

ACCEPTED MANUSCRIPT • OPEN ACCESS

Trapped flux in a small crystal of $\text{CaKFe}_4\text{As}_4$ at ambient pressure and in a diamond anvil pressure cell

To cite this article before publication: Sergey L Bud'ko *et al* 2024 *Supercond. Sci. Technol.* in press <https://doi.org/10.1088/1361-6668/ad45c7>

Manuscript version: Accepted Manuscript

Accepted Manuscript is “the version of the article accepted for publication including all changes made as a result of the peer review process, and which may also include the addition to the article by IOP Publishing of a header, an article ID, a cover sheet and/or an ‘Accepted Manuscript’ watermark, but excluding any other editing, typesetting or other changes made by IOP Publishing and/or its licensors”

This Accepted Manuscript is © 2024 The Author(s). Published by IOP Publishing Ltd.



As the Version of Record of this article is going to be / has been published on a gold open access basis under a CC BY 4.0 licence, this Accepted Manuscript is available for reuse under a CC BY 4.0 licence immediately.

Everyone is permitted to use all or part of the original content in this article, provided that they adhere to all the terms of the licence <https://creativecommons.org/licenses/by/4.0>

Although reasonable endeavours have been taken to obtain all necessary permissions from third parties to include their copyrighted content within this article, their full citation and copyright line may not be present in this Accepted Manuscript version. Before using any content from this article, please refer to the Version of Record on IOPscience once published for full citation and copyright details, as permissions may be required. All third party content is fully copyright protected and is not published on a gold open access basis under a CC BY licence, unless that is specifically stated in the figure caption in the Version of Record.

View the [article online](#) for updates and enhancements.

Trapped flux in a small crystal of $\text{CaKFe}_4\text{As}_4$ at ambient pressure and in a diamond anvil pressure cell

Sergey L Bud'ko ^{*}, Shuyuan Huyan , Mingyu Xu  and Paul C Canfield 

Ames National Laboratory and Department of Physics and Astronomy, Iowa State University, Ames, Iowa 50011, USA

E-mail: budko@ameslab.gov

Abstract.

In an extension of our previous work, [Sergey L Bud'ko et al 2023 *Supercond. Sci. Technol.* **36** 115001] the measurements of temperature dependent magnetization associated with trapped magnetic flux in a small single crystal of $\text{CaKFe}_4\text{As}_4$, using zero - field - cooled and field - cooled protocols were performed, on the same crystal, at ambient pressure without a pressure cell and at 2.2 GPa in a commercial diamond anvil cell (DAC), showing comparable results. The data show that with a proper care and understanding, trapped flux measurements in superconductors indeed can be performed on samples in DACs under pressure, as was done on superhydrides [V S Minkov et al 2023 *Nat. Phys.* **19** 1293].

Submitted to: *Supercond. Sci. Technol.*

1. Introduction

The phenomenon of trapped flux in superconductors has been detected and examined for more than half a century. [1] In type II superconductors it is more pronounced and ubiquitous, with the general physical picture given by considering Bean's critical state model [2, 3] and the pinning of vortices. More recently, the interest in trapped flux in superconductors was shifted to potential applications (see e.g. Ref. [4]), however the importance of this phenomenon as one of the experimental proofs of superconductivity was well appreciated. [5] Indeed trapped flux measurements were used as one of the experimental confirmations of superconductivity in H_3S at high pressure. [6] It was shown [6] that, in contrast to traditional dc magnetization measurements, the trapped flux magnetization data are almost unaffected by the background signal of the diamond

*Author to whom any correspondence should be addressed.

Trapped flux in small CaKFe₄As₄ crystal

anvil cell due to the virtual absence of external magnetic fields in this measurement protocol.

In Ref. [7] detailed measurements of magnetization associated with the flux trapped in superconducting crystals of MgB₂ as well as pure and Mn-substituted CaKFe₄As₄ at ambient pressure were reported. These data were proposed to serve as a baseline for interpretation of high pressure, trapped flux measurements in superhydrides. [6] Indeed, there was a remarkable similarity between the sets of data in Ref. [6] and Ref. [7]. This said, though, the issue of sample size, and associated signal, could be considered a remaining point that still needed bench-marking. The volume of our CaKFe₄As₄ sample in Ref. [7] was more than 1000 times larger than the sample volume that a high pressure DAC could be expected to accommodate.

In the desire to address concerns about sample size and signal associated with trapped flux measurements in a DAC, we present trapped flux measurements on a small CaKFe₄As₄ sample both at ambient pressure, without a DAC and under 2.2 GPa pressure in a commercial DAC and compare the resulting data sets with each other as well as with recent trapped flux result on hydride superconductors, also in DAC. [6] We also briefly discuss possible modifications of measurements protocols and some challenges that the use of commercial DACs presents.

2. Experimental details

Single crystals of CaKFe₄As₄ with sharp superconducting transitions ($T_c = 34.7$ K) were grown using high-temperature solution growth. [8, 9] These crystals grow as mirrorlike, metallic, micaceous plates with the crystallographic c axis is perpendicular to the plate surface (as determined by x-ray diffraction). The sample used in the measurements was a thin plate with the c - axis perpendicular to the plate and approximately of a cuboid shape with some irregularities. The width and the length of the sample were measured using an optical microscope as $\sim 0.1 \times 0.08$ mm², whereas the thickness or the mass were not determined due to resolution of available instruments and a concern for keeping the sample intact. Instead, the mass of ~ 0.5 μ g can be inferred from the low field magnetization measurements, shown in Fig. 1, assuming complete shielding, and the density (~ 5.2 g/cm³) inferred from the unit cell parameters as determined by x-ray diffraction. [10] The CaKFe₄As₄ crystal used in this work was cleaved and cut from one of the larger crystals, that showed no presence of secondary phases in magnetization measurements (see Ref. [9] for the details of how the samples are pre-selected). The size of the sample was specifically chosen to approximately match the size of the H₃S sample measured in Ref. [6]. As mentioned above, a detailed study of trapped flux in larger, mm-size, crystal of CaKFe₄As₄ is presented in Ref. [7].

Ambient pressure magnetization measurements were performed in a Quantum Design Magnetic Property Measurement System (MPMS3) SQUID magnetometer in the dc mode (30 mm scan length, a standard value for MPMS3) with a half-cylindrical quartz sample holder [11] with a small L - shaped adapter (of the mass ~ 4 mg) made

Trapped flux in small CaKFe₄As₄ crystal

3

out of 0.05 mm thick copper foil used to position the sample with $H||c$. The sample was attached to the adapter by a thin layer of Dow Corning high vacuum grease. At ambient pressure we followed exactly the same measurements protocols as in Ref. [7]. In brief, in field-cooled (FC) protocol the sample was cooled down from above T_c in the target field, H_M ; after the temperature was stabilized at the target base temperature (1.8 K), the magnetic field was decreased to $H = 0$; then after 1 min dwell time, $M(T)$ measurements started. In zero-field cooled (ZFC) protocol: the sample was cooled down from above T_c in $H = 0$; after the temperature was stabilized at the target base temperature, the magnetic field was increased to the target field, and then the magnetic field was decreased back to $H = 0$; then, after a 1 min dwell time, $M(T)$ measurements started.

The DC magnetization measurements under high pressure were performed in a Quantum Design MPMS-classic SQUID magnetometer, with the standard for this unit scan length of 60 mm. (Note that the use of different models of MPMS instruments for measurements at ambient pressure and under pressure in DAC in this work was dictated by scheduling and availability reasons.) To ensure better thermalization of the DAC, for each temperature point, after instrument temperature stabilization a delay of 45 sec. was implemented. 300 sec. wait time was used after the change of magnetic field. The same wait / delay times were used in our previous measurements with the same DAC in the same MPMS-classic (see e.g. [12]). For more convenient temperature control, in the trapped flux measurements with DAC we used $T = 5$ K as a base temperature. A commercial DAC, (Almax - easyLab Mcell Ultra [13]) with a pair of 700- μ m-diameter culet-sized diamond anvils and tungsten gasket with 300- μ m-diameter hole, was used. Nujol mineral oil, that solidifies at ~ 1.3 GPa at room temperature, served as the pressure medium. [14] The pressure at room temperature was measured by the R_1 fluorescence line of a ruby ball. [15] The background signal of the DAC with gasket, ruby ball and pressure medium but without sample was measured under 2 GPa using the same protocols as in the measurements with the sample. Given that our intent in this work is to use commercially available measurement systems as well as pressure cells, we do want to point out that there are ways to minimize the cell background even further by using specialty alloys rather than the more standard Be-Cu alloys. In Appendix A we briefly address this point.

The magnetization of the sample was analyzed using a point by point subtraction of the SQUID response with/without the sample, and then a dipole fitting on the resulting curve, following Ref. [16]. Examples of this procedure are shown in the Appendix B. Measurements under pressure were performed at one pressure point, 2.2 GPa. Although the chosen size of the sample and the DAC would allow us to go to significantly higher pressure, we wanted to ensure that we are clearly below the ~ 4 GPa critical pressure of the structural transition of the CaKFe₄As₄ sample's transition to half collapsed tetragonal phase [17], since no bulk superconductivity is observed above this critical pressure.

Trapped flux in small $\text{CaKFe}_4\text{As}_4$ crystal

4

3. Results

3.1. Ambient pressure

Low field ZFC and FC temperature dependent magnetization of $\text{CaKFe}_4\text{As}_4$ is shown in Fig. 1. The superconducting transition with $T_c \approx 34.7$ K is clearly seen in ZFC data, in agreement with the literature. [7, 8] No feature at T_c , within resolution, is observed in the FC data. As discussed in Refs. [8] and [7], this is consistent with $\text{CaKFe}_4\text{As}_4$ having relatively large pinning. Note that the measured diamagnetic signal from the sample is comparable (albeit factor of ~ 3 larger, with the difference coming from the sample volume and demagnetization factor) to those reported for H_3S and LaH_{10} . [18] Data for the temperature-dependent magnetization associated with the trapped field taken using FC and ZFC protocols are shown in Fig. 2 and the summary plot of the trapped field magnetization at 1.8 K as a function of the target magnetic field H_M using both FC and ZFC protocols is shown in Fig. 3. Fig. 3 can be understood based on Bean's critical state model [2, 3] used for systems with pinning. The process of flux trapping is discussed in more details in Refs. [6, 19, 20]. Taking differences in relative dimensions and demagnetization factors into account, these data are consistent with the previous study on a single crystal that was more than three orders of magnitude larger. [7] It should be noted that whereas the ZFC trapped flux data does go to zero at a finite field value, the FC trapped flux data goes through (0, 0) as any simple physical analysis would suggest (details of such analysis are provided in Ref. [21]). This is in contrast to what is suggested in the empirical analysis presented by Hirsch and Marsiglio, [22] where both ZFC and FC trapped flux lines go to zero at the same, finite, magnetic field value.

3.2. Sample in DAC at 2.2 GPa

The same sample of $\text{CaKFe}_4\text{As}_4$ was subsequently placed in a DAC, the pressure was increased to 2.2 GPa and magnetization measurements were performed. ZFC and FC $M(T)$ data in 25 Oe and 500 Oe applied field are shown in Fig. 4. The superconducting transition is seen in both sets of measurements with $T_c \approx 33.8$ K in the 25 Oe ZFC data set. This decrease of T_c under pressure is comparable with the literature. [17] It has to be mentioned that the 25 Oe data in Fig. 4 appear to be noisy and the signal in the normal state seems to be measurably larger than at ambient pressure (Fig. 1). The possible reasons include rather small signal from the sample on top of fairly large background (see Appendix B for the examples of the subtraction and Appendix A for discussion of the low temperature background associated with the commercial DAC that was used), possibly slightly different remnant field in the superconducting magnet in in background and sample measurements among others. The $M(T)$ data at 500 Oe [shown in Fig. 4(b)] are less noisy due to a larger signal (see Appendix C for more on this), the apparent transition seen in ZFC data is broader, in agreement with larger applied field and thin-plate-like geometry of the sample with magnetic field being perpendicular to

Trapped flux in small $\text{CaKFe}_4\text{As}_4$ crystal

5

the plate.

Data for temperature dependent magnetization associated with the trapped flux for the sample in DAC are shown in Fig. 5. They are similar to those obtained at the ambient pressure (Fig. 2) but with somewhat higher apparent noise levels. There is also an apparent difference in the higher temperature, normal state zeros for the two data sets. This is associated with inherent uncertainty of inferring a zero signal by subtracting two large numbers. A comparison of trapped field magnetization at 5 K vs target magnetic field, H_M under pressure and at ambient pressure is shown in Fig. 6. Given that the comparison is for 5 K, the data in Fig. 6 for the ambient pressure results are slightly different from the 1.8 K data plotted in Fig. 3 (above). The normalized data look remarkably similar. The same data in the absolute values (shown in the inset) show some difference, in particular in saturated state, at 10 kOe. For the pressure data, this discrepancy is likely a combination of some real increase of the trapped field magnetization (i.e. critical current density) under pressure combined with increased error bars of the measurements.

4. Discussion and summary

To have a more direct comparison of the trapped field related magnetization, in Fig. 7 we plot $H_M = 50$ kOe FC and ZFC magnetization data taken at ambient pressure and in DAC under 2.2 GPa. At $H_M = 50$ kOe we are well in the saturation region for the trapped field. For this comparison plot, 2.2 GPa data were shifted vertically so that $M_{trap} \approx 0$ in 35 - 40 K temperature region. These shifts, $\sim 1 \times 10^{-6}$ emu in the absolute values, are probably a consequence of several experimental and data analysis issues: accuracy of subtraction of background, reproducibility of the axial and radial position of the DAC as well as reproducibility of the remnant field in the superconducting magnet in background and sample measurements and others. Additional experimental effort is needed to further understand and possibly reduce these systematic deviations. With the foregoing all stated, we can make several observations: as expected, FC and ZFC data are laying on top of each other; the data show that T_c is slightly suppressed at 2.2 GPa; whereas at higher temperatures $M_{trap}(T)$ data at ambient and 2.2 GPa pressure are similar, there is a notable difference below ~ 25 K. This difference could be intrinsic, as saturated trapped field magnetization is proportional to the self-field critical current density. [7, 6] which could be affected by pressure. [23, 24] It is possible that the already anomalous (at ambient pressure) temperature dependence of critical current density (which is possibly related to CaFe_2As_2 intergrowths, as suggested in Ref. [25]) changes even further as the pinning landscape evolves under pressure. Additionally, part of this difference might be related to a possible deformation of the sample in a DAC under pressure.

Now we need to turn our attention to the important difference in protocols for trapped flux magnetization measurements between this work and Ref. [6]. The trapped flux magnetization measurements are performed in *nominal* zero applied field. As it

Trapped flux in small $\text{CaKFe}_4\text{As}_4$ crystal

was discussed in detail in Ref. [7], in reality there is a remnant magnetic field in the superconducting magnet of a SQUID magnetometer used for the measurements which depends on the superconducting magnet design and geometry as well as the history of magnetic fields applied prior to the measurement. In 70 kOe MPMS3 magnet the remnant field can be as high as 25 Oe. [7] Then the trapped flux magnetization signal from the sample would be entangled with the signal from the DAC in remnant field. The signal from the DAC depends on the details of the design and geometry of the DAC and materials used in the DAC. Almax - easyLab Mcell Ultra DAC [13] used in this work is made out of a Cu-Be alloy, other parts used are diamond anvils, tungsten gasket, plus very small amounts of pressure medium and epoxy used to glue the anvils. Of note on the geometry is the presence of several access ports in the vicinity of the sample position, that would contribute to the background signal. The DAC in Ref. [6] is made mainly from Cu - 3 wt.% Ti alloy, Cu - Be was used for a small piston and an anvil seat, other parts are diamond anvils, rhenium gasket and small amounts of epoxy. [26, 27] The main materials used in the construction of these two DACs, Cu - Be and Cu - Ti alloys, have significantly different magnetic susceptibility (see Appendix A) with Cu - Ti susceptibility being 4 - 6 times lower than that of Cu - Be, and staying below 1×10^{-7} emu/g in the whole temperature range. In addition, the measurements in this work cover $T \leq 40$ K temperature range, where Cu - Be has a distinct upturn in susceptibility. A combination of these factors explains the need for point-by-point background subtraction, even for trapped flux magnetization measurements, for the commercial DAC.

One of the possible modifications of the protocol of the trapped flux magnetization measurements, that could help to further mitigate cell background concerns further, would be to perform the measurements not in nominal $H = 0$, but in a finite $H = -H_{rem}$ magnetic field (H_{rem} is a remnant magnetic field in a superconducting magnet that depends on the magnet history). Two possible ways to perform such calibration were presented in the Appendix of Ref. [7]. The examples of the (partial) offsets of the remnant field by measurements in finite applied field were shown in the same publication having MgB_2 crystal at ambient pressure as an example.

To summarize, the data presented in this work show that it is possible to do reasonable magnetic measurements, including magnetization related to the trapped flux, on very small, similar in size to those in Ref. [6], superconducting samples in DAC. Moreover, with an appropriate care (point-by-point background subtraction), a commercial, Cu - Be DAC can be suitable for such measurements.

Acknowledgments

This work was supported by the U.S. Department of Energy, Office of Science, Basic Energy Sciences, Materials Sciences and Engineering Division. Ames National Laboratory is operated for the U.S. Department of Energy by Iowa State University under Contract No. DE-AC02-07CH11358. PCC thanks Shanti Deemyad for remarks

1
2 *Trapped flux in small CaKFe₄As₄ crystal*
3

4 that helped motivate this work.
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

Accepted Manuscript

Trapped flux in small $\text{CaKFe}_4\text{As}_4$ crystal

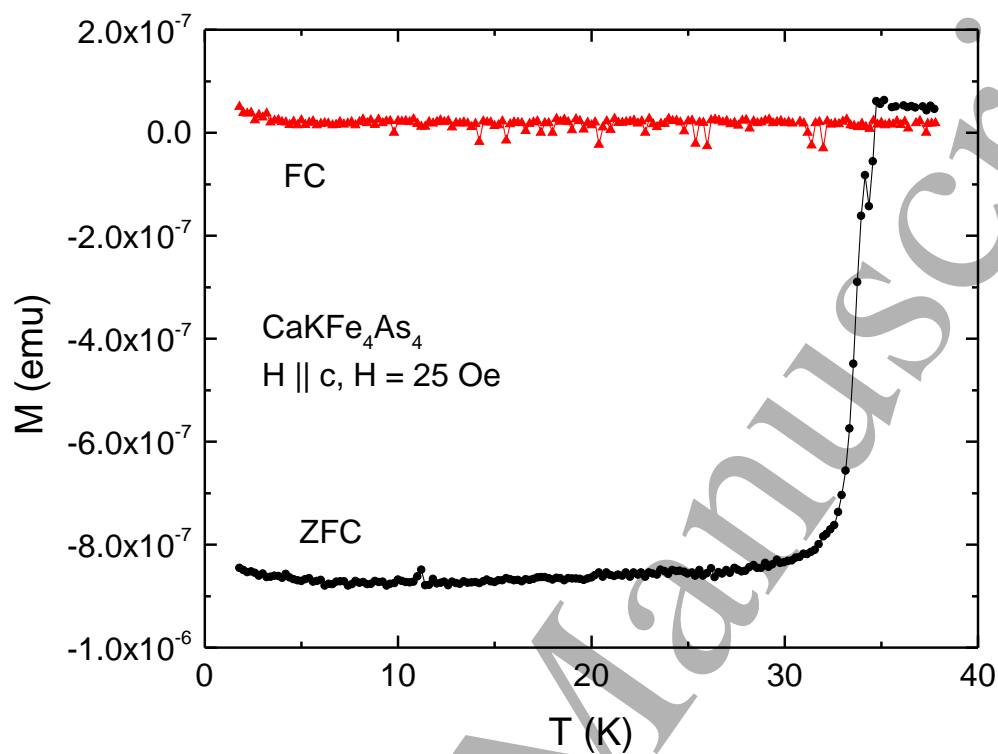


Figure 1. (color online) Temperature dependent zero-field-cooled (ZFC) and field-cooled (FC) magnetization, $M(T)$ of of an $\sim 0.5\mu\text{g}$ (see text for details) sample of $\text{CaKFe}_4\text{As}_4$ measured in 25 Oe magnetic field applied along the c -axis.

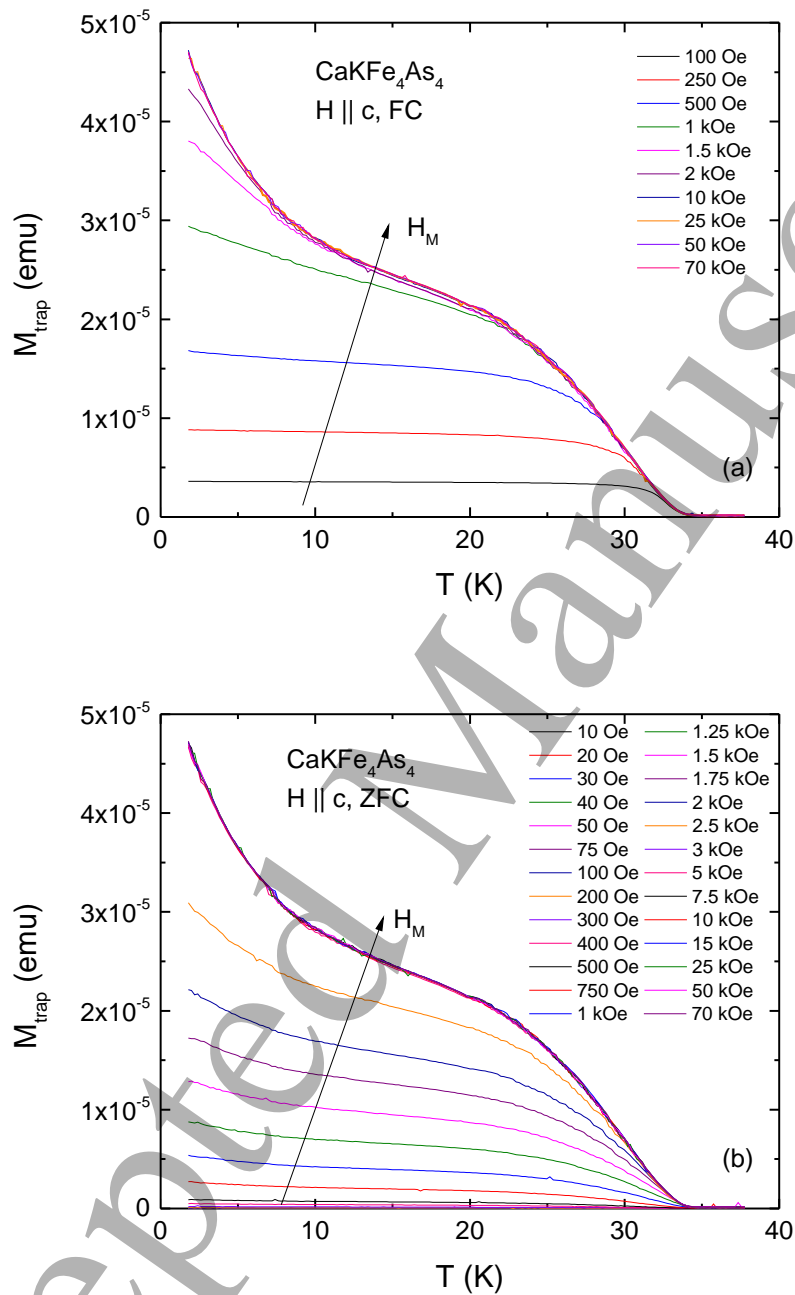
Trapped flux in small $\text{CaKFe}_4\text{As}_4$ crystal

Figure 2. (color online) Temperature dependent trapped flux magnetization of $\text{CaKFe}_4\text{As}_4$ measured in $H = 0$ using (a) FC and (b) ZFC protocols. Legends show target magnetic fields, H_M , in FC and ZFC experiments. Arrows point the direction of increase of H_M .

Trapped flux in small $\text{CaKFe}_4\text{As}_4$ crystal

10

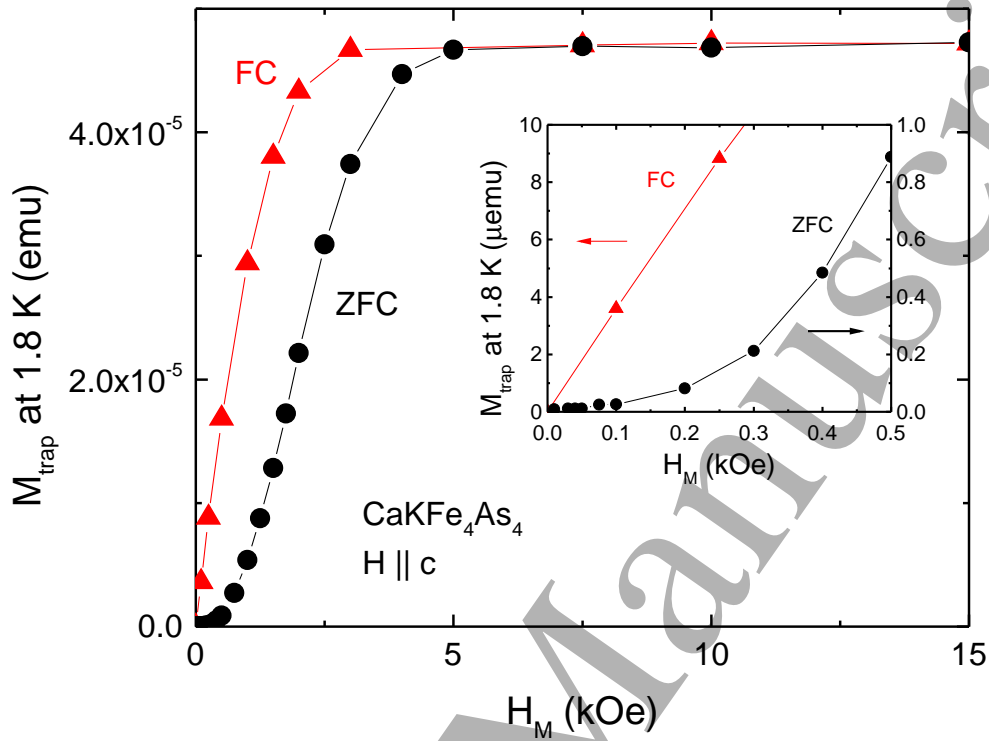


Figure 3. (color online) Trapped field magnetization at $T = 1.8$ K as a function of target field H_M in the ZFC and FC experiments. The inset shows an enlarged, low field, part of the data.

Trapped flux in small $\text{CaKFe}_4\text{As}_4$ crystal

11

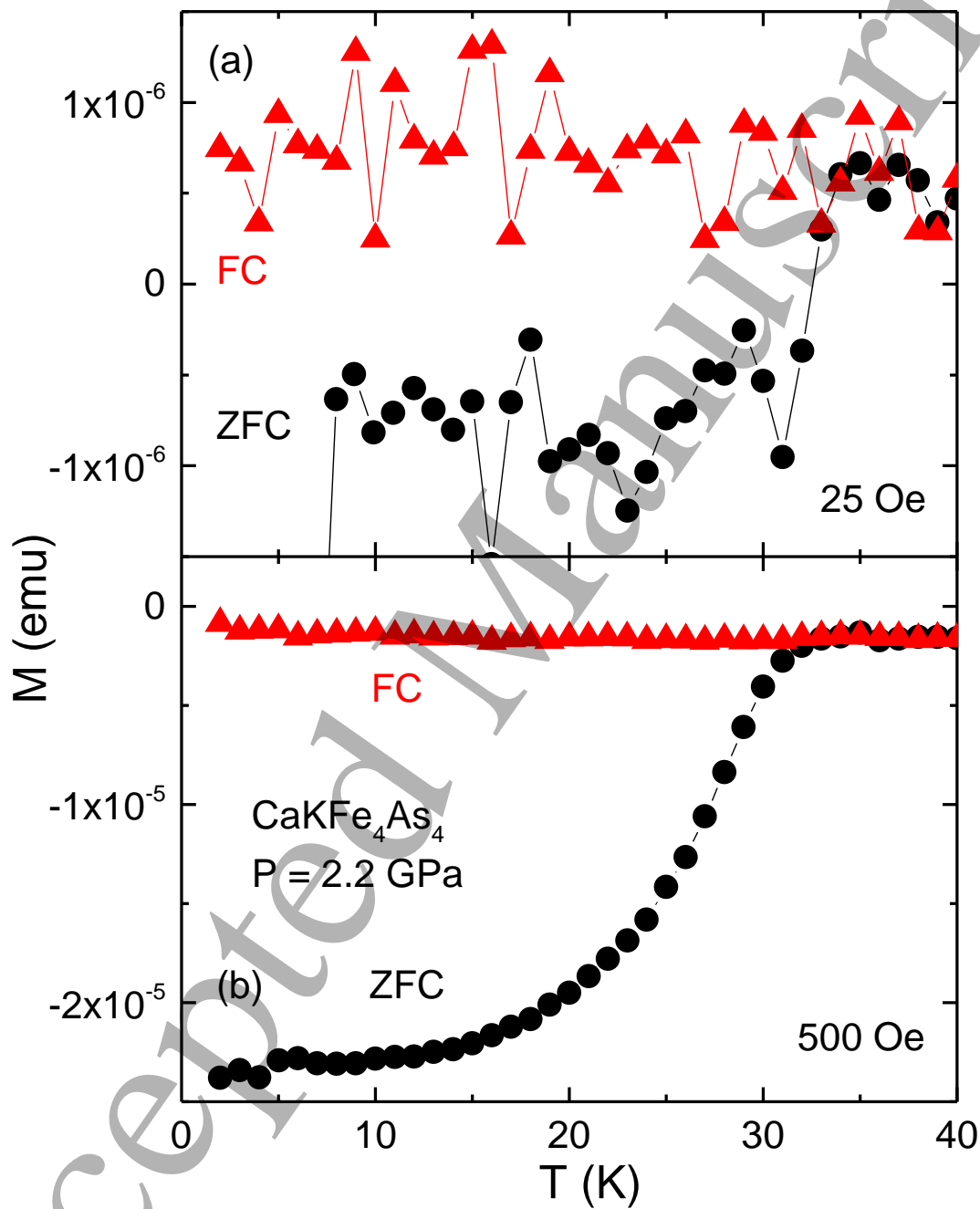


Figure 4. (color online) Temperature dependent zero-field-cooled (ZFC) and field-cooled (FC) magnetization, $M(T)$ of $\text{CaKFe}_4\text{As}_4$ in DAC under pressure of 2.2 GPa measured in (a) 25 Oe and (b) 500 Oe magnetic field applied along the c -axis.

Trapped flux in small $\text{CaKFe}_4\text{As}_4$ crystal

12

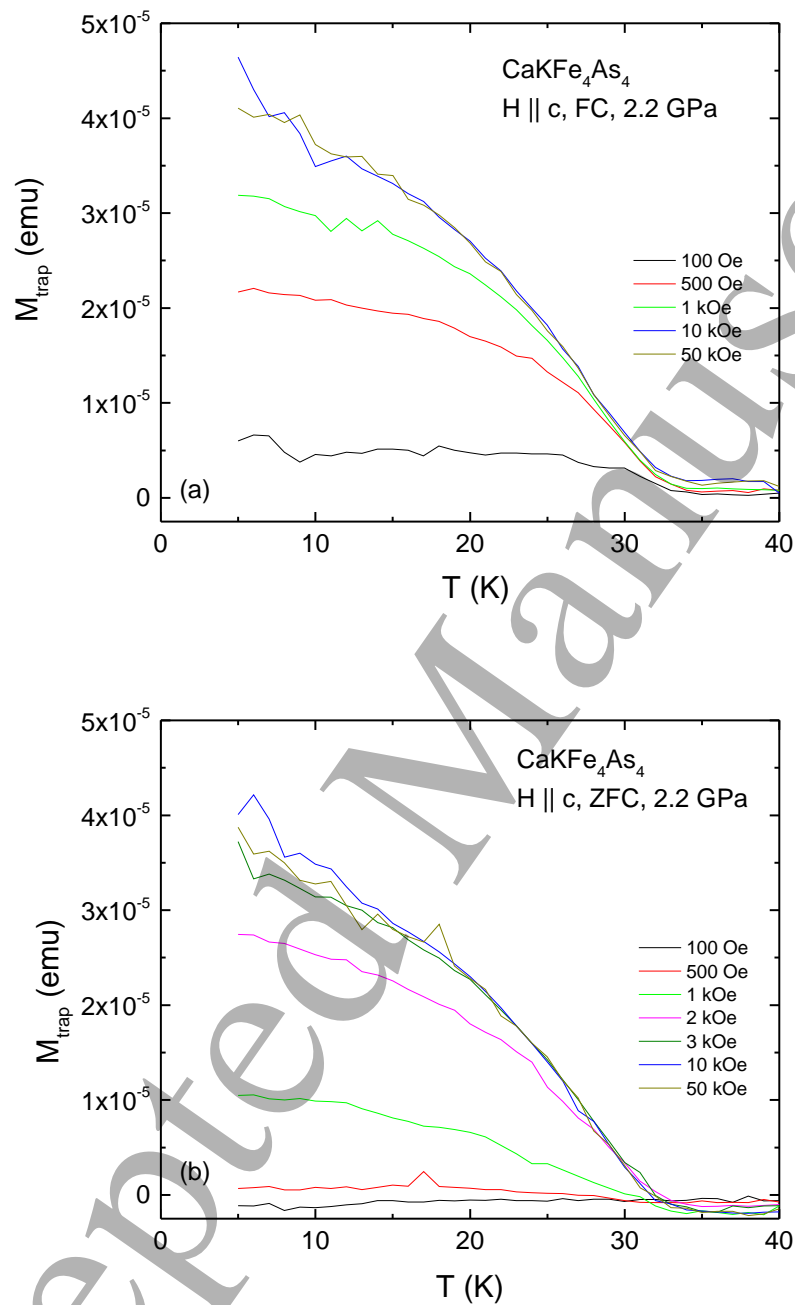


Figure 5. (color online) Temperature dependent trapped flux magnetization of $\text{CaKFe}_4\text{As}_4$ measured in $H = 0$ using (a) FC and (b) ZFC protocols in DAC under pressure of 2.2 GPa. Legends show target magnetic fields, H_M in FC and ZFC experiments.

Trapped flux in small $\text{CaKFe}_4\text{As}_4$ crystal

13

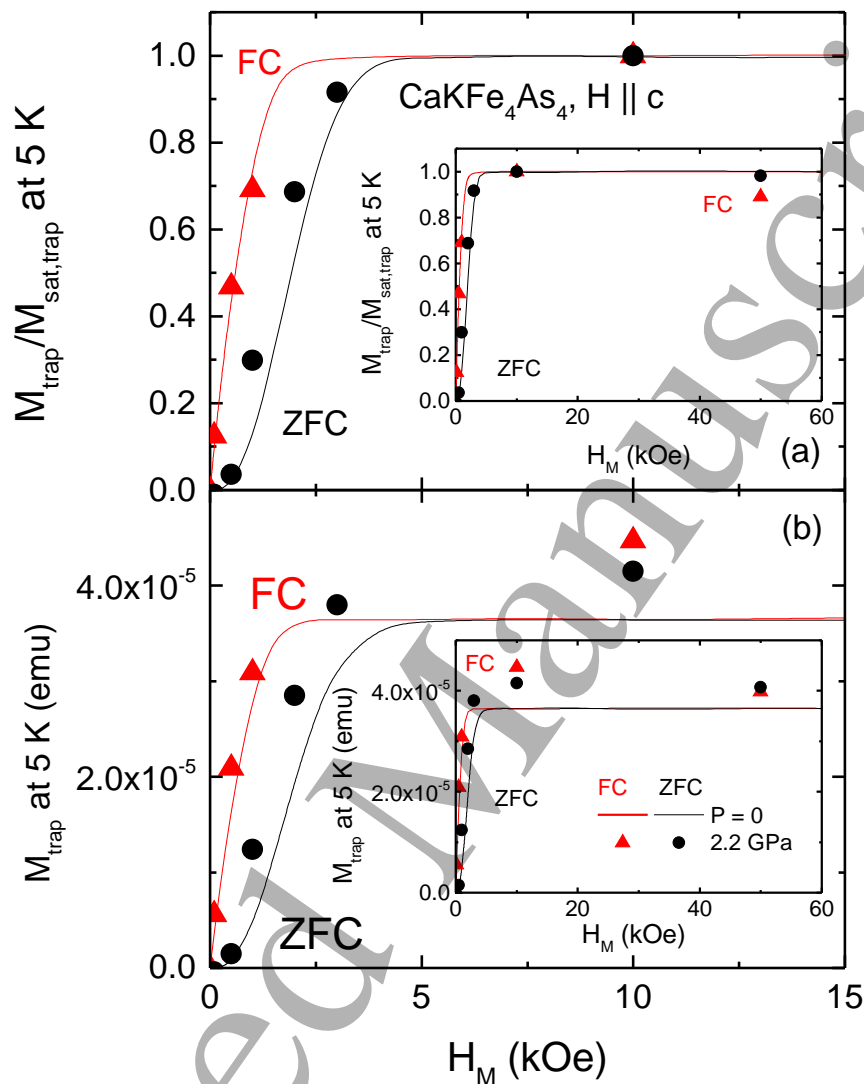


Figure 6. (color online) (a) Normalized to values at $H_M = 10$ kOe trapped field magnetization at $T = 5$ K as a function of target field H_M in the ZFC and FC experiments. Black -ZFC, red FC protocols. Lines - $P = 0$, filled symbols - measurements in DAC at 2.2 GPa. The data shown for $H_M \leq 15$ kOe. Panel (b) shows the same data without normalization. Insets show the corresponding data up to $H_M = 60$ kOe.

Trapped flux in small $\text{CaKFe}_4\text{As}_4$ crystal

14

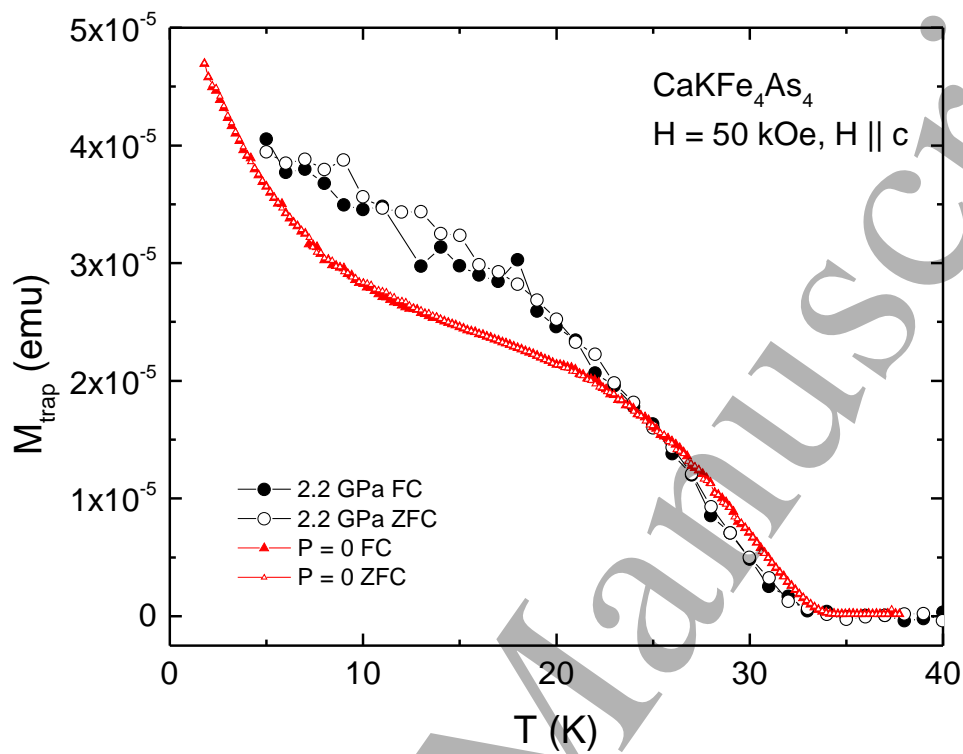


Figure 7. (color online) Comparison of temperature dependent trapped flux magnetization of $\text{CaKFe}_4\text{As}_4$ at ambient and 2.2 GPa pressure measured in nominal $H = 0$ after $H_M = 50$ kOe using FC and ZFC protocols. Data at 2.2 GPa were shifted vertically, so that they are zero in 35 - 40 K temperatures range.

1
2
3 *Trapped flux in small $\text{CaKFe}_4\text{As}_4$ crystal*

15

4 **Appendix A. Magnetic properties of DAC construction materials**

6
7 Figure A1 presents the results of magnetic measurements on Cu - 3 wt.% Ti alloy and
8 Cu - Be alloy on semi-log scale. Be - Cu commercial alloy contains ~ 97.9 wt. %
9 of Cu, ~ 1.9 wt. % of Be and ~ 0.2 wt. % of Co. Commercial (small batch) Cu -
10 3 wt.% Ti alloy nominally does not include magnetic components, but the data show,
11 smaller than in Be - Cu, low temperature, upturn that probably is associated with minor
12 transition metal impurities in the starting materials. Pure elemental Cu is diamagnetic.
13 Consequently, the $M(H)$ of the Be - Cu alloy at the base temperature is a combination
14 of a Brillouin - like increase and saturation of $M(H)$ associated with Co contribution
15 followed by a slow decrease due to diamagnetism of Cu. $M(H)$ of the Cu - 3 wt.% Ti
16 alloy apparently did not reach a clear saturation below 55 kOe. Note that in the whole
17 temperature range magnetic susceptibility, M/H , of Cu - Be is significantly, 4 - 6 times,
18 higher than that of Cu - 3 wt.% Ti, and the low temperature upturn in Cu - Be is more
19 pronounced.
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

Trapped flux in small $\text{CaKFe}_4\text{As}_4$ crystal

16

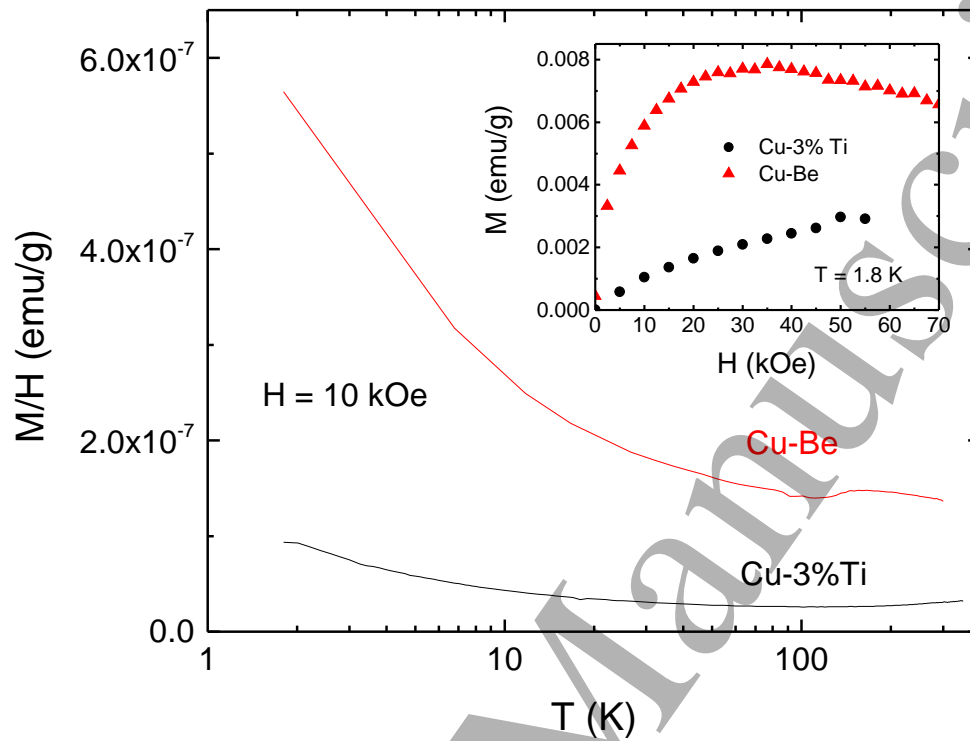


Figure A1. (color online) Temperature-dependent magnetic susceptibility, $M/H(T)$, of heat treated Cu - 3 wt.% Ti alloy and Cu - Be alloy measured in 10 kOe applied field. Inset: field - dependent magnetization measured at $T = 1.8$ K. Note that for Cu - Be alloy measurements a set screw from our Almax - easyLab Mcell Ultra was taken with expectation that it reflects the magnetic properties of the particular Cu - Be batch used to manufacture the DAC.

Appendix B. Examples of background subtraction

Figure B1 shows three examples of background subtraction for measurements of $\text{CaKFe}_4\text{As}_4$ crystal in DAC. For more details of the procedure refer to Ref. [16].

Trapped flux in small $\text{CaKFe}_4\text{As}_4$ crystal

17

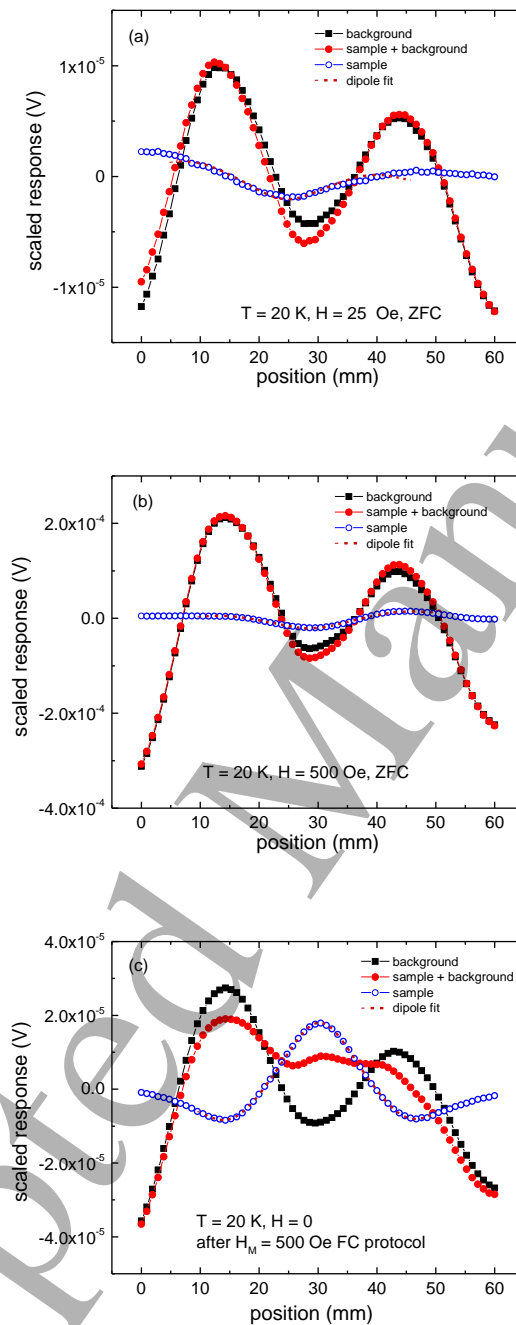


Figure B1. (color online) Examples of point-by-point background subtraction in measurements of $\text{CaKFe}_4\text{As}_4$ under 2.2 GPa pressure in a commercial DAC. All examples are for $T = 20$ K. (a) $M(T)$ ZFC measurements, $H = 25$ Oe; (b) $M(T)$ ZFC measurements, $H = 500$ Oe; (c) nominal $H = 0$ measurements of trapped flux magnetization using FC protocol with the target field $H_M = 500$ Oe.

1
2
3 *Trapped flux in small CaKFe₄As₄ crystal*

18

4 **Appendix C. Noise in FC magnetization measurements under pressure**

6
7 Figure C1 shows FC $M(T)$ measurements of CaKFe₄As₄ crystal in DAC in two different
8 applied fields, 25 Oe and 500 Oe presented above in Fig. 4 on the Y - axis scales
9 that span the same 2×10^{-6} emu. The random point-to point noise appears to be
10 smaller for 500 Oe data, but some drift is present in the data. It is possible that an
11 inherent uncertainty caused by large background subtraction and limited resolution of
12 the MPMS-classic contributes to this noise difference.
13
14

15 It is noteworthy, that a small feature corresponding to T_c apparently can be seen
16 in the 500 Oe FC data.
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

Trapped flux in small $\text{CaKFe}_4\text{As}_4$ crystal

19

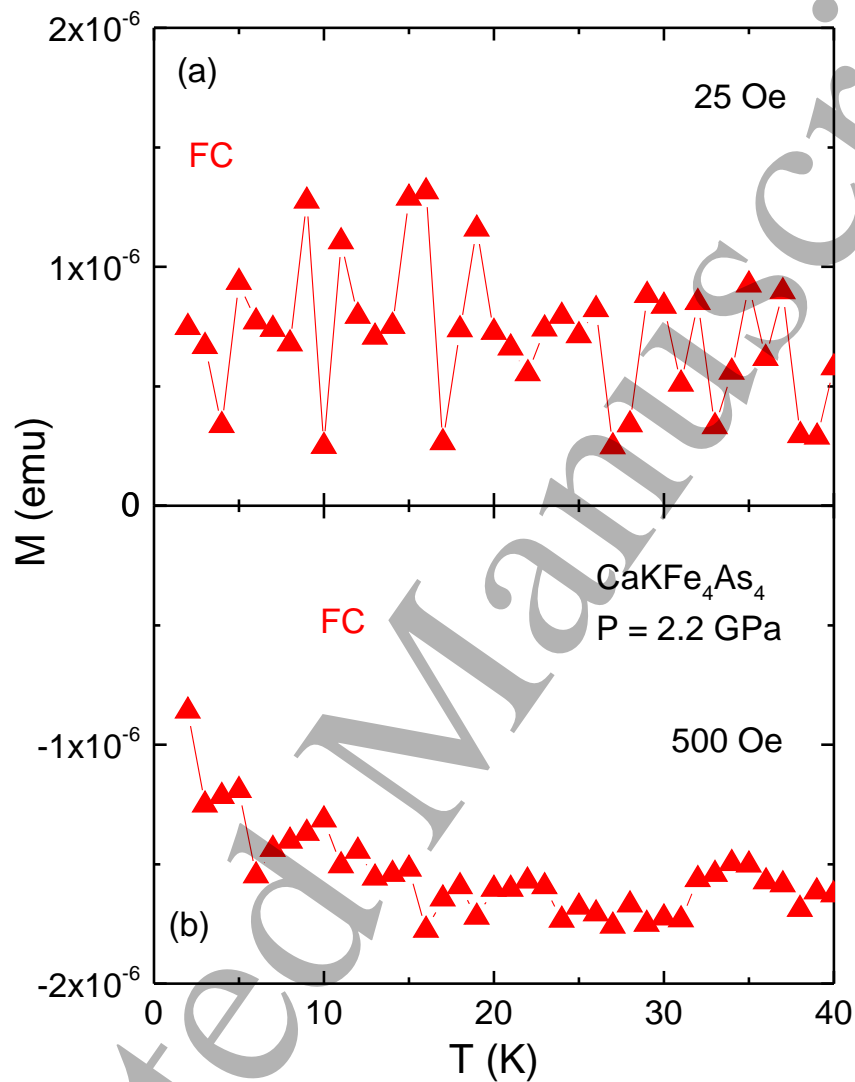


Figure C1. (color online) FC $M(T)$ measurements of $\text{CaKFe}_4\text{As}_4$ crystal in DAC in two different applied fields, (a) 25 Oe and (b) 500 Oe from Fig. 4 plotted on the Y-axis scales that span the same 2×10^{-6} emu.

Trapped flux in small CaKFe₄As₄ crystal

20

References

- [1] Pippard A B 1955 *Phil. Trans. R. Soc. A* **248** 97.
- [2] Bean C P 1962 *Phys. Rev. Lett.* **8** 250.
- [3] Bean Charles P 1964 *Rev. Mod. Phys.* **36** 31.
- [4] Hull John R and Strasik Michael 2010 *Supercond. Sci. Technol.* **23** 124005.
- [5] Müller K A, Takashige M and Bednorz J G 1987 *Phys. Rev. Lett.* **58** 1143.
- [6] Minkov V S, Ksenofontov V, Bud'ko S L, Talantsev E F and Erements M I 2023 *Nat. Phys.* **19**, 1293.
- [7] Bud'ko Sergey L, Xu Mingyu and Canfield Paul C 2023 *Supercond. Sci. Technol.* **36** 115001.
- [8] Meier W R, Kong T, Kaluarachchi U S, Taufour V, Jo N H, Drachuck G, Böhmer A E, Saunders S M, Sapkota A, Kreyssig A, Tanatar M A, Prozorov R, Goldman A I, Balakirev Fedor F, Gurevich Alex, Bud'ko S L and Canfield P C 2016 *Phys. Rev. B* **94** 064501.
- [9] Meier W R, Kong T, Bud'ko S L and Canfield P C, 2017 *Phys. Rev. Mater.* **1** 013401.
- [10] Iyo Akira, Kawashima Kenji, Kinjo Tatsuya, Nishio Taichiro, Ishida Shigeyuki, Fujihisa Hiroshi, Gotoh Yoshito, Kihou Kunihiro, Eisaki Hiroshi, and Yoshida Yoshiyuki 2016 *J. Am. Chem. Soc.* **138** 3410.
- [11] Quantum Design Application Note 1096-306, Rev. B1 (2016) <https://qdusa.com/siteDocs/appNotes/1096-306.pdf>
- [12] Huyan S, Mun E, Wang H, Slade T J, Li Z, Schmidt J, Ribeiro R A, Xie W, Bud'ko S L and Canfield P C 2024 arXiv:2401.09592, <https://doi.org/10.48550/arXiv.2401.09592>.
- [13] <https://almax-easylab.com/product/easylab-mcell-ultra/>
- [14] Adams David M, Long Gary J and Williams Alan D 1982 *Inorg. Chem* **21** 1049.
- [15] Shen Guoyin, Wang Yanbin, Dewaele Agnes, Wu Christine, Fratanduono Dayne E, Eggert Jon, Klotz Stefan, Dziubek Kamil F, Loubeyre Paul, Fat'yanov Oleg V, Asimow Paul D, Mashimo Tsutomu, Wentzcovitch Renata M M and other members of the IPPS task group 2020 *High Pres. Res.* **40** 299.
- [16] Coak Matthew J, Liu Cheng, Jarvis David M, Park Seunghyun, Cliffe Matthew J and Goddard Paul A 2020 *Rev. Sci Instr.* **91** 023901.
- [17] Kaluarachchi U S, Taufour V, Sapkota A, Borisov V, Kong T, Meier W R, Kothapalli K, Ueland B G, Kreyssig A, Valentí R, McQueeney R J, Goldman A I, Bud'ko S L and Canfield P C 2017 *Phys. Rev. B* **96** 140501.
- [18] Minkov V S, Bud'ko S L, Balakirev F F, Prakapenka V B, Chariton S, Husband R J, Liermann H P and Erements M I 2022 *Nat. Com.* **13** 3194.
- [19] Moshchalkov V V, Henry J Y, Marin C, Rossat-Mignod J and J.F. Jacquot J F 1991 *Physica C* **175** 407.
- [20] Altshuler E. , García S and Barroso J 1991 *Physica C* **177** 61.
- [21] Bud'ko Sergey L 2024 *J. Supercond. Nov. Magn.* **37** 473.
- [22] Hirsch J E, Marsiglio F 2022 *J. Supercond. Nov. Magn.* **35** 3141.
- [23] Bud'ko S L, Davis M F, Wolfe J C, Chu C W and Hor P H 1993 *Phys. Rev. B* **47** 2835.
- [24] Jung Soon-Gil, Kang Ji-Hoon, Park Eunsung, Lee Sangyun, Lin Jiunn-Yuan, Chareev Dmitriy A, Vasiliev Alexander N and Park Tuson 2015 *Sci. Rep.* **5** 16385.
- [25] Ishida Shigeyuki, Iyo Akira, Ogino Hiraku, Eisaki Hiroshi, Takeshita Nao, Kawashima Kenji, Yanagisawa Keichi, Kobayashi Yuuga, Kimoto Koji, Abe Hideki, Imai Motoharu, Shimoyama Jun-ichi and Eisterer Michael 2019 *npj Quantum Mater.* **4** 27.
- [26] Drozdov A P, Erements M I, Troyan I A, Ksenofontov V and Shylin S I 2015 *Nature* **525** 73.
- [27] Erements M I, Minkov V S, Drozdov A P, Kong P P, Ksenofontov V, Shylin S I, Bud'ko S L, Prozorov R, Balakirev F F, Sun Dan Sun, Mozaffari S and Balicas L 2022 *J. Supercond. Nov. Magn.* **35** 965.