Evidence of a multiple boson emission in Sm$_{1-x}$Th$_x$OFeAs

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Abstract - We studied a reproducible fine structure observed in dynamic conductance spectra of Andreev arrays in Sm$_{1-x}$Th$_x$OFeAs superconductors with various thorium concentrations ($x = 0.08–0.3$) and critical temperatures $T_c = 26–50$ K. This structure is unambiguously caused by a multiple boson emission (of the same energy) during the process of multiple Andreev reflections. The directly determined energy of the bosonic mode reaches $\epsilon_0 = 14.8 \pm 2.2$ meV for optimal compounds. Within the studied range of $T_c$, this energy as well as the large $\Delta_L$ and the small $\Delta_S$ superconducting gaps, nearly scale with critical temperature with the characteristic ratio $\epsilon_0/k_BT_c \approx 3.2$ (and $2\Delta_L/k_BT_c \approx 5.3$, respectively) resembling the expected energy $\Delta_L + \Delta_S$ of spin resonance and spectral density enhancement in $s^+$ and $s^+$ states, respectively.

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Fe-based superconductors Sm$_{1-x}$Th$_x$OFeAs belong to the oxypnictide families (so-called 1111), and have rather simple crystal structure, resembling the stack of superconducting FeAs blocks alternating with Sm$_{1-x}$Th$_x$O spacers along the c-direction [1]. Under electron doping, the $T_c$ varies in the wide range, reaching 54 K at $x \approx 0.3$ nominal concentration [1,2]. Band-structure calculations [3] showed the density of states at the Fermi level formed mainly by iron 3d states. For this reason, the (Sm,Th) substitution affecting the spacer structure barely does not seem to change the underlying pairing mechanism [4]. The Fermi surface consists of tubular sections, electron-like near the $M$-point of the first Brillouin zone, and hole-like near the $\Gamma$-point, both with no significant $k_z$ anisotropy [3,5].

The majority of theoretical and experimental studies [3–8] suppose two superconducting condensates developing below $T_c$. Earlier we reported the scaling between both gaps ($\Delta_L$—large gap; $\Delta_S$—small gap) and $T_c$, keeping $2\Delta_S/k_BT_c \approx 1.2–1.6$ and $2\Delta_L/k_BT_c \approx 5.0–5.7$ [4,9–11]. Similar $2\Delta_L/k_BT_c$ was obtained in the literature for Sm-1111 in point-contact probes [12,13], and for various other 1111 [14–20]. Both BCS ratios diverge from the weak-coupling BCS prediction due to a strong coupling in the “driving” bands where the large gap is developed, and a k-space proximity effect with the “driven” $\Delta_S$ bands. The pairing mechanism in Fe-based superconductors is still puzzling. Three basic models, $s^{++}$, $s^{\pm}$, and shape resonance model, were proposed so far [6,21–27]. A sharp peak in the imaginary spin susceptibility appearing at the nesting vector and a certain energy, is the signature of the $s^{\pm}$ mechanism mediated by spin fluctuations [28,29]. A number of neutron diffraction studies reported a clear “magnetic resonance” peak, which energy roughly scales with $T_c$ [30,31]. In the $s^{++}$ approach, the imaginary part of dynamic spin susceptibility demonstrates a smeared maximum rather than a peak [22,25,26]. More recent theoretical studies showed that in the framework of both $s^{++}$ and $s^{\pm}$ models the dynamic spin susceptibility has a feature near $\Delta_L + \Delta_S$ energy, a sharp peak related to spin resonance in the $s^{\pm}$ state, or spectral density enhancement above $\Delta_L + \Delta_S$ in the $s^{++}$ state [25,32].

Tunneling contact probes could provide information about electron-boson interaction [33–43]. For the tunneling normal metal-insulator-superconductor (NIS) junction, the derivative $d^2I/dV^2$ of the dynamic conductance spectrum at bias voltages $V > \Delta/e$ represents a spectral function of the electron-boson interaction [41]. In other words, the edge energy $\Delta$ changes into $\Delta + \epsilon_0$ for some electrons, where $\epsilon_0 < 2\Delta$ is a particular boson.
energy. In Nd-1111, the Eliashberg function extracted from $d^2I(V)/dV^2$ [14] well matches the calculated one, and the phonon density of states [44]. Scanning tunneling spectroscopy (STS) studies with BaFe$_{1-x}$K$_x$Fe$_2$As$_2$ revealed a fine structure attributed to a coupling of quasiparticles with a bosonic mode near 14 meV [43]. In contrast, in the STS probe with SmFeAsO$_{1−x}$F$_x$ [42], the minimum of the dip-hump structure was attributed to a sign of a resonance spin mode within the energy range $\varepsilon_{res} = 2−8$ meV. A strange correlation was detected in [42]: $\varepsilon_{res} + \Delta = 11−12$ meV = const. Some studies of NS point contacts in nearly optimal F-substituted SmFeAsO$_{0.8}$F$_{0.2}$ reported a dynamic conductance fine structure observed above the gap edge and therefore attributed to the electron-boson interaction. The complex shape of the $\omega$ spectrum at $\varepsilon_{res}$ 2–8 meV was fitted using a three-gap model solely, the largest gap had the BCS ratio 8.7. A close BCS ratio and the resembling fine structure were observed in BaFe$_{1.8}$Co$_{0.2}$As$_2$ [36–38]. A clear maximum offset of the largest gap bias was interpreted as a manifestation of the interaction of electrons with a bosonic mode with the energy $\varepsilon_0 ≈ 22$ meV for Sm-1111. However, the energy rapidly decreased with temperature and there seemed to have non-phononic origin. Similar looking high-bias features often emerge in point contact probes of 1111 oxypnictides [15,45–47], nonetheless, those fine structures were not assigned any physical meaning there. By contrast, in [45] it was pointed out that the position of those features varied with respect to contact resistance, thus doubting their essentiality. Generally speaking, there are difficulties in the interpretation of $dI(V)/dV$ spectra at $\Delta/\varepsilon$ above 2. In a typical run, the sample was compressed to 3 GPa at room temperature. While keeping the pressure constant, the temperature was ramped up within 1 h to the maximum value of 1430°C, maintained for 4.5 h, and finally quenched to the room temperature. Afterward, the pressure was released and the sample removed. Subsequently recorded X-ray powder diffraction patterns revealed high homogeneity of the samples and the presence of a single superconducting phase [1]. The amount of additional nonsuperconducting phases SmAs and ThO$_2$ was vanishingly small. The bulk character of superconductivity in Sm$_{1−x}$Th$_x$OFeAs samples was confirmed by magnetization measurements.

In order to form SnS Andreev contact, we used a “break-junction” technique. More details about our setup could be found elsewhere [33,49]. A plate-like sample was attached onto a springy sample holder and cooled down to $T = 4.2$ K. Then, the holder was gently curved, thus cracking the crystal. Two cryogenic surfaces coupled with a weak link were kept in the bulk of the sample during the studies. We did not separate the clefts to a more distant distance, facilitating clean and nondegraded cryogenic surfaces [33]. In Sm-1111, the weak link formally acts as thin normal metal [4,9–11], as the resulting $\Delta/\varepsilon$ resembles those of a clean classical SnS contact [50–53].

Steps and terraces commonly appear on cryogenic clefts and may realize SnSn−...S arrays typical for the break-junction studies of single crystals and even polycrystalline samples of layered compounds [4,33]. A layered grain splits when making the crack, and its $ab$ crystallographic plane oriented nearly parallel to the crack, and shows steps and terraces likewise in single crystal [4,33]. The array is a stack of $m$ identical SnS junctions along the c-direction. Tuning the curvature of the holder makes the terraces slide along the $ab$ planes, forming SnS junctions and arrays with various area and $m$. With this setup, one could probe with $x = 0.08–0.3$ and critical temperatures $T_c = 26–50$ K. For optimal compound, the energy of the characteristic bosonic mode reaches $\varepsilon_0 = 14.8 ± 2.2$ meV (or 118 ± 18 cm$^{-1}$), and scales with critical temperature, keeping nearly constant ratio $\varepsilon_0/k_B T_c ≈ 3.2$. The latter is close to the expected position of the resonance peak of imaginary spin susceptibility in the $s^+$ state [32] or enhanced spectral density peak in the $s^{++}$ state [26].

Polycrystalline Sm$_{1−x}$Th$_x$OFeAs samples with various thorium doping were synthesized by the high-pressure method. Overall details of the sample cell assembly and the high-pressure synthesis process may be found in [1,2]. Powders of SmAs, ThAs, Fe$_2$O$_3$, and Fe of high purity (≥ 99.95%) were weighed according to the stoichiometric ratio, thoroughly ground, and pressed into pellets. Then, the pellet containing the precursors was enclosed in a boron nitride crucible and placed inside a pyrophyllite cube with a graphite heater. All the preparatory steps were done in a glove box under argon atmosphere. The six tungsten carbide anvils generated pressure on the whole assembly. In a typical run, the sample was compressed to 3 GPa at room temperature. While keeping the pressure constant, the temperature was ramped up within 1 h to the maximum value of 1430°C, maintained for 4.5 h, and finally quenched to the room temperature. Afterward, the pressure was released and the sample removed. Subsequently recorded X-ray powder diffraction patterns revealed high homogeneity of the samples and the presence of a single superconducting phase [1]. The amount of additional nonsuperconducting phases SmAs and ThO$_2$ was vanishingly small. The bulk character of superconductivity in Sm$_{1−x}$Th$_x$OFeAs samples was confirmed by magnetization measurements.
dozens of Andreev contacts in one and the same sample, and collect reproducible and self-consistent data.

The multiple Andreev reflection effect (MARE) occurring in ballistic SnS contact with a constriction narrower than the carrier mean free path [54], causes a pronounced excess current ("foot") near the zero-bias region in the current-voltage characteristic (CVC), and a subharmonic gap structure (SGS)—a sequence of dynamic conductance dips (in case of transparency of NS interfaces as high as 95–98%). Their positions $V_n = 2\Delta/n e$, where $n$ is the natural subharmonic order [50–53], directly determine the value of the superconducting order parameter at any temperatures up to $T_c$ [50,53]. The first Andreev minimum could be shifted towards zero for several reasons [33,52,53]; if it is the case (see figs. 1–4), the gap value is determined using the positions of high-order subharmonics. In the two-gap superconductor, two sets of $dI(V)/dV$ features corresponding to the large and the small gap should be observed. The contact area typical for Sm-1111, is about 10–30 nm, as estimated [33], thus providing local measurements of energy parameters. Intrinsic MARE (IMARE) similar to the intrinsic Josephson effect [55] takes place in Andreev arrays and scales by a factor of $m$ the position of any features caused by the bulk. In particular, SGSs would appear at bias voltages $V_n = 2m \times \Delta_{L,S}/en$. The actual number of junctions in the array could be determined when normalizing the $dI(V)/dV$ by a factor of the natural $m$, until the positions of the main conductance features would coincide with those in the spectrum of the single SnS junction [4,33]. The IMARE spectroscopy of SnSn-...-S break-junctions is therefore a direct local probe providing a highly accurate bulk values of characteristic energy parameters [33].

When undergoing (I)MARE, an electron could emit a boson with the energy $\epsilon_0$ up to $2\Delta$. Boson absorption is nearly impossible, due to the lack of excited bosons at low temperatures. When the bosonic mode has a particular energy $\epsilon_0$, one should observe satellite dips beyond the SGS at bias voltages [34,39,40,48],

$$V_{n,k} = \frac{2\Delta + k\epsilon_0}{en},$$  \hspace{1cm} (1)

($k$ is a natural number of sequentially emitted bosons). Since the amount of electrons emitting a boson decreases with increasing $k$, the satellites are less pronounced. In case of sequential emitted bosons $k > 1$, $k$ equidistant satellites with diminishing intensity (due to $\Gamma$ broadening) would follow each gap subharmonic. One should not expect any $(k + 1)$-order feature if the $k$-th dip became smeared. The bosonic energy could be directly determined as a “distance” between $2\Delta$ and $(2\Delta + \epsilon_0)$ dips. When $\epsilon_0$ is small compared to $\Delta$ the bosonic features are identified unambiguously, since they appear next to the Andreev minimum and almost do not superpose with the SGS dips [48]. However, in case of $\epsilon_0 \sim \Delta$, the satellites are located far from the “parent” SGS dips, and may overlap with the high-order subharmonics ($n \geq 2$). In general, emerging dips may intensify the resulting conductance feature, likewise interfering.

The “break-junction” technique is a universal probe of the superconducting order parameter and electron-boson interaction [33]. It provides high quality of the contacts even in polycrystalline samples of layered compounds [33], giving the opportunity to resolve a clear fine structure accompanying SGS in dynamic conductance spectra. A satellite structure at bias voltages corresponding to eq. (1) was firstly observed in $dI(V)/dV$ of microwave irradiated SnS Andreev break-junctions in YBaCuO [34]. Later, in Mg(Al)B$_2$, Ponomarev et al. [39,40] reproducibly observed up to 4 satellites next to the large gap subharmonics ($2\Delta_S/en$). The bosonic mode was interpreted there as the Leggett plasma mode with maximum energy $\omega_L = 4-5\text{meV}$ for undoped magnesium diborides. Similar energy was obtained in tunneling SIS contact studies, extracted from a fine structure caused by a resonant excitation of the Leggett plasmons mode by the Josephson supercurrent [39,40]. According to the theory [56], that energy does not exceed the doubled small gap, and evolved as $\omega_L^2 \sim \Delta_S \cdot \Delta_T$ within nearly a full range of aluminum concentration and $T_T = 6-41\text{K}$ [39,40]. Here in Sm-1111, we reproducibly observe up to $k = 4$ equidistant satellites, which evidences their bosonic origin.

Figure 1 shows normalized CVC (blue line, left vertical scale), and $dI(V)/dV$ spectrum (red line, right scale) for Andreev array in the nearly optimal Sm$_{0.7}$Th$_{0.3}$OFeAs sample with $T_c \approx 49\text{K}$. SGSs of the large gap $\Delta_L \approx 11.3\text{meV}$ is shown by gray vertical ticks and $n_2$ labels, for the small gap $\Delta_S \approx 2.2\text{meV}$ by black arrows and $n_S$ labels, the bosonic features with the energy $\epsilon_0 \approx 14.8\text{meV}$ are labelled with $n_{res}$ and vertical magenta arrows. The inset shows the positions of the $\Delta_L$ (blue circles), $\Delta_S$ (open circles), and bosonic features (triangles for $k = 1$, rhombs for $k = 2$ emitted bosons) vs. the inverse number 1/$n$. Gray lines are guidelines.

![Fig. 1: (Color online) Current-voltage characteristic (blue line, left vertical scale), and $dI(V)/dV$ spectrum (red line, right scale) for Andreev array in the nearly optimal Sm$_{0.7}$Th$_{0.3}$OFeAs sample with $T_c \approx 49\text{K}$.
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The CVC is symmetric and non-hysteretic, and has a pronounced foot area with a significant excess current at low biases, typical for high-transparent SnS contact. The contact resistance \( R \approx 20 \, \Omega \) (per one SnS junction) is comparatively large indicating a ballistic transport. Taking the average product of bulk resistivity and carrier mean free path \( \rho l \approx 5 \times 10^{-10} \, \Omega \cdot \text{cm}^2 \) nearly constant for Sn-1111 \([57,58]\), and \( \rho \approx 0.09 \, \text{m}^{\circ} \cdot \text{cm} \) for the optimal single crystal from the same batch \([1]\), we use Sharvin formula \( R = \frac{1}{\pi e^2} \left( \frac{a}{d} \right) \) \([54]\), and get the contact dimension \( a \approx 33 \, \text{nm} \) which is less than \( l_d \approx 55 \, \text{nm} \). We note that for the experimental observation of MARE namely the \( l_m/2a \) ratio is essential \((l_m\text{—inelastic mean free path})\). Usually, \( l_m \) is several times larger than \( l_d \) facilitating the ballistic regime.

The dynamic conductance spectrum (red line, right scale in fig. 1) demonstrates four Andreev features of the large gap (marked with \( n_L = 1-4 \) and gray vertical lines) located at \( |V_n| \approx 23, 11.3, 7.5, 5.6 \, \text{mV} \). The positions \( V_n \) depend linearly on their inverse number \( 1/n \) (blue circles in the inset), thus composing the large gap SGS and directly determine the magnitude \( \Delta_L \approx 11.3 \, \text{meV} \). The dips more intensive than \( n_L = 4 \) and located at \( \pm 4.1 \, \text{mV} \) do not satisfy the expected positions of the 5th subharmonic of the large gap. These features, and those observed at \( \pm 2.2 \, \text{mV} \), obviously compose the second SGS related to the small gap \( \Delta_S \approx 2.2 \, \text{meV} \) (open circles in the inset). The obtained gap values are in good agreement with the earlier IMARE studies \([4,10,11]\), and resemble those in sister compounds GdO\(_{1-x}\)Fe\(_2\)FeAs with similar \( T_c \) \([10,48,59]\).

A rich fine structure resolved in the \( dI(V)/dV \) is labeled with \( n_{res} = 1, 2, 3 \) in fig. 1. Next to the main harmonic \( n_L = 1 \) of the large gap, the clearly visible satellite is located at \( eV_{res1} = 2\Delta_L + \varepsilon \approx 36 \, \text{meV} \) corresponding to a single \( k = 1 \) boson emitted by normal carriers. While, at the expected position of the \( k = 2 \) resonance (two sequentially emitted bosons), \( eV_{res2} = 2\Delta_L + 2\varepsilon_0 \approx 51 \, \text{meV} \), we observed only smeared feature. In the majority of the obtained \( dI(V)/dV \), the \( (n = 1, k > 1) \) peculiarities following \( 2\Delta_L \) dips are hardly observable. The reason for this lies in the short propagation time \( t_{cross} \) for the carriers driven by relatively high bias. In the ballistic regime applicable to our constriction, \( t_{cross} \sim 1/V^2 \), suggesting nearly no time for the resonant energy transmission for \( eV > 4\Delta_L \). At half of these biases, \( V_{res2} = V_{res1}/2 \approx \pm 18.7 \, \text{mV} \) the second boson-caused subharmonic \( (n = 2, k = 1) \) should appear in accordance with eq. (1). This position matches the external minimum of the doublet observed between the large gap subharmonics \( n_L = 1, 2 \). Indeed, the spectrum shows \( k = 2 \) dips at \( \pm 26.2 \, \text{mV} \) and \( k = 3 \) features of a vanishing amplitude at \( \pm 33.6 \, \text{mV} \). These minima are nearly equidistant (see the magenta arrows in fig. 1) and offset by \( \approx 7.4 \, \text{mV} \). This shift is exactly twice smaller than the distance \( |eV_{res1} - 2\Delta_L| \equiv \varepsilon_0 \). The \( n = 3, k = 1 \) bosonic feature is unresolved as a distinct dip since its expected position (open triangle in the inset) nearly matches the \( \Delta_L/e \). Nonetheless, the \( n = 3, k = 2 \) feature corresponds to the internal minimum in the doublet at \( \pm 17 \, \text{mV} \). The bosonic resonances accompanying \( n_L = 4 \) are hardly resolvable due to the minor intensity of the gap features. Overall, the fine-structure features observed in the \( dI(V)/dV \) could be interpreted as boson-caused since they satisfy eq. (1). For certain \( k \), their positions comprise a distinct subharmonic structure (triangles in the inset for \( k = 1 \), rhombs for \( k = 2 \)). With increasing \( k \), the satellites smear. Taking into account that some bosonic resonances merge with the large gap dips, we observe a gradual (with no missed \( k \) numbers) “comb” of satellites accompanying the \( n = 2, 3 \) SGS dips. According to formula (1), the energy of the bosonic mode could be directly determined as \( \varepsilon_0 = (enV_{res} - V_L)/k \approx 14.8 \, \text{meV} \).

A similar fine structure corresponding up to \( k = 4 \) emitted bosons was observed in another sample from the same batch. Figure 2 shows normalized CVC (blue line, left scale), and dynamic conductance (red line, right scale) of the Andreev array with \( T_c \approx 50 \, \text{K} \). The reversed negative voltage parts of \( I(V) \) and \( dI(V)/dV \) (dashed lines) show the high symmetry of the characteristics. In the spectrum, the small gap SGS is invisible (which is typical for IMARE studies of optimally doped Sn-1111 \([4]\) ), whereas three subharmonics of the large gap \( \Delta_L \approx 11.7 \, \text{meV} \) are clearly seen (gray vertical lines and \( n_L \) labels in fig. 2). As in fig. 1, we observe the single satellite offset \( 2\Delta_L/e \) bias. Herewith, the higher-order gap subharmonics are accompanied with multiple (sequential) bosonic resonances (arrows, \( n_{res} = 2, 3 \), and \( k = 1-4 \) labels). The doublet shape of the main SGS dip \( (n_L = 1) \) is not reproducible for other subharmonics therefore results from a
Multiple boson emission in Sm$_{1-x}$Th$_{x}$OFeAs

![Graph](image)

**Fig. 3:** (Color online) $I(V)$ (left scale), and dynamic conductance (right scale, corresponding colors) for two Andreev arrays in underdoped Sm$_{1-x}$Th$_{x}$OFeAs with $x < 0.08$ and $T_c \approx 26\,K$. SGS of the large gap $\Delta_L \approx 5.9\,mV$ is shown by gray vertical lines and $n_L$ labels, for the small gap $\Delta_S \approx 1.5\,mV$ by the black arrows, the features caused by boson emission with the energy $\varepsilon_0 \approx 7.4\,mV$ are labeled with $n_{res}$ and magenta vertical bars.

$n = 2, k = 2$ dip. All the dynamic conductance features satisfy to eq. (1). The resulting energy of the bosonic mode is the same order of magnitude, although a bit lower $\varepsilon_0 = 11 \pm 2\,mV$.

In underdoped Sm-1111 with critical temperature $T_c \approx 26\,K$ the obtained Andreev spectra demonstrate the main boson dips with $n, k = 1$ barely (fig. 3), probably relating with enhanced smearing $\Gamma$. The first feature $n_{res} = 1$ is located at $|V| \approx 19.3\,mV$ and approximately offset by $\varepsilon_0/e \approx 7.4\,mV$ the $2\Delta_L$ dip. The second feature at $8.8\,mV$ is observed between $n_L = 1, 2$ subharmonics of the large gap $\Delta_L \approx 5.9\,mV$. The third feature expected at $V_{res} \approx 6.7\,mV$ seems unobservable due to smeared "parent" dips $n_L = 3$. Note that although the $n_L = 1$ fragment comprising the two dips at $\approx 11.6$ and $\approx 8.8\,mV$ visually resembles the doublet typical for a case of the fourfold gap distribution in $k$-space (see [33]), the other $\Delta_L$ subharmonics are not doublet-like. Therefore, the large gap anisotropy cannot be a reason for the observed fine structure.

In order to compare the positions of the bosonic satellites relatively to the large gap SGS, in fig. 4 we show the fragments of $dI(V)/dV$ spectra at $T = 4.2\,K$ normalized by a value of $\Delta_L$. The characteristics were obtained in Andreev arrays of Sm-1111 samples with various thorium concentrations $x = 0.08–0.3$ and corresponding critical temperatures $T_c = 26–50\,K$. The upper spectrum is taken from fig. 1. The lower spectrum reproduces the upper curve in fig. 3 (the fragment comprising the $n_{res} = 1$ bosonic feature was stretched vertically for clarity). Clearly, within the significant $T_c$ variation, the positions of the bosonic resonances for $n_{res} = 1, 2, k = 1$ (arrows in fig. 4) are in a good agreement.

![Graph](image)

**Fig. 4:** (Color online) Dynamic conductance spectra for Andreev arrays in Sm$_{1-x}$Th$_{x}$OFeAs samples with various thorium concentrations and $T_c = 26–50\,K$. $dI(V)/dV$ are normalized with $\Delta_L$. SGS of the large gap is shown by gray vertical lines and $n_L$ labels. The $k = 1$ bosonic features are labelled with $n_{res}$ and arrows. The fragment of the lower $dI(V)/dV$ comprising the $n_{res} = 1$ feature was vertically stretched for clarity.

The summary of the data is presented as follows:

1) A “comb” of up to 4 equidistant satellites accompanying the $\Delta_L$ subharmonics is observed in $dI(V)/dV$ spectra of Andreev arrays. The satellites are located in agreement with eq. (1) and, therefore, seem to have electron-boson origin. Except for those merging with SGS dips, the intensity of the satellites decreases with $k$ increase.

2) This effect and the corresponding comb structure obviously have a bulk origin being observed during IMARE in SmS arrays; the bias voltages $V_{res}$ scale with the number of junctions $m$ in the array, together with both gaps SGSs. However, the satellites are less pronounced as compared with $\Delta_L$ dips, therefore, just a portion of carriers undergoing Andreev reflections emits a boson(s).

3) The position of the satellites well coincides for various Andreev arrays, and does not depend on the contact area and resistance, thus it cannot be considered as an artifact or caused by any dimensional effect.

4) The observed fine structure does not match both $2\Delta_{L,S}/e$ and $(\Delta_L + \Delta_S)/e$ subharmonic sequence. None of the satellites can relate to a distinct, the largest order parameter. In this case it would have the BCS ratio $2\Delta_3/k_BT_c > 8$. Although it agrees with PCAR results with fluorine-doped Sm-1111 [36], the presence of three distinct gaps was not confirmed unambiguously both theoretically and experimentally for oxypnictide family (for a review, see [4,6,7,10]). In addition, our preliminary data show that the temperature behaviour of this fine structure does not resemble the expected $\Delta(T)$. For this reason, we cannot attribute the satellites to a $\Delta_L$ anisotropy in the $k$-space. However, this issue requires further studies.

5) In table 1, we present the directly determined (using the data in figs. 1–4, no fitting is needed [50,53]) energy parameters of Sm-1111 within $T_c = 26–50\,K$. For an optimal
compound, \( \varepsilon_0 \) is up to 15 meV and agrees well with that determined for sister compounds GdO\(_{1-x}\)FeAs with similar \( T_c \) [48]. For the entire \( T_c \) range, the experimental value of \( \varepsilon_0 \) obviously does not exceed 2\( \Delta_T \), thus does not violate the MARE regime condition. Although carriers from each band undergo MAR, the boson emission is prohibited for normal carriers from the \( \Delta_s \)-band(s) due to \( \varepsilon_0 > 2\Delta_T \). This is the reason why the bosonic satellites are barely observed next to the \( \Delta_L \) subharmonics. Together with the large and the small gaps [4,10], the bosonic energy roughly scales with critical temperature, evidencing that the emitted bosons are not phonons. Although for the lowest \( T_c \sim 26 \) K, \( \varepsilon_0 \) meets the lowest-frequency optic phonon mode \( \hbar \omega_{\text{phon}} = 11-14 \) meV (determined in Raman spectroscopy [60],inelastic neutron and X-ray scattering studies [44,61] of various 1111), the latter remains nearly constant rather than scaling with decreasing \( T_c \).

6) Unlike magnesium diborides [39,40], one cannot consider the observed bosonic mode as the Leggett plasma mode [56]. Firstly, several theoretical studies have shown that Leggett plasmons are unobservable in iron pnictides [62,63]. Secondly, \( \varepsilon_0^2 \sim \Delta_L \cdot \Delta_S \) within the studied range.

7) Instead, \( \varepsilon_0 \approx \Delta_L + \Delta_S \) (see table 1), and it resembles the energy of the spin resonance peak in the \( s^+ \) state as predicted in [32] or the enhanced spectral peak in the \( s^{++} \) state [25]. For the bosonic mode, the average characteristic ratio is \( \varepsilon_0/k_B T_c \approx 3.2 \) (see table 1). However, it should not be confused with the weak-coupling limit of the BCS theory, since \( \varepsilon_0 \) does not represent the Cooper pair self-energy for any condensate. Note, for the “leading” large superconducting gap \( \Delta_L \), the characteristic ratio well exceeds the BCS limit for the studied samples: 2\( \Delta_T/k_B T_c \approx 5.3 \).

In conclusion, we have studied a fine structure reproducibly observed in dynamic conductance spectra of Andreev arrays in Sm\(_{1-x}\)Th\(_{x}\)FeAs oxypnictides with thorium concentrations \( x = 0.08-0.3 \) and corresponding critical temperatures \( T_c = 26-50 \) K. We unambiguously show that this structure is caused by a resonant sequential boson emission during IMARE. The directly determined energy of the bosonic mode scales with critical temperature together with \( \Delta_L \) and \( \Delta_S \). At \( T_c \sim 50 \) K, \( \varepsilon_0 \) reaches \( \approx 15 \) meV (120 \( \pm \) 20 cm\(^{-1}\)) and resembles that determined by us earlier for GdO\(_{1-x}\)FeAs with similar \( T_c \).

One cannot attribute the observed bosonic resonance with the Leggett mode or the optic phonon mode, nonetheless \( \varepsilon_0 \) is close to the expected position of the energy of the spin resonance peak in the \( s^+ \) state [32] or the enhanced spectral density maximum in the \( s^{++} \) state [25].

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REFERENCES

[1] Zhigadlo N. D., Katrych S., Weyneth S., Puźniak R., Moll P. J. W., Bukowski Z., Karpiński J., Keller H. and Batlogg B., Phys. Rev. B, 82 (2010) 064517.
[2] Zhigadlo N. D., Weyneth S., Katrych S., Moll P. J. W., Rogacki K., Bosma S., Puźniak R., Karpiński J. and Batlogg B., Phys. Rev. B, 86 (2012) 214509.
[3] Singh D. J., Physica C, 469 (2009) 418.
[4] Kuzmicheva T. E., Kuzmichev S. A., Pesvakov K. S., Pudalov V. M. and Zhigadlo N. D., Phys. Rev. B, 95 (2017) 094507.
[5] Charukisha A., Thirupathaiah S., Zabolotnyy V. B., Büchner B., Zhigadlo N. D., Batlogg B., Yaresko A. N. and Borisenko S. V., Sci. Rep., 5 (2015) 10392.
[6] Si Q., Yu R. and Abrahams E., Nat. Mater., 1 (2006) 16017.
[7] Johnston D. C., Adv. Phys., 59 (2010) 803.
[8] Borisenko S. V., Evtushinsky D. V., Liu Z.-H., Morozov I., Kappenberger R., Wurmehl S., Büchner B., Yaresko A. N., Kim T. K., Hoesch M., Wolf T. and Zhigadlo N. D., Nat. Phys., 12 (2016) 311.
[9] Kuzmicheva T. E., Kuzmichev S. A. and Zhigadlo N. D., JETP Lett., 99 (2014) 136.
[10] Kuzmicheva T. E., Kuzmichev S. A., Mikheev M. G., Ponomarev Ya. G., Tchesnokov S. N., Pudalov V. M., Klyubin E. P. and Zhigadlo N. D., Phys.-Usp., 57 (2014) 819.
[11] Kuzmicheva T. E., Kuzmichev S. A., Tchesnokov S. N. and Zhigadlo N. D., J. Supercond. Nov. Magn., 29 (2016) 673.
[12] Daghero D., Tortello M., Gonnelli R. S., Stepanov V. A., Zhigadlo N. D. and Karpiński J., Phys. Rev. B, 80 (2009) 060502(R).
[13] Wang Y. L., Shan L., Cheng P., Ren C. and Wen H. H., Supercond. Sci. Technol., 22 (2009) 015018.
[14] Tanaka M. and Shimada D., J. Supercond. Nov. Magn., 24 (2001) 1491.
[15] Samuely P., Szabo P., Pribulova Z., Tillman M. E., Bud’ko S. L. and Canfield P. C., Supercond. Sci. Technol., 22 (2009) 014003.
[16] Ponomarev Ya. G., Kuzmichev S. A., Mikheev M. G., Sudakova M. V., Tchesnokov S. N., Volkova O. S., Vasiliev A. N., Hänke T., Hess C., Behr G., Klingeler R. and Büchner B., Phys. Rev. B, 79 (2009) 224517.
