Resonant enhancement of sensitivity in a Magnetic Tunnel Junction based Spin Torque Oscillator

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In this work, we investigate the STO as a detector with in-plane geometry using field modulation Spin Torque ferromagnetic resonance (FM-STFMR), during which microwave signal is injected into the device and output response is measured in terms of RMS voltage across lock-in amplifier. The microwave signal injected externally to STO, efficiently synchronizes signal at two times the frequency of free oscillation of the nanomagnet (f_0). The synchronization efficiently enhances signal sensitivity at $2f_0$ which opens other potential for development of spintronic devices. The effect of synchronization in STO under applied input RF power follows a consistent decrease in sensitivity with increasing power. Better synchronization at $2f_0$ is noticed above threshold current and shows good agreement with the results of numerical simulations.

PACS numbers: Valid PACS appear here
Keywords: Suggested keywords

Spin transfer torque (STT) predicted by Slonczewski and Berger[1,2] has attracted researchers in nano-scale Spintronics devices. STT[3-5] manipulates magnetization dynamics with an application of spin polarized currents. Spin polarized current interaction with the local spins leads to the precession of magnetization that can be applied for the technology applications so called Spin Torque oscillator. These Spin Torque oscillators (STOs)[6-7] are nano-sized magneto-resistive devices that can produce a microwave signal in the GHz range with wide frequency tunability, a phenomena which is receiving increasing importance for a number of possible microwave applications e.g., microwave detectors, wireless communication and modulators. STO devices are capable of detecting microwave signals. Spin torque ferromagnetic resonance (STFMR) is a technique[8-9] used to investigate these devices as a microwave detector. In STFMR experiments, a microwave currentwith frequency fe close to the resonance frequency f_0 of nano-magnet is applied to the nanomagnetic device. A dc voltage is produced by mixing of the microwave current with the signal generated by the dynamical response of the nanomagnet via a phenomenon called spin torque diode effect [10]. The microwave signal injected externally to STO, efficiently synchronizes signal at two times the frequency of free oscillation of the nanomagnet (f_0). The synchronization efficiently enhances signal sensitivity at $2f_0$ which opens other potential for development of spintronic devices. By modeling the dependence of this voltage on the applied microwave frequency, one can extractinformation about the resonance frequencies, linewidth and magnitude of spin torques. The efficiency of in-plane STO devices is insufficient for practical applications. However, these devices have higher frequency tunability considerable for real applications as compared to PMA based out of plane arrangements [11-15]. For practical applications, higher frequency tunability with higher sensitivity is a requisite. The diode sensitivity is well defined by: V_{pp}/P_{rf}. The phenomenon of synchronization is presently the centre of research, as it opens other potential for developing and improving the quality STOs. Moreover, the tentativestudy of synchronization isrestricted to a small number of STOs. In this article, we perform spin torque diode measurement in an in-plane magnetic field on CoFeB/MgO/CoFeB device using recently explored STFMR[8-9] technique and more sensitive Field Modulation[16] STFMR Technique. A direct comparison with amplitude modulation in terms of background noise (or signal quality) and sensitivity, showed that the field modulation method is much superior out of the two measurement methods. The parametric synchronization at $2f_0$ in STO under applied input RF power follows a consistent decrease in sensitivity with increasing power. Better synchronization at $2f_0$ is seen above threshold current.

A. Experimental Set-up

We investigate MgO based Magnetic Tunnel Junctions[17] with circular cross section with a diameter of 150 nm consisting of the multilayers of IrMn(5)/CoFe(2.1)/Ru(0.81)/CoFe(1)/CoFeB(1.5)/ MgO(1)/CoFeB(3.5) (thicknesses in nm) Fig 1(a) (inset) where the bottom CoFe layer is the pinned layer (PL), the composite CoFe/CoFeB represents the Reference Layer (RL), and the top CoFeB layer is the Free Layer

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(FL). The measured TMR of theinvestigated device is 73%. We assume that a positive current corresponds to electrons flowing from the RL to the FL. The RL magnetization direction is taken to be $\theta = 0°$ with the applied external magnetic field. All measurements are performed at room temperature. We performSTFMR using in-plane magnetic field on CoFeB/MgO/CoFeB device using Field Modulation Technique. Figure 1(b) shows the actual set-up where a microwave-frequency current I_{RF} and adirect current I_{DC} are applied simultaneously through bias-tee to a MTJ, which excites the free layer magnetization and causes resistance oscillations at driving frequency of I_{RF}. Two Helmholtz coils are attached with the big pole pieces to add a small ac field of 4-5 Oe. These coils are supplied with the reference frequency from the lock-in amplifier to get a sensitive signal.

B. Results and Discussion

We explore experimental results of spectra using amplitude modulation (AM) and a direct comparison with field modulation (FM) STFMR as shown in figure 1(c). The oscillating frequencies and processional modes in both modulation schemes are approximately near but vary in peak to peak voltages V_{pp} with applied external magnetic field.The AM-STFMR spectra suffers from background oscillations is due to the continuous variation of IRFfrequency dependence of the microwave cable and circuitry. However, frequency dependent background noise is removed in case of field modulating STFMR. The voltage VRMS measured across a lock-in amplifier is result of mixing between resistance oscillation and I_{RF}. Figure 1(c) illustrates the measured V_{RMS} voltage at 7 mA as a function of frequency at -10 dBm power supplied through signal source. By making the linewidth narrower, we may expect much larger diode sensitivity[11]. The comparisons of sensitivity at f_0 and $2f_0$ with applied input RF power for both the methods are shown in figure 1(d). Sensitivity decreases with power[14-15]. There is a qualitative similarity in response but the sensitivity is enhanced 2 times in field modulation compared to amplitude modulation (AM). The highest sensitivity for AM-STFMR is 4.2 mV/mW as compared to 10.2 mV/mW for FM-STFMR. Thus FM-STFMR is sensitive compared to AM-STFMR. The increase in peak voltage with an applied bias near threshold current is expected as effective damping is reduced as a result of increase in spin transfer torque at higher bias[19]. Stronger synchronization is observed at $2f_0$ above threshold bias as shown in figure 2. The LLGS equation under the macrospin approximation was solved in spherical coordinates using the 4th order Runge-Kutta method with a fixed time step of 0.5ps. A value of 1000 emu/cc was taken as the saturation magnetization for the free layer. Fixed layer was assumed to be aligned along x-direction with small in-plane and out-of-plane deviation. Polarization efficiency was taken to be 0.65. The contribution from field like torque term was neglected. The STFMR curves were simulated by injecting small RF current I_{RF} at a particular frequency along with the DC bias. The average of oscillating voltage generated due to this excitation over one period is taken as the V_{mix}. Scanning the frequency over a large range (2-15 GHz) and calculating V_{mix} at each point gives the complete STFMR curve. The sensitivity of f_0 increase with increase in dc bias. However stronger synchronization is seen at $2f_0$ above threshold current as shown in figure 3. Figure 3 (a) shows experimental results which are in good agreement with the results of numerical simulations.The increase in sensitivity with an applied bias above threshold current is expected as effective damping is reduced as a result of increase in spin transfer torque at higher bias[19].Sensitivity decrease with applied input RF power as shown in figure 4. The decrease in sensitivity of resonant peaks is due to distribution of power over the entire sweep range. In conclusion, we measured the magnetization spectra using two methods: AM-STFMR and FM-STFMR. FM technique eliminates background magnetic signals with better signal quality.The microwave signal injected externally efficiently synchronizes signal at twice the frequency of free oscillation of the nanomagnet (f_0). The synchronization efficiently enhances signal sensitivity at $2f_0$. Sensitivity increases with applied bias results reduction in damping and increase in STT at higher currents.Better synchronization at $2f_0$ is noticed above threshold current and shows good agreement with the results of numerical simulations. However, more devices should be explored to present information concerning the behavioral data consistency.

This sample document demonstrates proper use of REVTEX 4.1 (and LATEX 2_ε) in manuscripts prepared for submission to AIP journals. Further information can be found in the documentation included in the distribution or available at `http://authors.aip.org` and in the documentation for REVTEX 4.1 itself.

When commands are referred to in this example file, they are always shown with their required arguments, using normal TEX format. In this format, `#1`, `#2`, etc. stand for required author-supplied arguments to commands. For example, in `\section{#1}` the `#1` stands for the title text of the author's section heading, and in `\title{#1}` the `#1` stands for the title text of the paper.

Line breaks in section headings at all levels can be introduced using \\. A blank input line tells TEX that the paragraph has ended.

C. Second-level heading: Formatting

This file may be formatted in both the `preprint` (the default) and `reprint` styles; the latter format may be used to mimic final journal output. Either format may be used for submission purposes; however, for peer review and production, AIP will format the article using the `preprint` class option. Hence, it is essential that authors check that their manuscripts format acceptably under `preprint`. Manuscripts submitted to AIP that do not format correctly under the `preprint` option may be delayed in both the editorial and production processes.

The `widetext` environment will make the text the width of the full page, as on page 4. (Note the use the

`\pageref{#1}` to get the page number right automatically.) The width-changing commands only take effect in `twocolumn` formatting. It has no effect if `preprint` formatting is chosen instead.

1. Third-level heading: Citations and Footnotes

Citations in text refer to entries in the Bibliography; they use the commands `\cite{#1}` or `\onlinecite{#1}`. Because REVTEX uses the `natbib` package of Patrick Daly, its entire repertoire of commands are available in your document; see the `natbib` documentation for further details. The argument of `\cite` is a comma-separated list of *keys*; a key may consist of letters and numerals.

By default, citations are numerical;[?] author-year citations are an option. To give a textual citation, use `\onlinecite{#1}`: (Refs. **? ? ?**). REVTEX "collapses" lists of consecutive numerical citations when appropriate. REVTEX provides the ability to properly punctuate textual citations in author-year style; this facility works correctly with numerical citations only with `natbib`'s compress option turned off. To illustrate, we cite several together[? ? ? ?] , and once again (Refs. **? ? ? ?**). Note that, when numerical citations are used, the references were sorted into the same order they appear in the bibliography.

A reference within the bibliography is specified with a `\bibitem{#1}` command, where the argument is the citation key mentioned above. `\bibitem{#1}` commands may be crafted by hand or, preferably, generated by using BibTEX. The AIP styles for REVTEX 4 include BibTEX style files `aipnum.bst` and `aipauth.bst`, appropriate for numbered and author-year bibliographies, respectively. REVTEX 4 will automatically choose the style appropriate for the document's selected class options: the default is numerical, and you obtain the author-year style by specifying a class option of `author-year`.

This sample file demonstrates a simple use of BibTEX via a `\bibliography` command referencing the `aipsamp.bib` file. Running BibTEX (in this case `bibtex aipsamp`) after the first pass of LATEX produces the file `aipsamp.bbl` which contains the automatically formatted `\bibitem` commands (including extra markup information via `\bibinfo` commands). If not using BibTEX, the `thebibiliography` environment should be used instead.

a. Fourth-level heading is run in. Footnotes are produced using the `\footnote{#1}` command. Numerical style citations put footnotes into the bibliography[3]. Author-year and numerical author-year citation styles (each for its own reason) cannot use this method. Note: due to the method used to place footnotes in the bibliography, *you must re-run BibTeX every time you change any of your document's footnotes.*

I. MATH AND EQUATIONS

Inline math may be typeset using the `$` delimiters. Bold math symbols may be achieved using the `bm` package and the `\bm{#1}` command it supplies. For instance, a bold α can be typeset as `$\bm{\alpha}$` giving $\boldsymbol{\alpha}$. Fraktur and Blackboard (or open face or double struck) characters should be typeset using the `\mathfrak{#1}` and `\mathbb{#1}` commands respectively. Both are supplied by the `amssymb` package. For example, `$\mathbb{R}$` gives $\mathbb{R}$ and `$\mathfrak{G}$` gives $\mathfrak{G}$

In LATEX there are many different ways to display equations, and a few preferred ways are noted below. Displayed math will center by default. Use the class option `fleqn` to flush equations left.

Below we have numbered single-line equations, the most common kind:

$$\chi_+(p) \lesssim [2|\mathbf{p}|(|\mathbf{p}|+p_z)]^{-1/2} \begin{pmatrix} |\mathbf{p}|+p_z \\ px+ip_y \end{pmatrix} , \tag{1}$$

$$\left\{ 1\!\!1234567890abc123\alpha\beta\gamma\delta1234556\alpha\beta\frac{1\sum_b^a}{A^2} \right\}. \tag{2}$$

Note the open one in Eq. (2).

Not all numbered equations will fit within a narrow column this way. The equation number will move down automatically if it cannot fit on the same line with a one-line equation:

$$\left\{ ab12345678abc123456abcdef\alpha\beta\gamma\delta1234556\alpha\beta\frac{1\sum_b^a}{A^2} \right\}. \tag{3}$$

When the `\label{#1}` command is used [cf. input for Eq. (2)], the equation can be referred to in text without knowing the equation number that TEX will assign to it. Just use `\ref{#1}`, where `#1` is the same name that used in the `\label{#1}` command.

Unnumbered single-line equations can be typeset using the `\[`, `\]` format:

$$g^+g^+ \rightarrow g^+g^+g^+g^+ \dots ~,~~q^+q^+ \rightarrow q^+g^+g^+ \dots ~.$$

A. Multiline equations

Multiline equations are obtained by using the `eqnarray` environment. Use the `\nonumber` command at the end of each line to avoid assigning a number:

$$\begin{aligned} \mathcal{M} =& ig_Z^2(4E_1E_2)^{1/2}(l_i^2)^{-1}\delta_{\sigma_1,-\sigma_2}(g_{\sigma_2}^e)^2\chi_{-\sigma_2}(p_2) \\ &\times[\epsilon_j l_i \epsilon_i]_{\sigma_1}\chi_{\sigma_1}(p_1), \end{aligned} \tag{4}$$

$$\begin{aligned} \sum |M_g^{\text{viol}}|^2 &= g_S^{2n-4}(Q^2)~N^{n-2}(N^2-1) \\ &\times \left(\sum_{i<j}\right) \sum_{\text{perm}} \frac{1}{S_{12}} \frac{1}{S_{12}} \sum_\tau c_\tau^f ~. \end{aligned} \tag{5}$$

Note: Do not use `\label{#1}` on a line of a multiline equation if `\nonumber` is also used on that line. Incorrect cross-referencing will result. Notice the use `\text{#1}` for using a Roman font within a math environment.

To set a multiline equation without *any* equation numbers, use the `\begin{eqnarray*}`, `\end{eqnarray*}` format:

$$\sum |M_g^{\rm viol}|^2 = g_S^{2n-4}(Q^2)\ N^{n-2}(N^2-1) \times \left(\sum_{i<j} \right) \left(\sum_{\rm perm} \frac{1}{S_{12}S_{23}S_{n1}} \right) \frac{1}{S_{12}} \ .$$

To obtain numbers not normally produced by the automatic numbering, use the `\tag{#1}` command, where `#1` is the desired equation number. For example, to get an equation number of (2.6′),

$$g^+g^+ \rightarrow g^+g^+g^+g^+ \dots \ , \quad q^+q^+ \rightarrow q^+g^+g^+ \dots \ . \tag{2.6′}$$

A few notes on `\tag{#1}`. `\tag{#1}` requires `amsmath`. The `\tag{#1}` must come before the `\label{#1}`, if any. The numbering set with `\tag{#1}` is *transparent* to the automatic numbering in REVTeX; therefore, the number must be known ahead of time, and it must be manually adjusted if other equations are added. `\tag{#1}` works with both single-line and multiline equations. `\tag{#1}` should only be used in exceptional case - do not use it to number all equations in a paper.

Enclosing single-line and multiline equations in `\begin{subequations}` and `\end{subequations}` will produce a set of equations that are "numbered" with letters, as shown in Eqs. (6a) and (6b) below:

$$\left\{ abc123456abcdef\alpha\beta\gamma\delta1234556\alpha\beta \frac{1\sum^a_b}{A^2} \right\}, \tag{6a}$$

$$\mathcal{M} = ig_Z^2(4E_1E_2)^{1/2}(l_i^2)^{-1}(g_{\sigma_2}^e)^2\chi_{-\sigma_2}(p_2) \times [\epsilon_i]_{\sigma_1}\chi_{\sigma_1}(p_1). \tag{6b}$$

Putting a `\label{#1}` command right after the `\begin{subequations}`, allows one to reference all the equations in a subequations environment. For example, the equations in the preceding subequations environment were Eqs. (6).

1. Wide equations

The equation that follows is set in a wide format, i.e., it spans across the full page. The wide format is reserved for long equations that cannot be easily broken into four lines or less:

$$\mathcal{R}^{(\rm d)} = g_{\sigma_2}^e \left(\frac{[\Gamma^Z(3,21)]_{\sigma_1}}{Q_{12}^2-M_W^2} + \frac{[\Gamma^Z(13,2)]_{\sigma_1}}{Q_{13}^2-M_W^2} \right) + x_W Q_e \left(\frac{[\Gamma^\gamma(3,21)]_{\sigma_1}}{Q_{12}^2-M_W^2} + \frac{[\Gamma^\gamma(13,2)]_{\sigma_1}}{Q_{13}^2-M_W^2} \right) \ . \tag{7}$$

This is typed to show the output is in wide format. (Since there is no input line between `\equation` and this paragraph, there is no paragraph indent for this paragraph.)

II. CROSS-REFERENCING

REVTeX will automatically number sections, equations, figure captions, and tables. In order to reference them in text, use the `\label{#1}` and `\ref{#1}` commands. To reference a particular page, use the `\pageref{#1}` command.

The `\label{#1}` should appear in a section heading, within an equation, or in a table or figure caption. The `\ref{#1}` command is used in the text where the citation is to be displayed. Some examples: Section **??** on page **??**, Table I, and Fig. 1.

III. FIGURES AND TABLES

Figures and tables are typically "floats"; LaTeX determines their final position via placement rules. LaTeX isn't always successful in automatically placing floats where you wish them.

Figures are marked up with the `figure` environment, the content of which imports the image (`\includegraphics`) followed by the figure caption (`\caption`). The argument of the latter command should itself contain a `\label` command if you wish to refer to your figure with `\ref`.

Import your image using either the `graphics` or `graphix` packages. These packages both define the `\includegraphics{#1}` command, but they differ in the optional arguments for specifying the orientation, scaling, and translation of the figure. Fig. 1

is small enough to fit in a single column, while Fig. 2 is too wide for a single column, so instead the `figure*` environment has been used.

The analog of the `figure` environment is `table`, which uses the same `\caption` command. However, you should type your caption command first within the `table`, instead of last as you did for `figure`.

TABLE I. This is a narrow table which fits into a text column when using `twocolumn` formatting. Note that REVTeX 4 adjusts the intercolumn spacing so that the table fills the entire width of the column. Table captions are numbered automatically. This table illustrates left-aligned, centered, and right-aligned columns.

Left[a]	Centered[b]	Right
1	2	3
10	20	30
100	200	300

[a] Note a.
[b] Note b.

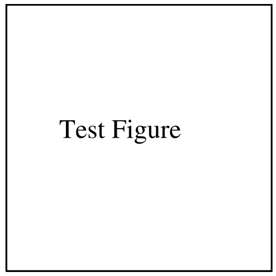

FIG. 1. A figure caption. The figure captions are automatically numbered.

TABLE II. Numbers in columns Three–Five have been aligned by using the “d” column specifier (requires the `dcolumn` package). Non-numeric entries (those entries without a “.”) in a “d” column are aligned on the decimal point. Use the “D” specifier for more complex layouts.

One	Two	Three	Four	Five
one	two	three	four	five
He	2	2.77234	45672.	0.69
C[a]	C[b]	12537.64	37.66345	86.37

[a] Some tables require footnotes.
[b] Some tables need more than one footnote.

The heart of any table is the `tabular` environment, which represents the table content as a (vertical) sequence of table rows, each containing a (horizontal) sequence of table cells. Cells are separated by the `&` character; the row terminates with `\\`. The required argument for the `tabular` environment specifies how data are displayed in each of the columns. For instance, a column may be centered (`c`), left-justified (`l`), right-justified (`r`), or aligned on a decimal point (`d`). (Table II illustrates the use of decimal column alignment.)

Extra column-spacing may be be specified as well, although REVTEX 4 sets this spacing so that the columns fill the width of the table. Horizontal rules are typeset using the `\hline` command. The doubled (or Scotch) rules that appear at the top and bottom of a table can be achieved by enclosing the `tabular` environment within a `ruledtabular` environment. Rows whose columns span multiple columns can be typeset using LATEX's `\multicolumn{#1}{#2}{#3}` command (for example, see the first row of Table III).

The tables in this document illustrate various effects. Tables that fit in a narrow column are contained in a `table` environment. Table III is a wide table, therefore set with the `table*` environment. Lengthy tables may need to break across pages. A simple way to allow this is to specify the `[H]` float placement on the `table` or `table*` environment. Alternatively, using the standard LATEX 2_ε package `longtable` gives more control over how tables break and allows headers and footers to be specified for each page of the table. An example of the use of `longtable` can be found in the file `summary.tex` that is included with the REVTEX 4 distribution.

There are two methods for setting footnotes within a table (these footnotes will be displayed directly below the table rather than at the bottom of the page or in the bibliography). The easiest and preferred method is just to use the `\footnote{#1}` command. This will automatically enumerate the footnotes with lowercase roman letters. However, it is sometimes necessary to have multiple entries in the table share the same footnote. In this case, create the footnotes using `\footnotemark[#1]` and `\footnotetext[#1]{#2}`. `#1` is a numeric value. Each time the same value for `#1` is used, the same mark is produced in the table. The `\footnotetext[#1]{#2}` commands are placed after the `tabular` environment. Examine the LATEX source and output for Tables I and IV for an illustration.

All AIP journals require that the initial citation of figures or tables be in numerical order. LATEX's automatic numbering of floats is your friend here: just put each `figure` environment immediately following its first reference (`\ref`), as we have done in this example file.

ACKNOWLEDGMENTS

We wish to acknowledge the support of the author community in using REVTEX, offering suggestions and encouragement, testing new versions, ...

Appendix A: Appendixes

To start the appendixes, use the `\appendix` command. This signals that all following section commands refer to appendixes instead of regular sections. Therefore, the `\appendix` command should be used only once—to set up the section commands to act as appendixes. Thereafter normal section commands are used. The heading for a section can be left empty. For example,

```
\appendix
\section{}
```

will produce an appendix heading that says “APPENDIX A” and

```
\appendix
\section{Background}
```

will produce an appendix heading that says “APPENDIX A: BACKGROUND” (note that the colon is set automatically).

If there is only one appendix, then the letter “A” should not appear. This is suppressed by using the star version of the appendix command (`\appendix*` in the place of `\appendix`).

Appendix B: A little more on appendixes

Observe that this appendix was started by using

```
\section{A little more on appendixes}
```

Note the equation number in an appendix:

$$E = mc^2. \tag{B1}$$

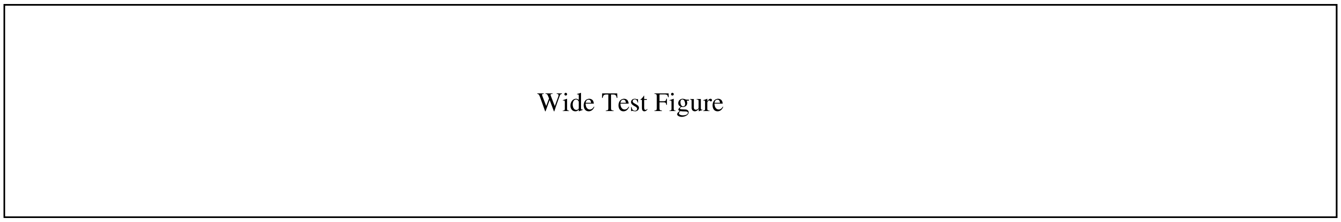

FIG. 2. Use the `figure*` environment to get a wide figure, spanning the page in `twocolumn` formatting.

TABLE III. This is a wide table that spans the page width in `twocolumn` mode. It is formatted using the `table*` environment. It also demonstrates the use of `\multicolumn` in rows with entries that span more than one column.

	D_{4h}^1		D_{4h}^5	
Ion	1st alternative	2nd alternative	lst alternative	2nd alternative
K	$(2e)+(2f)$	$(4i)$	$(2c)+(2d)$	$(4f)$
Mn	$(2g)$[a]	$(a)+(b)+(c)+(d)$	$(4e)$	$(2a)+(2b)$
Cl	$(a)+(b)+(c)+(d)$	$(2g)$[b]	$(4e)$[a]	
He	$(8r)$[a]	$(4j)$[a]	$(4g)$[a]	
Ag		$(4k)$[a]		$(4h)$[a]

[a] The z parameter of these positions is $z \sim \frac{1}{4}$.
[b] This is a footnote in a table that spans the full page width in `twocolumn` mode. It is supposed to set on the full width of the page, just as the caption does.

TABLE IV. A table with more columns still fits properly in a column. Note that several entries share the same footnote. Inspect the LaTeX input for this table to see exactly how it is done.

	r_c (Å)	r_0 (Å)	κr_0		r_c (Å)	r_0 (Å)	κr_0
Cu	0.800	14.10	2.550	Sn[a]	0.680	1.870	3.700
Ag	0.990	15.90	2.710	Pb[b]	0.450	1.930	3.760
Au	1.150	15.90	2.710	Ca[c]	0.750	2.170	3.560
Mg	0.490	17.60	3.200	Sr[d]	0.900	2.370	3.720
Zn	0.300	15.20	2.970	Li[b]	0.380	1.730	2.830
Cd	0.530	17.10	3.160	Na[e]	0.760	2.110	3.120
Hg	0.550	17.80	3.220	K[e]	1.120	2.620	3.480
Al	0.230	15.80	3.240	Rb[c]	1.330	2.800	3.590
Ga	0.310	16.70	3.330	Cs[d]	1.420	3.030	3.740
In	0.460	18.40	3.500	Ba[e]	0.960	2.460	3.780
Tl	0.480	18.90	3.550				

[a] Here's the first, from Ref. **?** .
[b] Here's the second.
[c] Here's the third.
[d] Here's the fourth.
[e] And etc.

1. A subsection in an appendix

You can use a subsection or subsubsection in an appendix. Note the numbering: we are now in Appendix B 1.

a. A subsubsection in an appendix

Note the equation numbers in this appendix, produced with the subequations environment:

$$E = mc, \tag{B2a}$$

$$E = mc^2, \tag{B2b}$$

$$E \gtrsim mc^3. \tag{B2c}$$

They turn out to be Eqs. (B2a), (B2b), and (B2c).

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