;@2=J*D6EAF3BNK*1kBh;09bD4GH8rN.BS<'N(

Third Harmonic AC Susceptibility in Oxide Superconductors

6e=#9)6HBg3X >pJs9)3XIt EE;R>pJs9)3X2J

>.EDIt Aq;J, KLB< NIJ?, >>2< >HCK

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Abstract—In order to investigate the effect of reversible motion of fluxoids, the third harmonic of complex AC susceptibility was measured for Y-based superconducting powder and QMG-processed bulk specimens. The critical current density was estimated from the experimental results using the theoretical model of Campbell for the reversible motion of fluxoids and compared with the estimation from DC magnetization. Deviation from the estimated value from DC magnetization is remarkable when the applied AC magnetic field is small. It is considered that the reversible fluxoid motion at low AC magnetic fields is much more prominent than expected in the present theory.

1. O8aK

Bh;09bD4GH8rN.BS<'N χ_3' (χ_3'') $O4pK\GH<~GH?tIU6a$N%N%$%:$dNL;R2=<'B+$NG4@-NO$N1F6A$r:o=|$G$-!"$h$j@53N$J%T%s%K%s%08z2L$N>pJs$,F@ilkH4|BT5l$F$$j!";@2=J*D6EAF3BN$NI>2A$KMQ$$$ilF$-$F$$$k[1]!"NL;R2=<'B+$N2D5U1?F0$,82Cx$J:]$K$O!"D>N.<'2=$N%^%$%J!<%+!<%V$N8{G[$d8rN.BS<'N($N4pK\GH@.J,$d9bDGH@.J,$O40A4$KIT2D5U$J Bean $NNW3&>uBV%b%G%k$NM=A[$+$i30lk3H$,CN$ilF$$$k[2]!#NL;R2=<'B+$N2D5U1?F0$OD6EAF3BN$NM-8z%5%$%: d $, Campbell $N8rN.<'3&$N?/F~?<$5 λ_0' $HF1Ey$+hj>.$5$$;~$K82Cx$KJk!#$3$3$G!"M-8z%5%$%:$OD6EAF3<WJCEEN.$N%k!<%W$N>.$5$$J}$NH>7B$GM?$($ilk!#

Rb_3C_{60} D6EAF3J4BN$N χ_3', χ_3'' $N8rN.<'3&0MB8@-$N<B837k2L$O!"NL;R2=<'B+$N2D5U1?F0$r9MN8$7$? Campbell %b%G%k$rbH$K?tCM7W;;$7$?7k2L$HHf3S5l$F$$$k[2]7k2L!" χ_3', χ_3'' $N%T!<%/$NCM$ONL;R2=<'B+$N2D5U1?F0$,82Cx$J:]$K Bean %b%G%k$NM=A[hj$b6KC<$K>.5+C?!#$^$?%T!<%/NCMOD>N.<'3&$rA}2C$5$;$?:]$d9b29$KJk$$DlF8:>/7?!#3liN7k2L$O Campbell $N8rN.<'3&$N?/F~?<$5 λ_0' $H29EY0MB8@-$+$i@bL@$9k3H,G-$k!#$D$^$j9b$$<'3&$d29EY$K$*$$$F$O λ_0' $,A}2C$7!"$=$N7k2LH7$FNL;R2=<'B+$N2D5U1?F0$O82Cx$HJk!#7+7J$,$i!"M χ_3'' ONE1KO χ $N%T!<%/$N@dBPCM$NJ}$,@5$N%T!<%/$hjbBg$-$$$HM=B,7F$$$kNKBP7F!"<B83$

$O@5$N%T!<%/NCM,Bg$-$$7k2L$rF@$?!#3N7k2L$+$i9b$$8rN.<' 3&K*$$$FM}O@$
M=A[hj$b5^B.$K2D5U$+$iIT2D5U$K0\9T$7$F$$$kbN$H9M$(il$?!# χ_3'' $N87$+$7 χ
N.<' 3&0MB8@-KD$$$FOh$j>\:Y$J8!F$$,I,MWG"$k!#

;@2=J*D6EAF3BNK*$$$F9b29$GNL;R2=<' B+$N2D5U1?F0$N4BN C_{60} HF1MM$K82
CxG"kH4|BT5l$k!#$J$<$J$i;@2=J*D6EAF3BN;nNA$K$*$$$F$O%/%i%C%/$d<e7k9
Kh$jJ,3d$5lk3H$,$"$j!"$=Nh$&$J;~KOD6EAF3BN$NM-8z%5%$%:$,>.$5$/$
$k!#$3$3$G$OBh;09bD4GH8rN.BS<' N($K5Z$\$9NL;R2=<' B+$N2D5U1?F0$N8z2LKD$$$
Y 7O$ND6EAF3J4BN$H QMG K!Kh$j@=:n$5l?%P%k%/$N;nNA$K$D$$$FB,Dj7?!#7k2L
$O Campbell %b%G%k$rbHK7$??tCM7W;;$rMQ$$$F2r@Or7$F!"D>N.<' 2=B,Dj$N7k2L
$HHf3S$7$?!#FC$KBh;09bD4GH8rN.BS<' N($+$i5aa?NW3&EEN.L)EYKD$$$F8!F$$r$
3J$&!#

2. <B83

<B83$KMQ$$$?;nNA$O Y 7O$ND6EAF3J4BN$H QMG(Quench and Melt Grouwth) K!Kh$C
$F:n@=$5l?%P%k%/:`G"$k!#>F7kK!$G:nil$? Y-Ba-Cu-O $rJ4:U$7$F!"@d1oBN$G
$"$k Y_2O_3 $NJ4BN$H 1:2 $G:.9g$7$?!#$3$N:.9gJ4$r$*$h$= 2 t/cm^2 $N05NO$G2!$78G$a!"
%(%]%-%7<y;i$G8GDj$7$?!#$3$NJ4BN;nNA$G$O!"8D!9$ND6EAF3J4$N percolative path $OB8
:_7J$$$H4|BT5l!"hC$F30It$N8rN.<' 3&Kh$jM6F3$5lk<WJCEEN.$OD6EAF3J4$
FbItKN$_N.$lkH9M$($ilk!#9JoAD6EAF3BN$NM-8z%5%$%: d $OJ4BN$N%5%$%:$
F1$8$H9M$($i$l!"$*$*$h$= $d = 1 \sim 10\ \mu$m G"$k!# QMG ;nNA$O $4.55 \times 3.20 \times 0.85$ mm
NBg-5N%9%i%VG"$j!" c <4$O9-$$LLKBP7$F?bD>$KG[8~7F$$$k!# QMG ;nNA$N
>l9gKO!"<WJCEEN.$O%/%i%C%/$JINh&$J7g4Y$N$?$a$K;nNAFb$r6Q0l$KN.$l$k;v$
G-$J$$!#7?$,$C$F!" QMG ;nNA$rN.lkEEN.$r;nNAA4BN$rN.lk%P%k%/$JEEN.$H
%/%i%C%/KhCFJD$89~$ail$?6I=jE*$JEEN.NOBH7F6a;w7?;~!"8e<TKD$$$
$O d $O a-b LL$K1hCFB8:_9k%/%i%C%/$N4V3V$HF1$8H7FIl@1K7J1lPJ$i
$J$$$N$OD>N.<' 2=$N%R%9%F%j%7%9$+$i5aak;~KO!";nNA$N8|$5 $D = 0.85$ mm
$rMQ$$$k;vG"$k!#$7$?$,CF QMG ;nNAK*$$$F$O!"D>N.<' 2=$h$j5a$a$k J_c
$NNW3&EEN.L)EY$HEy7/OJ$/!"6I=j$NCM$HM"AwEEN.L)EY$N$"$k<o$NJ?6QCM$G$"$
[4] !#4pK\GH8rN.BS<' N($N5uIt$+$i5a$a$?NW3&29EY$OJ4BN;nNA$H QMG ;nNA$K$*$$$F$=
l>$l 90.5 K $H 90.2 K G"C?!#

4pK\GH$HBh;09bD4GH8rN.BS<' N($\chi_1', \chi_1'', \chi_3', \chi_3''$) $N8rN.<' 3&0MB8@-$r01Dj$N29EY$*
hSD>N.<' 3&$N2<$GB,Dj7?!#D>N.H=lK=E>v9k8rN.$N<' 3&$O QMG ;nNA$ND9<j
J}8~$K1h$C$F0u2C$7$?!#D>N.<' 3&$O 6 T $^$G!"8rN.<' 3&$O 0.03 T $^$G0u2C7?!#29EY
$O%,%9%X%j%&%`Cf$G 60 K $+$i T_c $^$GD4@0$7$?!#D>N.<' 2=B,Dj$O SQUID(MPMS-7) $r
MQ$$$FB,Dj7?!#

3. 7k2L$*$h$S8!F$

Figure 1(a) $H (b) $K $= $1 $> $1 81 K $K $* $1 $k J4 BN ;nNA $H 87 K $K $* $1 $k QMG ;nNA $N χ_3'' $N8rN.<' 3& 0MB8@-$r<($9!#N>J} $N;nNA $K $* $$ $FD>N.<' 3& $, A}2C$9$k $K $D $1 $F χ %T!<%/CM$OC1D4$K8:>/7F$$$k;v$,$o$+$k!#$^$?29EY$r>e>:$5$;$?;~KbF1MM$J7 2L$rF@$F$$$k!#3liN7k2L$O>e=R$Nh&$K λ_0' $N2ENY<' 3& 0MB8@-$+$i@bL@$9$k;v$, G-$k!#$^$?@5$N%T!<%/$, Fig. 1(b) GO4QB,5l$F$$$kNKBP7F!" Fig. 1(a) GO$J $$!#3NM}M3OFsD$N;nNA$N4V$G $\zeta d/2$ $N2CM$,0c$&$?aG$"$k!#NW3&EEN.L)EY J_c H λ_0' $O<!$N4X78$,$"$k[5]!#

$$\lambda_0' = \left(\frac{H_0 d_{\rm i}}{J_{\rm c}}\right)^{1/2} \tag{1}$$

$3$3$G!" H_0 $OD>N.<' 3& G"$j!" $d_{\rm i} = d_{\rm f}/\zeta$ $OAj4X5wN% HhPl$k!# $d_{\rm f}$ $O<' B+@~4V5wN% G"$j!" ζ $O%T%s;_$a$N<oN`$K0MB8$9$kDj?tG"$k!#J4BN;nNA$K$*$$$F$O QMG ;nNA hj $J_{\rm c}$ $,>.$5$$$?$a λ_0' $,Bg$-$/!"$^$? d $,>.$5$$$N$G!" $\lambda_0'/(d/2)$ $,>.$5$/$J$k!#$7$? $,$C$F!"J4BN;nNA$NJ}$,<' B+@~$N2D5U1?F0$,82Cx$G$"$k!# QMG ;nNAK*$$$F$O@5$N %T!<%/CM$,Ii$N%T!<%/$N@dBPCM$hjbBg$-$/!"3l$O C_{60} $NRh2L[2] $HF1$8G"$k!#

$3$3$G!" χ_1'', χ_3', χ_3'' $N%T!<%/$r<($98rN.<' 3& NBg-5r$I>2A$7!"$=$N7k2L $rD>N.<' 2=$N%R%9%F%j%7%9$+$i5aa?CM$HHf3S$9$k!# χ_1'', χ_3', χ_3'' $N%T!<%/$r<($98rN. <' 3& NBg-$5 $H_{{\rm mp}\chi_1''}$, $H_{{\rm mp}\chi_3'}$, $H_{{\rm mp}\chi_3''}$ $O $d/2\lambda_0'$ KhCF0l0U$K7h$^$k!#Nc$($P χ_1'' $N>l 9g$K$O6a;wE*$K<!Nh$&$KJk[5]!#

$$H_{{\rm mp}\chi_1''}/H_{\rm p} = 3^{1/2}[1 + 2(2\lambda_0'/d)^2] \tag{2}$$

$3$3$G!" $H_{\rm p} = J_{\rm c}d/2$ $OCf?4E~C#<' 3& G"$k!# χ_3', χ_3'' KD$$$F$bF1MM$K?tCM7W;;$N7k 2L$h$j0J2<$N6a;w<0$rF@$?!#

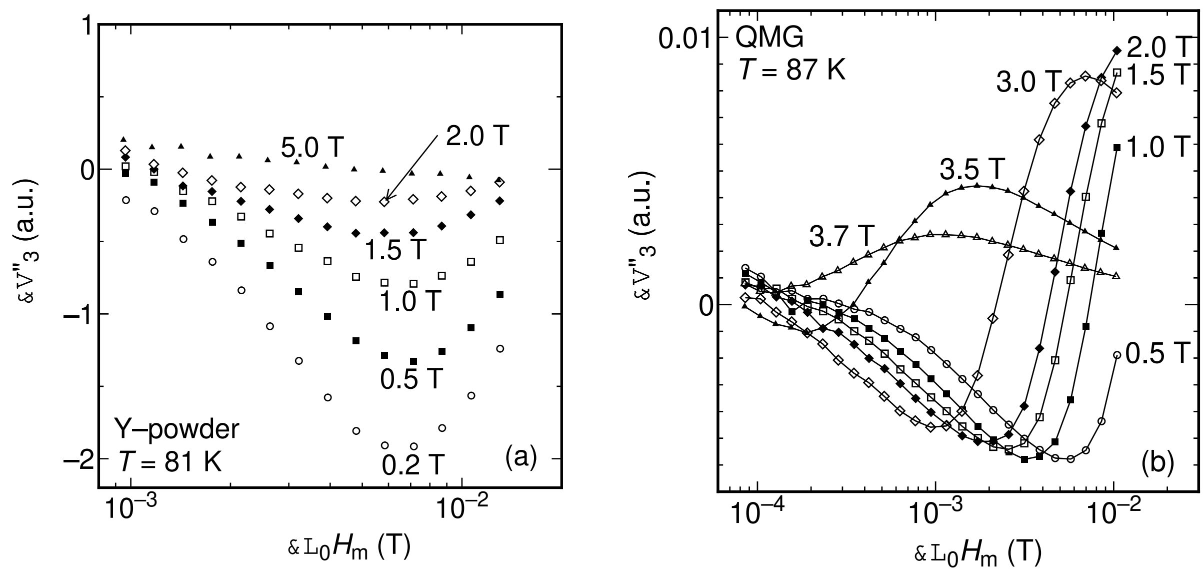

Fig. 1: AC magnetic field dependence of χ_3'' in various DC magnetic fields in (a) powder specimen at 81 K and (b) QMG specimen at 87 K.

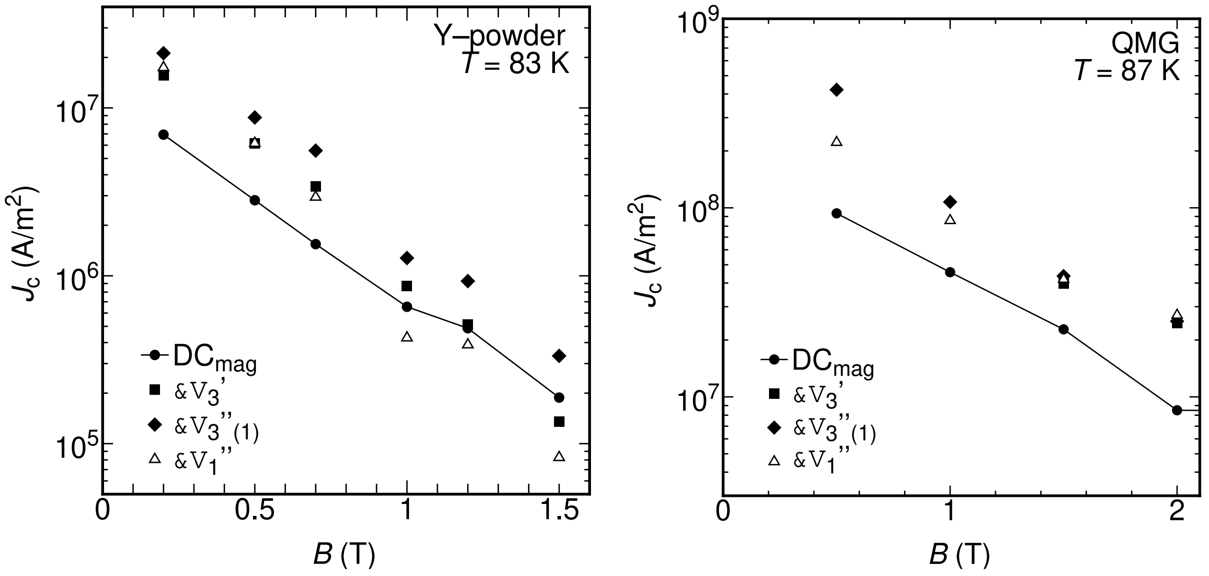

Fig. 2: Critical current density estimated from the various peak fields of AC susceptibilities and DC magnetization for (a) powder specimen and (b) QMG specimen.

$$H_{\mathrm{mp}\chi_3'}/H_{\mathrm{p}} = (8/3)[1 + 3(2\lambda_0'/d)^2] \tag{3}$$

$$H_{\mathrm{mp}\chi_3''}/H_{\mathrm{p}} = 1.41[1 + 2(2\lambda_0'/d)^2] \tag{4}$$

0lJ}!"D>N.<'2=$N%^%$%J!<%+!<%V$N8{G[S_0' $K $d/2\lambda$ $j0l0U$K7h$^$j!"

$$S = 1 - \frac{2\lambda_0'}{d}\tanh\left(\frac{d}{2\lambda_0'}\right). \tag{5}$$

Nh$&$KI=5l$k[6]# 7?$,CF!" $d/2\lambda_0'$ $r S $NB,DjCM$h$j5a$a$k;v$,G-$k!#$3$l $rMQ$$$F $H_{\mathrm{mp}\chi_1''}/H_{\mathrm{p}}$, $H_{\mathrm{mp}\chi_3'}/H_{\mathrm{p}}$, $H_{\mathrm{mp}\chi_3''}/H_{\mathrm{p}}$ $O (2)–(4) <0$h$j5a$a$k;v$,G-!"3lH* N*NN%T!<%/<' 3&$NB,DjCM$h$j5a J_c ak;v$,G-$k!#0lJ}!"D>N.<'2=$N%R%9%F %j%7%9 ΔM $+$i$Q $\neq 2\Delta M/D$ hj5aa?!#

J4BN;nNAK*1kMM!9$J8rN.BS<'N($N%T!<%/$HD>N.<'2=$+iN7ha?$r J_c
Fig. 2(a) $K<($9!#$3$3$G d $O 5 μm $H2>Dj$7$?!#$3$N;nNA$N>l9gKOB8 :_9kNO6I =j$NNW3&EEN.L)EY$N$_$G$"$j!"7?$,$C$FD>N.<'2=$bF1$8 7k2L$HJkO:G"$k!#$ $?D>N.<'2=$+$i5a$a$F$$$kCM$OIT2D5U$N6K8BGNCM$r5a$a$F$$$kNG!"??NCMK6 $$$H9M$($ilk!#7+7J$,$i!"D>N.<'2=$+$i5aaF$?$r J_c $N.BS<'N($+$i5a$a $F$$$kCMKHfY$F>.$5$$;v$, Fig. 2(a) hjo+$k!#$3Nh$&$K8rN.BS<'N($+$i5a$a $F$$$kCMOJ$*2aBgI>2A$5lF$$$k!#5i$K!"$=l>lN%T!<%/$+$i5aa?CM$O0c$ $F$$$k!#D^$j χ_3'' NIiN%T!<%/$+$i5aa? J_c $,0lHVBg$-$/!"<!$K χ_1'' $+$i5aa?CM$G $"$j!" χ_3' $+$i5aa?CM$,0lHV>.$5$$!#0lJ}!" Bean %b%G%k$+$iM=A[5l$k%T!<%/$N<' 3&$O Table I$K<(7F$"$k!#3N=gHV$O $d/2\lambda_0'$ Nh$&$K<'B+@~$N2D5U1?F0$,82Cx $J:]$G$b@.$jN)$D!#$7$?$,CF!"M}O@M=A[$H<B837k2L$N0c$$$O8rN.<'3&$,>.$5$$$H$ mG82CxG"$k;v$,o+$k!#8@$$49$($k$H Campbell %b%G%k$K$*$$$F<'B+@~$NJQ0L$, >.$5$$NN0h$G<B837k2L$+iN30l,L\N)$D!#

Table I: The normalized amplitudes of AC magnetic fields at the peaks of various AC susceptibilities predicted by Bean's model.

	negative peak of χ_3''	χ_1''	χ_3'	positive peak of χ_3''
peak AC field normalized by H_p	1.38	1.41	2.67	9.65

A0=RNh$&$K QMG ;nNAK*$$$F!"D>N.<' 2=$+$i5a$a$$1G$1I$kj/ JNCM$HM"Aw
NW3&EEN.L)EYN"$k<o$NJ?6QG"$k!#01J}!" QMG :`$JIG$OD>N.<' 2=$N%R%9%F%j%7
%9NBg-5,$[$\;nNA%5%$%:$KHfNc9k3H$,CN$ilF$*$j!"$"$?$+$b%P%k%/$JE
N.$,01MM$KN.lF$$$kh&$K8+$J$9$3H,G-kh$&$K;Wol$F$$$k!#3l$,BEE
G"lP:#$N8rN.BS<'N(B,Dj$K$*$$$F$b0u2C8rN.<'3&$,Hf3SE*Bg$-$$$?aK!"Ey2
E*$K01<oN`$N<WJCEEN.$,;nNAA4BN$r6Q01$KN.$l$F$$$k$H2>Dj$9k3H,G-$k!#$
$?$,CF$3$3GO8rN.BS<'N($+$i5aakNK!"D>N.<'2=$+$i5aa?;~$N;n
NA$N8|$5 $D = 850\ \mu\mathrm{m}$ $rMQ$$!"J4BN;nNA$HF1$8h&K7$F7W;;$7$?!#$3Nh$&$K7F
5aailkCM$O!" Campbell %b%G%k$,@5$7$1lPD>N.<'2=$+$i5aail?bN$H
CMKJkbNH4|BT5l$k!#$7$+$7 Fig. 2(b) $N QMG ;nNA$N7k2L$+$io+kh$&$K!"
$=$l$>$l$+$i5aail?NCM$O0[$J$j!" $+$i5aa?NCM$,01HVBg$-$/!"<!$K
χ_1'' $+$i5aa?CM!" $+$i5aa?CM!":G8e$KD>N.<'3&$+$i5a$a$?CM$HJC$F$$$k!#$3
$&$7$?0c$$$N860xH7FO!"<B:]KOFs<oN`$NEEN.$,B8:_9k3H$H!" Campbell %b
%G%k$+$iNO$:$lH,9M$($ilk!#7+$7!"F@$ilF$$$k7k2L$OJ4BN;nNA$HF1$87
8~$,$"k3H+$i!"$3$N>l9g$b Campbell %b%G%k$+$iNO$:$l$,<g0x$G$"$k$H;W$o$l
$k!#

QMG ;nNAK*1k8!F$$G$O!"K\Mh$OFs<oN`$N<WJCEEN.$,$"$kH3mr!"D>N.<'
2=$,;nNA%5%$%:$KHfNc$9kH$$$&3H$+$i!"Ey2AE*$K01<oN`$N<WJCEEN.$H2>Dj$r$
$?!#$7$+$7<B:]$OFs<oN`$N<WJCEEN.$N1F6A$,$"$k3H!"$^$?FC$K8rN.<'3&$NHs>o$
>.$5$$$H3mGO6I=j$N<WJCEEN.$,<g$K<'2=$K1F6A$rM?$(k3H+$i!">e=R$N8!F
$OLdBj$r4^sG$$$k!#7?$,$C$F!"@53N$KFs<oN`$NNW3&EEN.L)EY$r:N$jF~$l$??7$
M}O@$N9=C[$,K>$^$l$k!#

4. $^$H$a

3NJs9pGO Y 7OD6EAF3BN$N4pK\GH$HBh;09bD4GH$N8rN.BS<'N($rB,Dj$7!"<!$N$h
$&$J7kO@$rF@$?!#

- 9b<'3&$d9b29$KJkK7$?$,CF$T!<%/$NCM$OC1D4$K8:>/$7!"<'B+@~$N2D
5U1?F0$O82Cx$HJk!#

- 8rN.BS<'N($\chi_1\chi'_3$, χ''_3) $HD>N.<'2=$+$i5a$a$$$N$J_c$$Hf3S$+$i!"8rN.BS<'N($+$i8+ @Qbil?$J_c$$O8rN.<'3&$K0MB8$7$F$$$k;v$,$o$+$C$?!#<'B+@~$NJQ0L$N>.$5$$ NN0hK*$$$F!"<'B+@~$N2D5U1?F0$, Campbell %b%G%k$N2>Dj$hjbhj82CxG" $k;v$,?dB,5l$k!#

<U<-

QMG;nNA$rDs6!$7$F$$$?$@$$$??7F|E4$NLZB<7=01;a$K?<$/46<UCW$7$^$9!#

;29MJ88%

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