, exhibit frustration due to the antiferromagnetic interactions on a triangular plaquette if the magnetic moments have a component in the triangular ab plane. The magnetic moments then form a 120° structure, with the extra twofold degeneracy of chirality being broken at the antiferromagnetic transition. Simply speaking, the extra degeneracy arises from the possibility that the 120° spin structure on a given plaquette can be arranged clockwise or counterclockwise when moving around the plaquette. It has been suggested that the chiral degeneracy leads to new universality classes for three-dimensional XY and Heisenberg models.[1,2] The largest changes of the critical exponents are predicted to occur in the specific-heat exponent α, where the chiral XY and chiral Heisenberg universality classes are predicted to show $\alpha=0.34$ and 0.24, compared to $\alpha=-0.01$ and -0.12 for the standard XY and Heisenberg models, respectively.[2] This scenario has been confirmed very recently by a sixth-order field-theoretical expansion.[3] However, whether this concept of new universality classes is indeed applicable is a strongly debated question. Especially within recent years theoretical studies have supplied growing support for a weakly first-order scenario for both chiral phase transitions (see Refs. 4–6 and references therein). An experimental indication for this behavior was found recently.[7]

In any case, the frustration enhances the degeneracy giving rise to different physics with rich phase diagrams and strongly modified critical behavior, which has been studied experimentally for a large number of different triangular-lattice antiferromagnets.[8] A well-studied example is the easy-plane system $CsMnBr_3$, for which a number of experiments[9–13] revealed a critical behavior in line with the theoretical prediction.[2] For ABX_3 systems with easy-axis anisotropy like $CsMnI_3$ (as well as $CsNiCl_3$), chiral behavior can be induced by applying a spin-flop field along the easy c direction thus forcing the spins into the ab planes. At the spin-flop field B_M ($\sim$6.4 T for $CsMnI_3$ and $\sim$2.3 T for $CsNiCl_3$) the magnetic energy is equal to the anisotropy energy, i.e., full isotropy in spin space is attained and chiral Heisenberg behavior is found.[14–17] For higher fields, an easy-plane anisotropy is induced and XY chirality occurs.[16,17]

Not many triangular-lattice antiferromagnets with negligible anisotropy exist. Besides the above-mentioned materials at their spin-flop fields, only the hexagonal antiferromagnet VBr_2 is known. Indeed, for VBr_2 critical exponents were found in line with the behavior predicted for a chiral Heisenberg system.[18] The possibility to tune a chiral Heisenberg system is offered by the solid solution $CsMn(Br_xI_{1-x})_3$ that spans the range from an easy-axis system ($x=0$) to an easy-plane system ($x=1$). This system, therefore, allows us to study the crossover in the magnetic phase diagrams and its influence on the critical behavior. In particular, the composition with $x=0.19$ presents an almost isotropic system and should therefore follow chiral Heisenberg behavior.[19] Magnetization measurements of $CsMn(Br_xI_{1-x})_3$ that gave some information on the magnetic phase diagrams have already been reported by Ono *et al.*[19] Here we report on detailed specific-heat and magnetocaloric-effect measurements.

The spin Hamiltonian that describes the system is given by

$$\mathcal{H}=-J_c\sum_{i,j}^{\text{chain}}\mathbf{S}_i\cdot\mathbf{S}_j-J_{ab}\sum_{i,j}^{\text{plane}}\mathbf{S}_i\cdot\mathbf{S}_j+D\sum_i(S_i^z)^2 -g\mu_B\sum_i\mathbf{B}\cdot\mathbf{S}_i. \tag{1}$$

The summation (i,j) is over nearest neighbors, with the first sum along the c direction and the second sum in the ab plane, with the exchange constants J_c and J_{ab}, respectively. $D<0$ corresponds to an easy-axis system, $D>0$ to an easy-plane system. For $CsMnBr_3$, $J_c=-0.89$ meV, $J_{ab}=-1.7$ μeV, and $D=12$ μeV,[20] for $CsMnI_3$, $J_c=-1.5$ meV, $J_{ab}=-7.6$ μeV, and $D=-3.8$ μeV.[21] For both materials we are dealing with the $S=5/2$ spins of Mn^{2+}.

The topology of the magnetic phase diagrams for ABX_3 antiferromagnets depends crucially on the sign of D and on the ratio D/J_{ab}. Systems with Ising anisotropy ($D<0$) show two successive phase transitions at T_{N1} and T_{N2} for $B=0$ (see, e.g., Refs. 14, 16, and 17). In the low-temperature phase ($T<T_{N2}$) the spins order in three sublattices where one-third of the spins align along the c axis, whereas the other two-

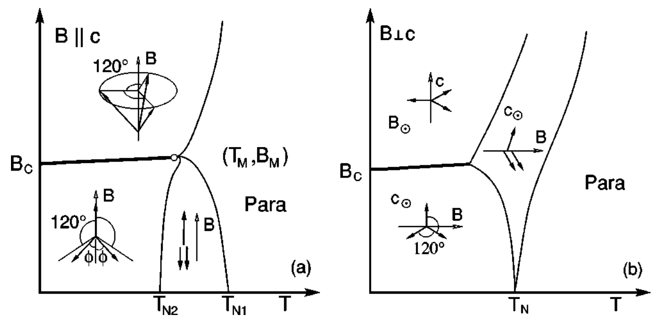

FIG. 1. (a) Schematic phase diagram of a triangular-lattice antiferromagnet with easy-axis anisotropy ($D<0$) for $B\|c$. The phase lines meet at the multicritical point (T_M,B_M). B_c is the critical field for the spin-flop transition. (b) The schematic phase diagram for systems with a small easy-plane anisotropy $0<D<3|J_{ab}|$ for $B\perp c$. The insets sketch the spin arrangements.

thirds are tilted by an angle Φ [which depends on the ratio D/J_{ab} (Ref. 8)] with respect to the c axis [see Fig. 1(a)]. For $CsMnI_3$ this angle is $\Phi=51°$.[21] All spins lie within a plane that includes the c axis. At higher temperatures in the intermediate phase ($T_{N2}<T<T_{N1}$) the tilted spins have an additional degree of freedom, i.e., their components within the basal ab plane are not defined. For $T>T_{N1}$ in the paramagnetic phase only short-range ordered independent spin chains exist along the c axis. For a magnetic field applied within the basal plane ($B\perp c$) the two phase boundaries shift somewhat to higher temperatures (at least up to 6 T for $CsMnI_3$ and $CsNiCl_3$) without changing the principal spin topology.[14,22]

Of much more relevance is the case when B is applied along c [Fig. 1(a)]. For $T<T_{N2}$, a first-order phase transition occurs at the spin-flop field B_c above which the three sublattices form a 120° umbrellalike structure. The c-axis spin component grows with further increasing B. For classical spins with $J_c \gg J_{ab}$, B_c at $T=0$ is given by

$$(g\mu_B B_c)^2 = 16|J_c D|S^2. \tag{2}$$

At the multicritical point (T_M,B_M) the three phase lines merge tangentially into the first-order spin-flop line.[23,24] At this point full isotropy in spin space is achieved that leads to a chiral Heisenberg universality as experimentally observed for $CsNiCl_3$ (Refs. 16 and 17) and $CsMnI_3$.[14]

For systems with easy-plane anisotropy ($D>0$) only one phase transition at T_N from the paramagnetic to the chiral 120° structure exists at $B=0$. The critical behavior, therefore, is of the chiral XY type. A magnetic field applied along the c direction does not change the symmetry of the ground state. Consequently, the critical behavior stays essentially constant.[12] A much richer phase diagram can be observed for $B\perp c$. The phase diagram as predicted for $D<3|J_{ab}|$ is shown in Fig. 1(b).[25] At $T<T_N$ and $B<B_c$ the chiral phase exists. The competition between the Zeeman energy and the anisotropy energy leads to a spin-flop phase above B_c that is also given by Eq. (2).[8] Thereby, the spin triangle is oriented perpendicularly to B. Between the chiral low-temperature and the paramagnetic high-temperature phase, a collinear spin structure evolves where the spins remain in the ab plane

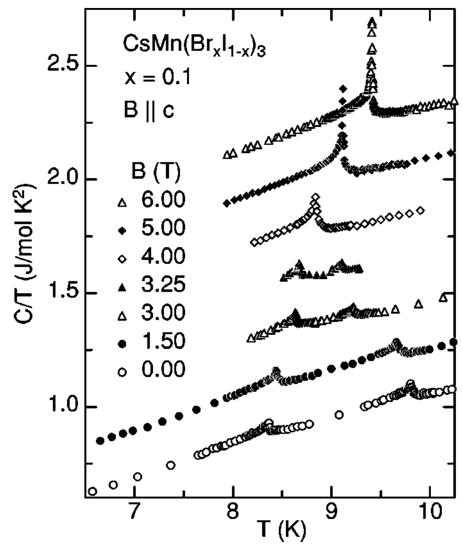

FIG. 2. Specific heat C divided by temperature T vs T for $CsMn(Br_{0.1}I_{0.9})_3$ in a magnetic field B parallel to the c direction. Data are shifted consecutively by 0.2 J/mol K^2 with respect to $B=0$.

with two spins of a triangle pointing parallel and one in the opposite direction. With increasing field the spin components along B become larger.

Experimentally, very little is known about the phase diagrams and the critical properties of easy-plane systems with such a small anisotropy ($D<3|J_{ab}|$).[8] On the other hand, for materials with $D>3|J_{ab}|$, like $CsMnBr_3$, the phase diagram has been very well established.[10,14,26] Due to the stronger anisotropy D the spin-flop phase is absent for such XY systems with only the chiral phase and the collinear structure remaining.[8]

II. EXPERIMENT

Single-crystalline samples of $CsMn(Br_xI_{1-x})_3$ were grown by the Bridgman technique at the Tokyo Institute of Technology.[19] For the measurements pieces of 24–111 mg were cleaved from the crystals. The specific heat C was measured by a standard semiadiabatic heat-pulse technique. Magnetic fields up to 14 T were applied either along or perpendicular to the clearly visible c axis of the crystals. The magnetocaloric effect, $(\delta T/\delta B)_S = -(T/C)(\delta S/\delta B)_T$, was measured in the same calorimeter. S denotes the entropy of the system. Upon changing the magnetic field by small steps ΔB, the resulting temperature variation ΔT was recorded. Taking into account the small eddy-current heating the magnetocaloric effect $\Delta T/\Delta B$ was extracted. For more details on the experiment see Ref. 27.

III. RESULTS AND DISCUSSION

The specific heat of the sample with the smallest Br concentration, $CsMn(Br_{0.1}I_{0.9})_3$, is shown in Fig. 2 for different fields B aligned along the c direction. This easy-axis system shows two consecutive zero-field transitions, which merge into one at the spin-flop field of about 4 T. The steep

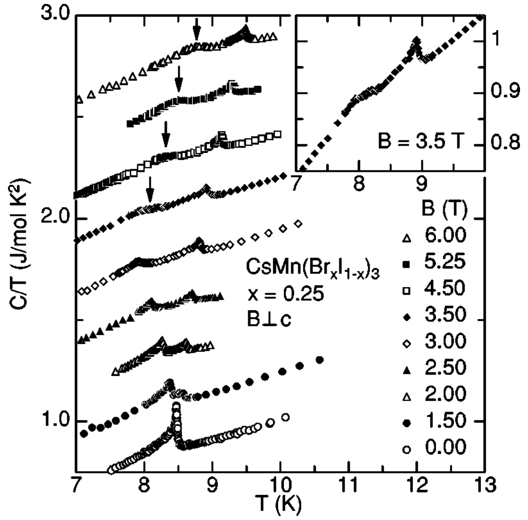

FIG. 3. C/T vs T for $CsMn(Br_{0.25}I_{0.75})_3$ in $B\perp c$. Data are shifted consecutively by 0.2 J/mol K^2 with respect to $B=0$. The arrows indicate the phase transitions between the spin-flop phase and the intermediate collinear phase. The inset shows an enlargement of the data at $B=3.5$ T.

anomaly found beyond this field resembles that found for pure $CsMnI_3$ that was analyzed in terms of a chiral Heisenberg model at the spin-flop field $B_M\approx 6.4$ T.[14] The substitution of 10% of the I^- ions by Br^- with the concomitant increase of the (negative) anisotropy D towards zero reduces considerably the spin-flop field and likewise the width of the intermediate phase ($T_{N2}=8.36$ K$<T<T_{N1}=9.80$ K). This trend continues further for a sample with $x=0.18$ (data not shown) where $T_{N1}=8.50$ K, $T_{N2}=8.40$ K, and $B_M\approx 1$ T (see also Figs. 6 and 7 below).

The data for $x=0.25$, on the other hand, resemble those of the pure easy-plane system $CsMnBr_3$,[14,26] where a magnetic field in the ab plane quickly removes the chiral degeneracy and leads to a splitting of the zero-field transition (Fig. 3). In contrast to pure $CsMnBr_3$, however, the anomaly at lower temperatures changes its appearance above about 3 T, i.e., the anomaly (visualized by the arrows in Fig. 3) becomes much more rounded and the feature in C shifts towards higher temperatures for increasing B rather than to lower T as in $CsMnBr_3$.[14,26] Indeed, what is reflected by the low-temperature anomalies in Fig. 3 are two different phase transitions; from the chiral phase to the collinear phase at low B and from the spin-flop phase to the collinear phase at B larger than about 3 T [see Fig. 1(b) and also the phase diagram in Fig. 6 below]. This result, therefore, reflects the fact that the anisotropy D for $x=0.25$ has switched from negative to positive, with $D<3|J_{ab}|$. We found a similar behavior with a considerably reduced width of the collinear phase in the specific heat of a sample with $x=0.20$ (data not shown).

Consequently, the anisotropy D should become zero somewhere between $x=0.18$ and $x=0.20$. A good candidate for such a chiral Heisenberg system is therefore $CsMn(Br_{0.19}I_{0.81})_3$. For an isotropic Heisenberg system only one phase-transition line from the paramagnetic to the chiral phase is expected, independent of the magnetic-field orientation. Indeed, magnetization and susceptibility data could not observe any spin-flop line or splitting of the zero-field transition.[19] Our specific-heat data for $B\|c$ [Fig. 4(a)] are in line with these observations. We particularly can resolve only a single strong anomaly at T_N that becomes somewhat larger with increasing field up to 6 T, similar to what is observed for $x=0.1$ above B_M.

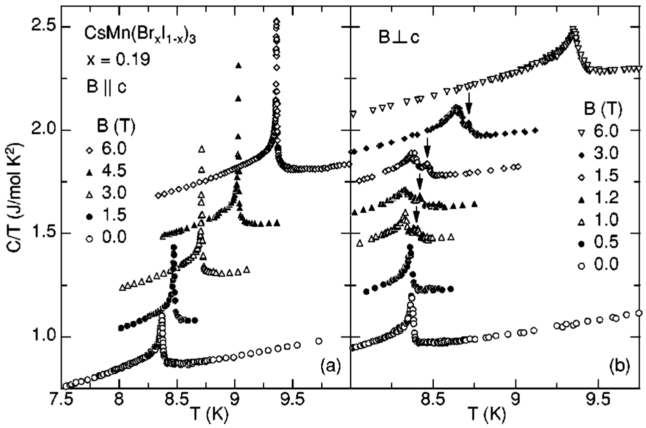

FIG. 4. C/T vs T for $CsMn(Br_{0.19}I_{0.81})_3$ in magnetic fields (a) B parallel and (b) B perpendicular to the c direction. Data are shifted by different amounts with respect to $B=0$. The arrows highlight the small anomaly indicating the transition from the intermediate phase to the paramagnetic phase.

However, measurements of $CsMn(Br_{0.19}I_{0.81})_3$ for $B\perp c$ [Fig. 4(b)] reflect a small residual planar anisotropy, as evidenced by a slight splitting of the transition in fields between 1 and 3 T. The anomaly at lower temperatures is still relatively sharp and large at $B=1$ T, but becomes clearly reduced at 1.2 T that indicates the junction with the spin-flop phase line. At higher fields the phase lines merge and only one anomaly remains at 6 T.

In order to determine the complete phase diagrams including the expected spin-flop lines (see Fig. 1) we measured the magnetocaloric effect for all samples. Since the spin-flop transition at B_c is almost temperature independent, the specific heat is not sensitive to this transition, contrary to magnetocaloric-effect measurements that cross the corresponding phase line at an approximately right angle. Figure 5(a) shows the magnetocaloric effect for the samples with $x=0.18$ and $x=0.19$ at $T\approx 7$ K in fields aligned parallel to the c axis. For $x=0.18$, a clear step at about 0.9 T is visible that signals the spin-flop transition in line with the data of Ono *et al.*[19] The spin-flop field at each temperature was estimated from the position of the maximum in the derivative of the magnetocaloric-effect data. For $x=0.19$, $\Delta T/\Delta B$ increases monotonically without any detectable step or anomaly. This confirms that $CsMn(Br_{0.19}I_{0.81})_3$ has no Ising-like anisotropy.

Instead the anisotropy D has switched to an XY type, as the specific-heat data [Fig. 4(b)] show. Consequently, a spin-flop line is expected for fields perpendicular to c [see Fig. 1(b)]. Indeed, magnetocaloric-effect data could verify this phase diagram by showing a steplike feature at about 1.2 T almost independent of temperature [Fig. 5(b)]. Therefore, the critical concentration for which $D=0$ should be just below $x=0.19$.

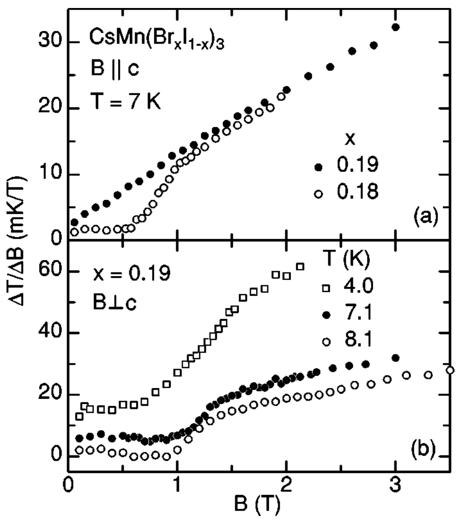

FIG. 5. Magnetocaloric effect of (a) $CsMn(Br_{0.19}I_{0.81})_3$ and $CsMn(Br_{0.18}I_{0.82})_3$ in $B\|c$ and (b) of $CsMn(Br_{0.19}I_{0.81})_3$ for three different temperatures in $B\perp c$. Data in (b) are shifted consecutively by 5 mK/T with respect to $T=8.1$ K.

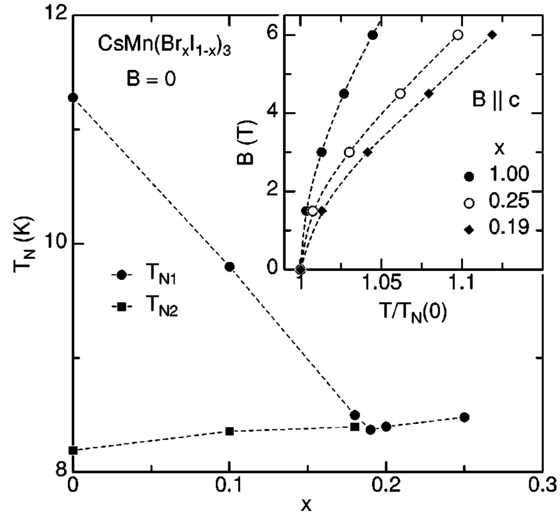

FIG. 7. Transition temperatures T_{N1} and T_{N2} of $CsMn(Br_xI_{1-x})_3$ at $B=0$ as a function of x. The data for $CsMnI_3$ are from Ref. 22. Lines are guide to the eye. The inset shows the field dependence of the normalized transition temperatures for three concentrations in $B\|c$.

Figure 6 summarizes the results in terms of (B,T) phase diagrams for various x. In Fig. 6(a), the absolute magnitude of the easy-axis anisotropy $(D<0)$ decreases with increasing x, getting close to zero for $x=0.18$. From the reduced spin-flop field $B_c\approx 1$ T for $x=0.18$ one can estimate with Eq. (2) that $|J_cD|$ has reduced to about 2.5% of the value for $CsMnI_3$. Since J_c should depend little on x, this means that $|D|$ has reduced to about 95 neV corresponding to 1.1 mK. The phase diagrams for $x=0.10$ and $x=0.18$ fully agree with the predicted behavior for easy-axis systems [Fig. 1(a)].[8]

The phase-diagram topology changes for easy-plane systems with $D>0$. In Fig. 6(b), the absolute magnitude of D increases with x, with a small anisotropy present for $x=0.19$. As for $B\|c$, the phase diagrams for $B\perp c$ $(D>0)$ are in full agreement with mean-field calculations and verify nicely the predictions for easy-plane systems with $D<3|J_{ab}|$.[25]

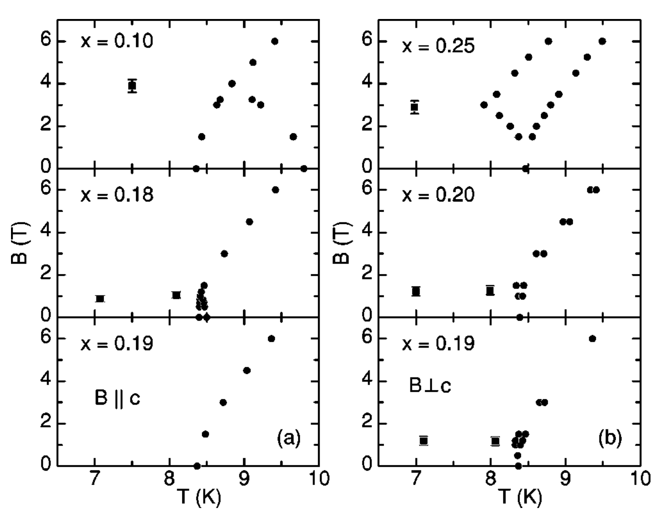

FIG. 6. Phase diagrams of $CsMn(Br_xI_{1-x})_3$ (a) for fields along the c direction for $x\leqslant 0.19$ and (b) for fields perpendicular to c for $x\geqslant 19$.

The phase diagram of the transition temperatures vs Br concentration x is shown in Fig. 7. The lower Néel temperature T_{N2} increases slightly with x, whereas T_{N1} rapidly decreases. The two phase lines merge at a critical concentration x_c somewhere between $x=0.18$ and $x=0.19$. The phase diagram is in line with that reported by Ono *et al.*[19] With our specific-heat and magnetocaloric-effect measurements, however, we were able to resolve the spin-flop line and the intermediate collinear phase for $x=0.19$ at fields between 1 and 3 T proving that the critical concentration with $D=0$ must be slightly less than $x=0.19$.

For completeness, the inset of Fig. 7 shows a comparative B-T phase diagram for different chiral XY systems with B aligned along the c direction. The data for $CsMnBr_3$ are from Ref. 28. With increasing field the phase transition from the paramagnetic to the chiral phase shifts to higher temperatures. This effect is less prominent for larger x indicating that the field-induced T_N increase becomes larger for reduced D.

As a final point, we discuss the critical behavior of $CsMn(Br_xI_{1-x})_3$. In order to describe the specific-heat data close to the critical temperature T_c we applied the usual fit function[29]

$$C^{\pm}=(A^{\pm}/\alpha)|t|^{-\alpha}+B+Et, \tag{3}$$

where $t=(T-T_c)/T_c$ and the superscript $+$ $(-)$ refers to $t>0$ $(t<0)$. The first term describes the leading contribution to the singularity in C and the nonsingular contribution to the specific heat is approximated by $B+Et$. After a good fit of the data had been achieved except very close to T_c, a Gaussian distribution of T_c with width δT_c was introduced. This procedure is able to describe a rounding of the transitions caused by sample inhomogeneities (see also Refs. 14 and 15).

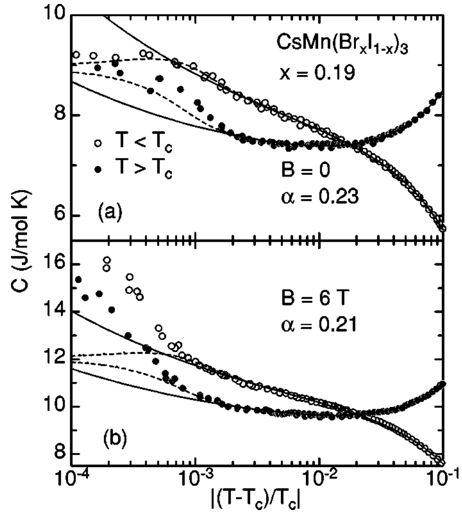

FIG. 8. Specific heat C of $CsMn(Br_{0.19}I_{0.81})_3$ vs $\ln|(T-T_c)/T_c|$ for (a) $B=0$ and (b) $B=6$ T. The solid lines are fits according to Eq. (3), the dash-dotted lines are fits including a Gauss-distributed smearing of T_c.

Figure 8(a) shows the specific heat C for $x=0.19$ vs the reduced temperature $|t|$ at $B=0$. The data are compatible with an exponent $\alpha=0.23(7)$ of the specific heat if we include a Gaussian broadening of $\delta T_c/T_c\approx 4.2\times 10^{-4}$. The dashed lines indicate the fit with these parameters, while the solid lines represent a fit with $\delta T_c=0$. The exponent α as well as the experimental amplitude ratio $A^+/A^-=0.54(13)$ are in line with the chiral Heisenberg model, which predicts $\alpha=0.24(8)$ and $A^+/A^-=0.54(20)$.[2] This is in accordance with the small easy-plane anisotropy that obviously is too small to force the system to XY chirality. The available results of neutron-scattering experiments for $x=0.19$ are rather inconclusive.[30] While the exponent $\beta=0.28(2)$ of the sublattice magnetization agrees well with the theoretical value of a chiral Heisenberg system ($\beta=0.30$), the exponents of the susceptibility, $\gamma=0.75(4)$, and of the correlation length, $\nu=0.42(3)$, are at variance with the predictions ($\gamma=1.17$ and $\nu=0.59$). Furthermore, the experimentally found exponents are in contradiction with the fundamental scaling laws $\alpha+2\beta+\gamma=2$ and $\alpha+d\nu=2$ (d is the dimension), which should be fulfilled at universal second-order phase transitions.

Theoretically, the region around the multicritical point where a chiral Heisenberg scenario is expected should not be large.[31] This would imply that either the increase of the Br concentration ($x>x_c$) or the application of a large magnetic field ($B>B_M$) should drive the system quickly to chiral XY behavior with $\alpha=0.34(6)$, which for $CsMnBr_3$ ($x=1$) has been observed.[11,12] Nevertheless, for $x=0.20$ and for $x=0.25$ the critical exponents remain approximately constant with $\alpha=0.25(7)$ and $\alpha=0.20(6)$, respectively, suggesting that the chiral Heisenberg behavior is rather stable.

Another unexpected result becomes obvious from the analysis of the specific-heat data of $x=0.19$ in $B=6$ T applied along the c direction [Fig. 8(b)]. A magnetic field of this strength, i.e., much larger than B_M, should induce XY chirality for a system with Ising anisotropy as previously observed for $CsNiCl_3$ (Refs. 16 and 17) and, in this work, with $\alpha=0.37(10)$ for $CsMn(Br_{0.1}I_{0.9})_3$ at $B=6$ T (not shown). Likewise, for an easy-plane system like $CsMnBr_3$ the critical behavior remains chiral XY-like for fields applied along c.[12] However, for $x=0.19$ (as well as for $x=0.18$, data not shown) in a magnetic field of 6 T, C for $t\geqslant 10^{-3}$ still follows a chiral Heisenberg-like behavior with $\alpha=0.21(8)$ [$\alpha=0.23(6)$ for $x=0.18$] and increases much more strongly for $t\rightarrow 0$, which can neither be described by a reasonable critical exponent nor by a T_c distribution. This possibly indicates a crossover to a weakly first-order transition, similar as previously observed for $CsCuCl_3$ close to T_c at $B=0$.[7]

In conclusion, we have mapped out in detail the impact of an axial vs a planar anisotropy on the magnetic phase diagrams of triangular-lattice antiferromagnets by fine tuning x of the system $CsMn(Br_xI_{1-x})_3$. In particular, the predicted phase diagram [Fig. 1(b)] of easy-plane systems with small anisotropy could by accurately verified. The critical concentration, for which the spin anisotropy vanishes, was found to be located between $x=0.18$, a system with small axial anisotropy ($D<0$), and $x=0.19$, a system with small planar anisotropy ($D>0$). The critical behavior at $B=0$ for $x=0.19$, $x=0.20$, and $x=0.25$ can be described with critical exponents α as predicted from Monte Carlo simulations for the chiral Heisenberg universality class.[2] Thereby, rounding effects due to sample inhomogeneities prevent the possible detection of a crossover to a first-order scenario as proposed recently.[5] In a magnetic field $B=6$ T, the samples with $x=0.18$ and $x=0.19$ show a weakly first-order phase transition. For $10^{-3}<t<0.1$, the data can be described by chiral Heisenberg critical exponents. For all other samples with either larger planar or larger axial symmetry, no indication for a first-order phase transition was detected.

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[1] H. Kawamura, J. Phys. Soc. Jpn. **54**, 3220 (1985); **55**, 2095 (1986).

[2] H. Kawamura, J. Phys.: Condens. Matter **10**, 4707 (1998), and references therein.

[3] A. Pelissetto, P. Rossi, and E. Vicari, Phys. Rev. B **63**, R140414 (2001).

[4] D. Loison and K.D. Schotte, Eur. Phys. J. B **5**, 735 (1998).

[5] M. Tissier, B. Delamotte, and D. Mouhanna, Phys. Rev. Lett. **84**, 5208 (2000).

[6] D. Loison and K.D. Schotte, Eur. Phys. J. B **14**, 125 (2000).

[7] H.B. Weber, T. Werner, J. Wosnitza, H.v. Löhneysen, and U. Schotte, Phys. Rev. B **54**, 15 924 (1996).

[8] M.F. Collins and O.A. Petrenko, Can. J. Phys. **75**, 605 (1997).
[9] H. Kadowaki, S.M. Shapiro, T. Inami, and Y. Ajiro, J. Phys. Soc. Jpn. **57**, 2640 (1988).
[10] T.E. Mason, B.D. Gaulin, and M.F. Collins, Phys. Rev. B **39**, 586 (1989).
[11] J. Wang, D.P. Belanger, and B.D. Gaulin, Phys. Rev. B **66**, 3195 (1991).
[12] R. Deutschmann, H.v. Löhneysen, J. Wosnitza, R.K. Kremer, and D. Visser, Europhys. Lett. **17**, 637 (1992).
[13] V.P. Plakhty, J. Kulda, D. Visser, E.V. Moskvin, and J. Wosnitza, Phys. Rev. Lett. **85**, 3942 (2000).
[14] H. Weber, D. Beckmann, J. Wosnitza, H.v. Löhneysen, and D. Visser, Int. J. Mod. Phys. B **12**, 1387 (1995).
[15] H.v. Löhneysen, D. Beckmann, J. Wosnitza, and D. Visser, J. Magn. Magn. Mater. **140-144**, 1469 (1995).
[16] D. Beckmann, J. Wosnitza, H.v. Löhneysen, and D. Visser, Phys. Rev. Lett. **71**, 2829 (1993).
[17] M. Enderle, G. Furtuna, and M. Steiner, J. Phys.: Condens. Matter **6**, L385 (1994).
[18] J. Wosnitza, R. Deutschmann, H.v. Löhneysen, and R.K. Kremer, J. Phys.: Condens. Matter **6**, 8045 (1994).
[19] T. Ono, H. Tanaka, T. Kato, and K. Iio, J. Phys.: Condens. Matter **10**, 7209 (1998).
[20] U. Falk, A. Furrer, H.U. Güdel, and J.K. Kjems, Phys. Rev. B **35**, 4888 (1987).
[21] A. Harrison, M.F. Collins, J. Abu-Dayyah, and C.V. Stager, Phys. Rev. B **43**, 679 (1991).
[22] D. Beckmann, J. Wosnitza, H.v. Löhneysen, and D. Visser, J. Phys.: Condens. Matter **5**, 6289 (1993).
[23] M.L. Plumer, K. Hood, and A. Caillé, Phys. Rev. Lett. **60**, 45 (1988).
[24] H. Kawamura, A. Caillé, and M.L. Plumer, Phys. Rev. B **41**, 4416 (1990).
[25] M.L. Plumer, A. Caillé, and K. Hood, Phys. Rev. B **39**, 4489 (1989).
[26] B.D. Gaulin, T.E. Mason, M.F. Collins, and J.Z. Larese, Phys. Rev. Lett. **62**, 1380 (1989).
[27] F. Pérez, T. Werner, J. Wosnitza, H.v. Löhneysen, and H. Tanaka, Phys. Rev. B **58**, 9316 (1998).
[28] R. Deutschmann, J. Wosnitza, and H. v. Löhneysen (unpublished).
[29] A. Kornblit and G. Ahlers, Phys. Rev. B **8**, 5163 (1973).
[30] T. Ono, H. Tanaka, T. Kato, K. Iio, K. Nakajima, and K. Kakurai, J. Magn. Magn. Mater. **177-181**, 735 (1998); T. Ono, H. Tanaka, T. Kato, K. Nakajima, and K. Kakurai, J. Phys.: Condens. Matter **11**, 4427 (1999).
[31] H. Kawamura, Phys. Rev. B **47**, 3415 (1993).