Trace transition metals in sapphire for high Q microwave resonator applications

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TALK OUTLINE

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- MOTIVATION
- HIGH Q RESONATOR EXAMPLE
- ENERGY DISSIPATION SOURCES
- TRACE ELEMENT DETERMINATIONS
- SUMMARY AND CONCLUSION

ACKNOWLEDGMENTS

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MOTIVATION

- Principal motivation is the design and fabrication microwave resonators having Q values significantly greater than existing ones (i.e. $Q > 10^9$); applications in particle accelerators or communications.

HIGH Q RESONATOR EXAMPLES

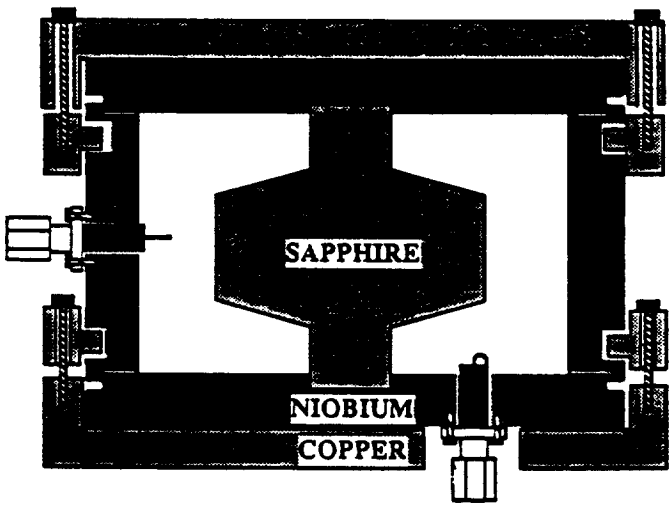
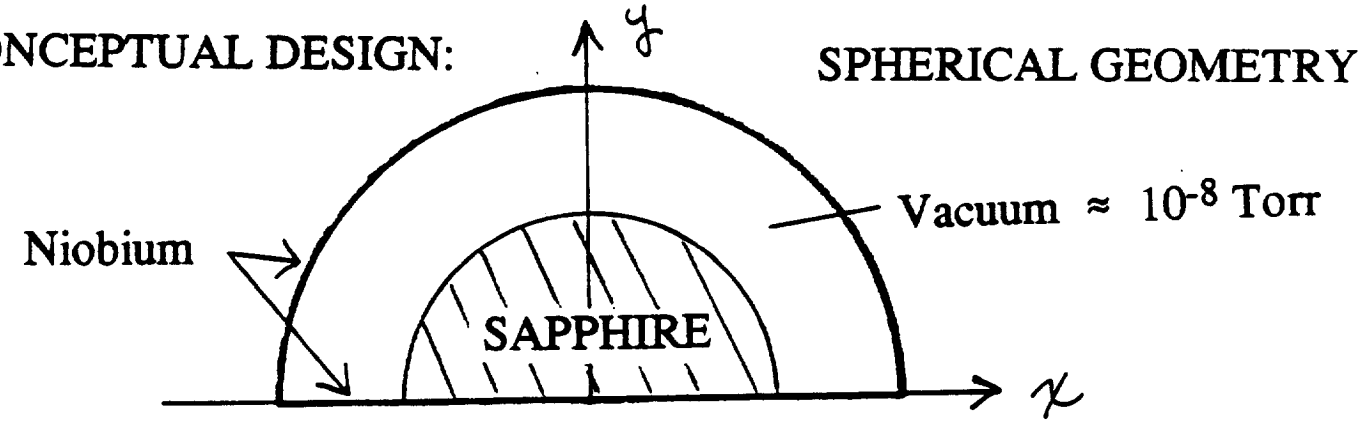


Fig. 2. Cut-away schematic diagram of the niobium shield and dielectric resonator. The niobium shield is clamped together with a copper shell. The knife edges are on the inside edge of the cylindrical part of the shield. This figure also demonstrates the coupling arrangement.

A.N. Luiten, A.G. Mann, A.J. Miles, and D. G. Blair, *IEEE Transactions on Instrumentation and Measurement*, 42, No.2,April 1993, 439-443.

CONCEPTUAL DESIGN:



ENERGY DISSIPATION SOURCES

1. Residual niobium wall loss resistances on the order of 10's of nano-Ω's even at very low temperatures.

2. Surface defects on the sapphire crystal itself.

3. Volume dielectric losses.

    -- Paramagnetic impurities, such as Fe^{+3} , Ti^{+3}, and Cr^{+3},even on the level of < 1 ppm.

    -- Defects resulting from other impurities and/or fabrication details

TRACE ELEMENT DETERMINATION

From conventional NAA theory, the number of atoms of a particular element

$$N = \frac{N_\gamma \, 100 \, \lambda}{f I_\gamma \varepsilon_\gamma (\sigma \Phi_{th} + I_{res} \Phi_{epi})(1-e^{-\lambda t_I})e^{-\lambda t_{decay}}(1-e^{-\lambda t_{count}})}$$

where the times for irradiation, cooling and counting of the samples, in addition to the spectrometer's photopeak detection efficiency, ε_γ, are empirical quantities determined by experiment design.

Table I. Isotopic properties of the impurities of interest .

Target nuclide	Isotopic abundance (%)	Thermal cross section (barns)	Observed radionuclide	Half-Life	γ-ray energy (keV)	γ-ray intensity (%)
^{50}Cr	4.35	15.9	^{51}Cr	27.7 d	320.1	9.83
^{58}Fe	0.28	1.28	^{59}Fe	44.5 d	1099.3	56.5
^{47}Ti	7.3	(a)	^{47}Sc	3.35 d	159.4	68

(a) The production of ^{47}Sc occurs through the (n,p) threshold reaction and can be described in terms of a reaction rate per target nucleus, R_{TN}, at the irradiation location. R_{TN} has the same physical meaning as the term $(\sigma\Phi_{th} + I_{res}\Phi_{epi})$ for neutron capture.

For fast neutron induced reactions the reaction rate per target nucleus, R_{TN}, is given by

$$R_{TN} = \int_{E_{th}}^{\infty} \sigma(E)\Phi'(E)dE \qquad (1)$$

or, from NAA theory,

$$R_{TN} = \frac{W}{mN_A f} \cdot \frac{N_\gamma \lambda 100}{I_\gamma \varepsilon_\gamma (1 - e^{-\lambda t_I}) e^{-\lambda t_d} (1 - e^{-\lambda t_c})} \qquad (2)$$

where we define the quantity TF as

$$TF \equiv (1 - e^{-\lambda t_I}) e^{-\lambda t_d} (1 - e^{-\lambda t_c}) \qquad (3)$$

R_{TN} is measured for the interference and companion reactions.

Let 1 => (n,x) and 2 => (n,y),

$$\frac{\int \sigma_{n,y}(E)\Phi'(E)dE}{\int \sigma_{n,x}(E)\Phi'(E)dE} \cdot \frac{T_{1/2}(1)\, I_{\gamma 1}\, f_1}{T_{1/2}(2)\, I_{\gamma 2}\, f_2} = \frac{N_{\gamma 1}}{N_{\gamma 2}} \cdot \frac{\varepsilon_{\gamma 2}}{\varepsilon_{\gamma 1}} \cdot \frac{(TF)_2}{(TF)_1} \qquad (4)$$

$$\left[\frac{N_{\gamma 1}}{N_{\gamma 2}} \frac{\varepsilon_{\gamma 2}}{\varepsilon_{\gamma 1}} \frac{(TF)_2}{(TF)_1} \right]_u = \left[\frac{N_{\gamma 1}}{N_{\gamma 2}} \frac{\varepsilon_{\gamma 2}}{\varepsilon_{\gamma 1}} \frac{(TF)_2}{(TF)_1} \right]_k \qquad (5)$$

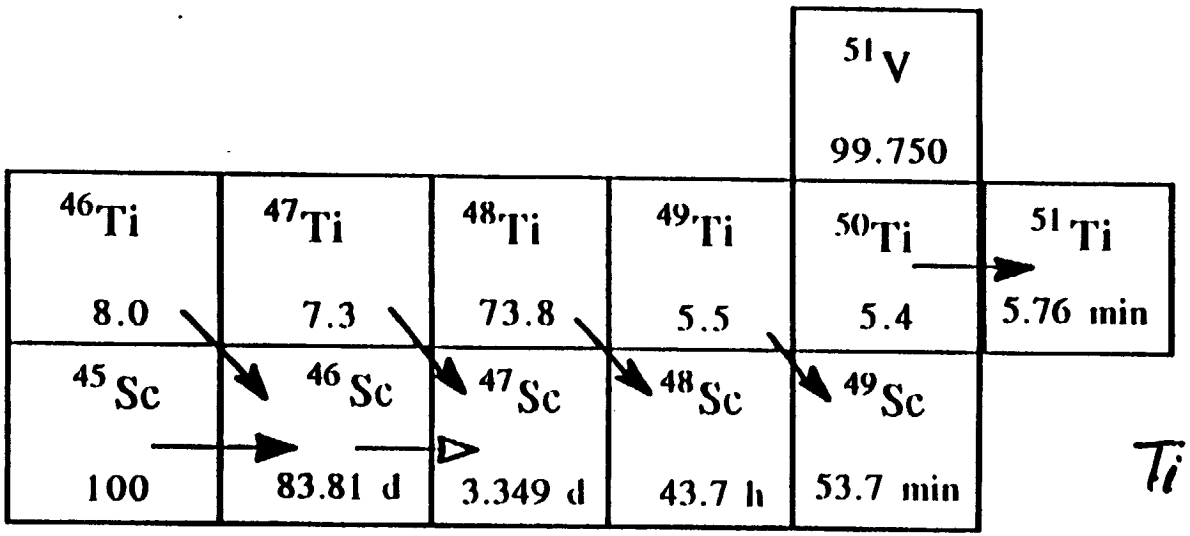
u = unknown sample k = known sample

Experiment Parameters

Sample Material:	High purity sapphire *(Hemex*)*
Sample Mass:	3.25 g
TRIGA Power Level:	20 kW
Sample Location:	Graphite Reflector
Thermal Flux:	8.0×10^{10} (/cm^2·s)
Epithermal Flux:	2.7×10^{9} (/cm^2·s)
Irradiation Time:	99 h
Cooling Times:	~ 4 days
Counting Intervals:	~ 2 - 8 days
Spectrometer:	High Purity Ge Typical Resolution: 1.9 keV, FWHM @ 1.33 MeV

*Crystal Systems Inc., Salem, MA, USA

Reaction paths for Sc nuclide production



$$^{45}Sc \xrightarrow{(n,\gamma)} {}^{46}Sc \xrightarrow{(n,\gamma)} {}^{47}Sc$$

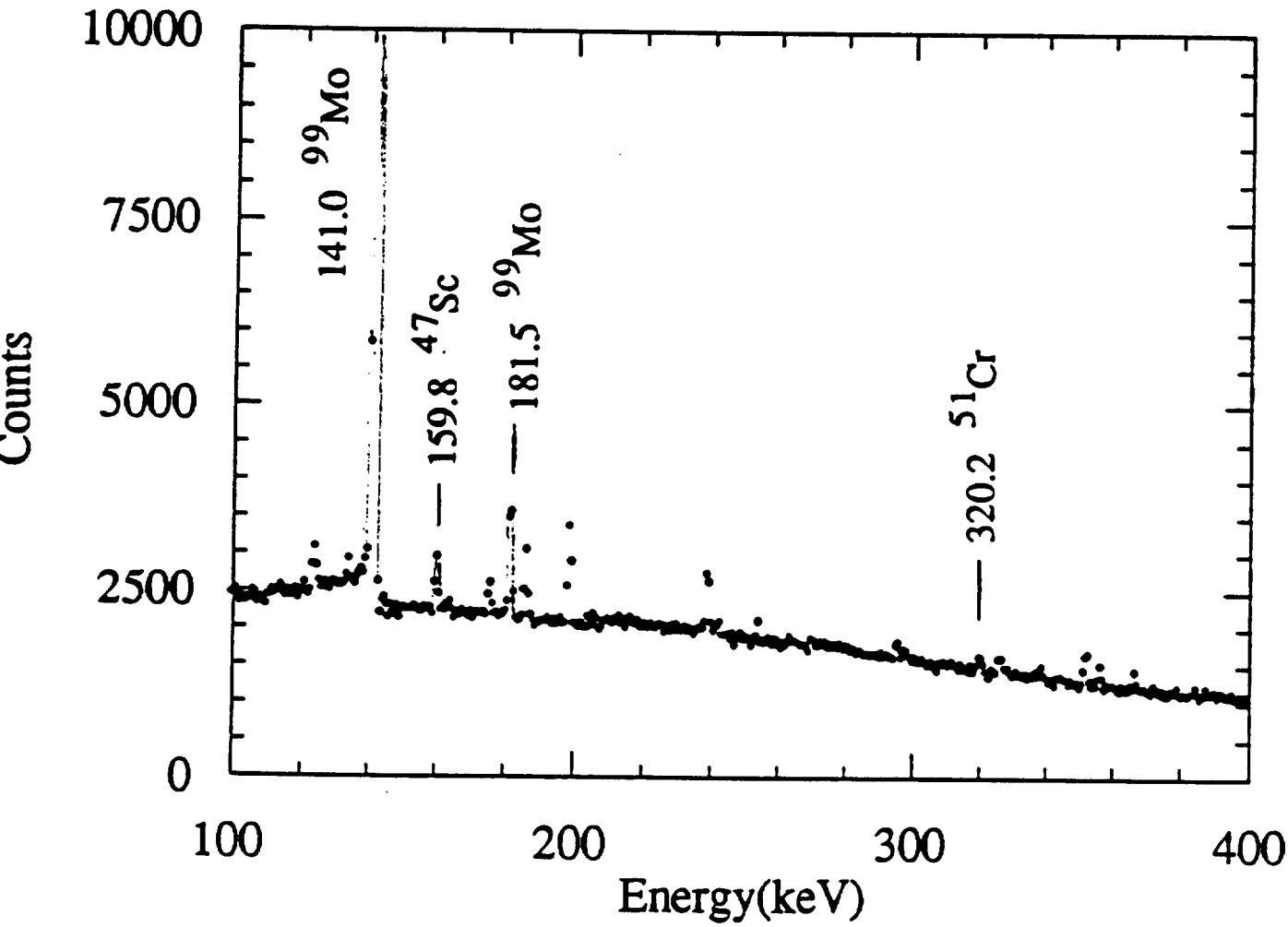
$$^{47}Ti(n,p)\,^{47}Sc$$

Ti interference:

$$^{27}Al + n_{fast} \rightarrow {}^{24}Na + {}^{4}He$$

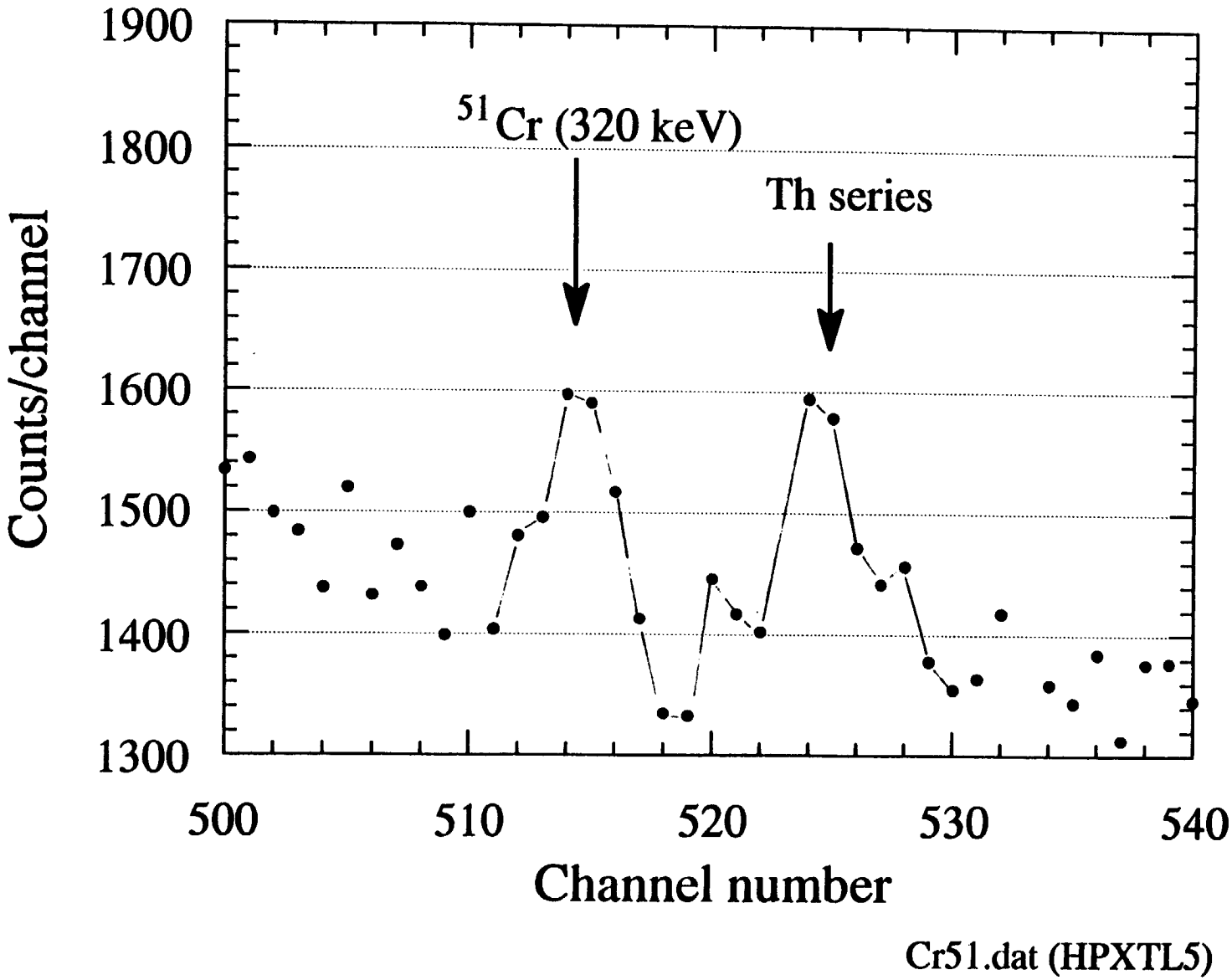
$$^{24}Na \xrightarrow[T_{1/2} = 14.7\,h]{} {}^{24}Mg + \beta^- + E_\gamma$$

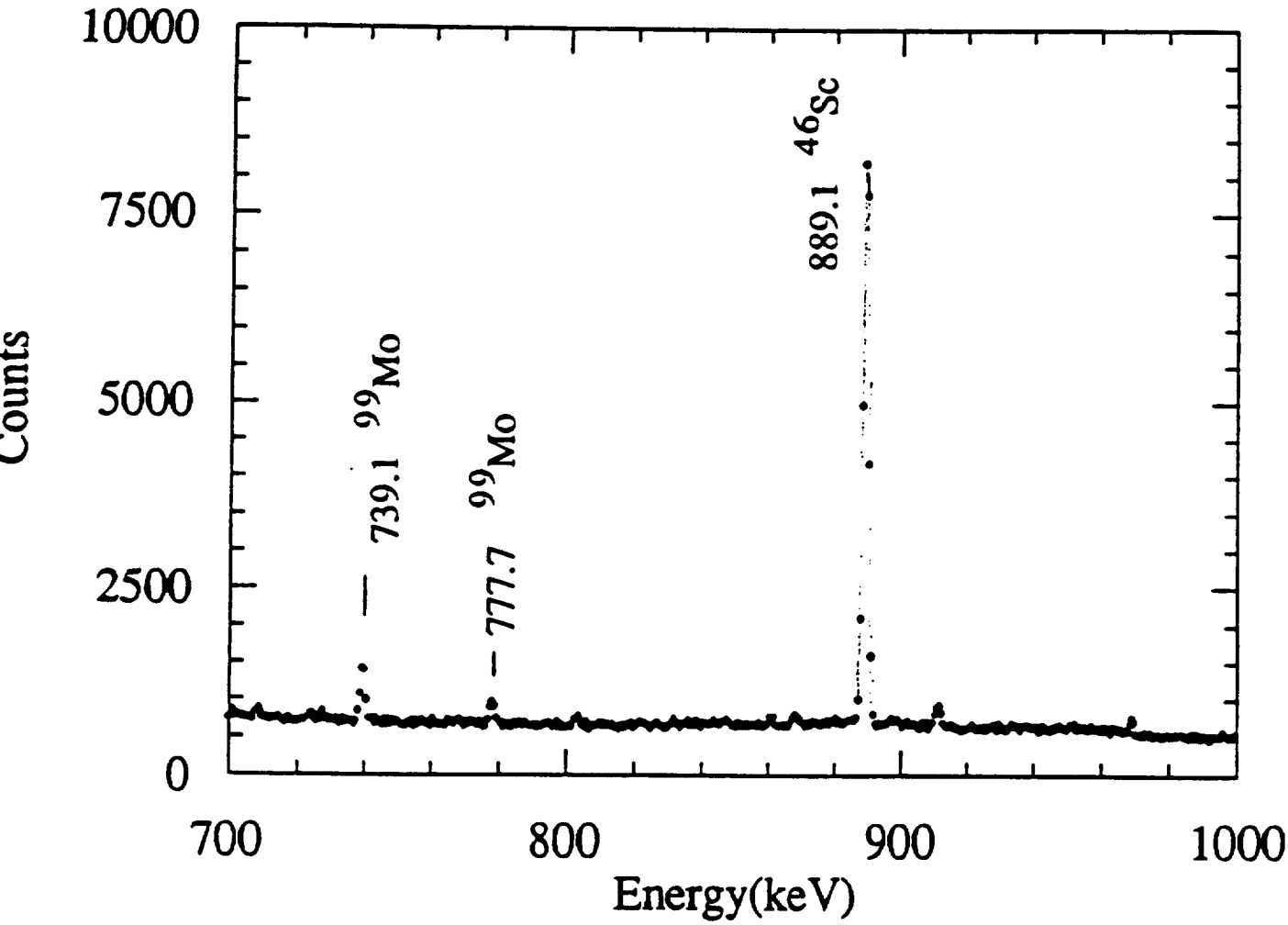
$E_\gamma = 2754$ keV
1369 keV



Partial spectrum of gamma rays from HEMEX specimen.

HPXTL5.chn


1900
1800
1700
1600
1500
1400
1300
Counts/channel
^{51}Cr (320 keV)
Th series
500
510
520
530
540
Channel number
Cr51.dat (HPXTL5)



Partial spectrum of gamma rays from HEMEX specimen.

HPXTL5.chn

Results

Table II. Observed impurity concentrations given in nanogram of impurity per gram of sample.

Element	Relative Concentration by mass ng/g	Observed radionuclide	Half-Life	γ-ray energy (keV)	γ-ray intensity (%)
Ti	300 ± 29	^{47}Sc	3.34 d	159.4	68
Sc	3 ± 0.20	^{46}Sc	86.6 d	889.1	99.98
Cr	5 ± 1	^{51}Cr	27.7 d	320.2	9.83
Fe	≤ 1000	^{59}Fe	44.5 d	1099.3	56.5
Mo	1500 ± 227	^{99}Mo	2.75 d	141.0 739.5 777.9	90.7 12.14 4.35

The errors are compounded uncertainties and correspond to one standard deviation.

SUMMARY AND CONCLUSIONS

- For sapphire microwave resonators, commercially available high purity sapphire hold promise for the improvement of Q values.

- Relatively high concentration of Mo could be contribute to volumetric losses, as well as Fe.

- Neutron activation provides a useful probe for the measurement of impurity levels of interest.

- Improvements in sensitivity should be realizable via more intense neutron sources and/or those having greater thermalization

Note 1, Linda Turner, 08/17/99 08:15:18 PM
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