# Application of zone refining to the development of NaI(Tl) detectors for SABRE North


Sabre North collaboration

Università degli Studi di Milano · Università del Salento · INFN Istituto Nazionale di Fisica Nucleare · RMD A Dynasil Company · MELLEN · LSC Laboratorio Subterráneo Canfranc · Jagiellonian University in Kraków · Sapienza Università di Roma · Università degli Studi di Padova


## The SABRE Project: Sodium Iodide with Active Background REjection

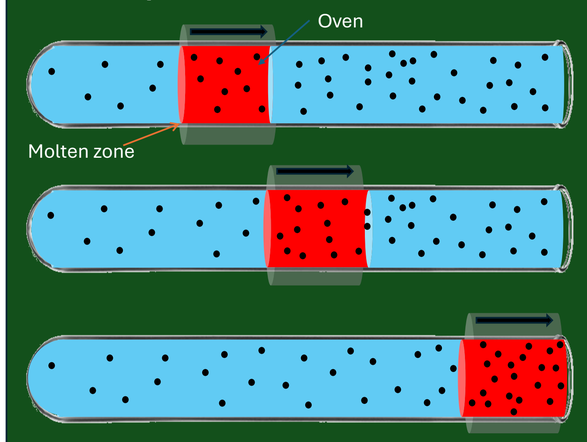
**GOAL: Search for Dark Matter through the annual modulation of the experimental rate.**

**STRATEGY:**

- Development of ultra-high purity NaI(Tl) crystals (~0.5 counts/keV/kg/day )
  - High purity NaI powder - further improved with Zone Refining technique
  - Clean crystal growth method
  - Reducing total detector background will increase the relative amplitude of a DM modulation signal $S_m/(S_0+B)$, 1-2% of the rate in DAMA/LIBRA.
- Low energy threshold
  - High QE PMTs directly coupled to the crystal
- Passive shielding + active veto
  - Unprecedented background rejection and sensitivity with a NaI(Tl) experiment
    - With active veto order of 90% K background rejection (only SABRE South)
- Two identical detectors in northern (LNGS) and southern hemispheres (SUPL)
  - seasonal backgrounds have opposite phase in northern and southern hemispheres
  - dark matter signal has same phase

## Zone Refining (ZR) Technique

A narrow region of a crystal is melted, and this molten zone is moved through the crystal. The molten region melts impure solid at its forward edge and leaves a wake of purer material solidified behind it as it moves through the ingot.



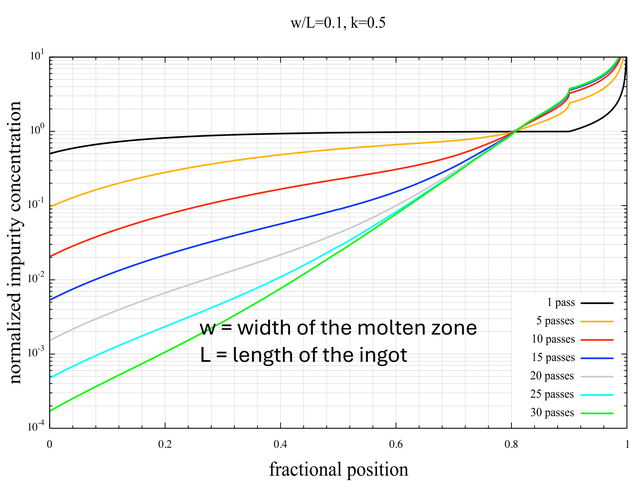

After solidification in the interface between liquid and solid a fraction k (*coefficient of segregation*) of impurities contained in the liquid remain in the solid

$$C_S = kC_L$$

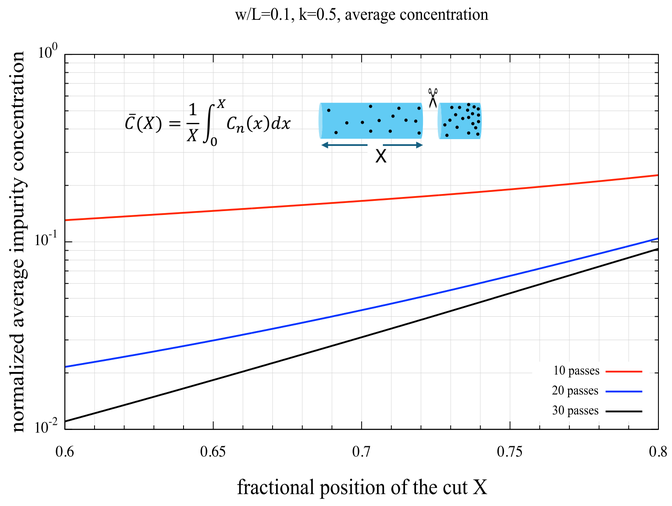
where $C_s$ ($C_L$) is the concentration of pollutant per volume unit in the solid (liquid). If k<1 (k>1) the pollutant remains preferably in the molten (frozen) zone.

The procedure can be repeated many times to increase the purity of the ingot. After cutting the tail we remain with a purified ingot.

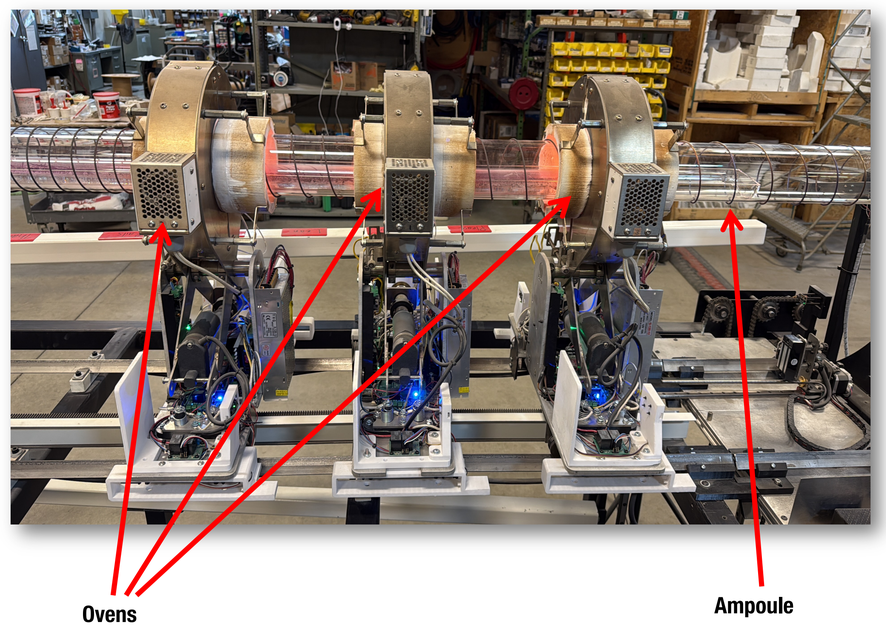
**Distribution of impurities after *n* passes**




**Average impuritiey concentrations as function of the cut**

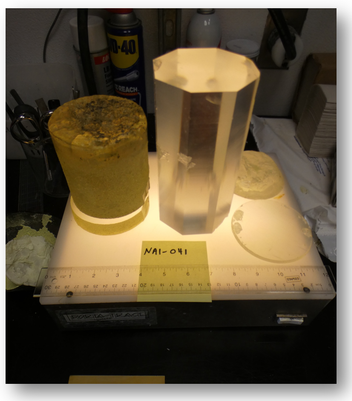



**Zone refiner at MELLEN company (Concord, NH)**




## ZR Experimental Procedure

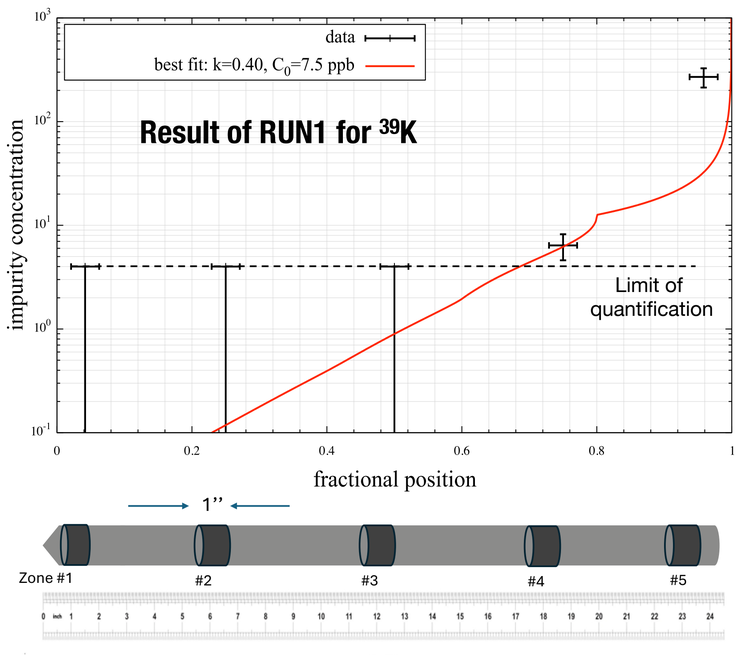
- Astrograde (former sigma-Aldrich) NaI powder used to grow the crystal
- Ampoule preparation @ RMD (Boston) with carbon coatiing or $SiCl_4$ vapour treatement to prevent sticking of molten powder to ampoule
- Zone refining done @ Mellen Company (Concord)
- Ampoule length L=122cm (48”), molten zone width w=12cm
- 26 passes @ 1.5” per hour
- The purified part of the ingot is crumbled and recast in a single crystal through the *Bridgman method i.e.,* by melting the NaI in a vertical cylindrical crucible which is extracted very slowly (1cm/day) from the oven.
- Two runs has been considered for this anaysis (RUN1 and RUN2)



## ZR Sample Analysis

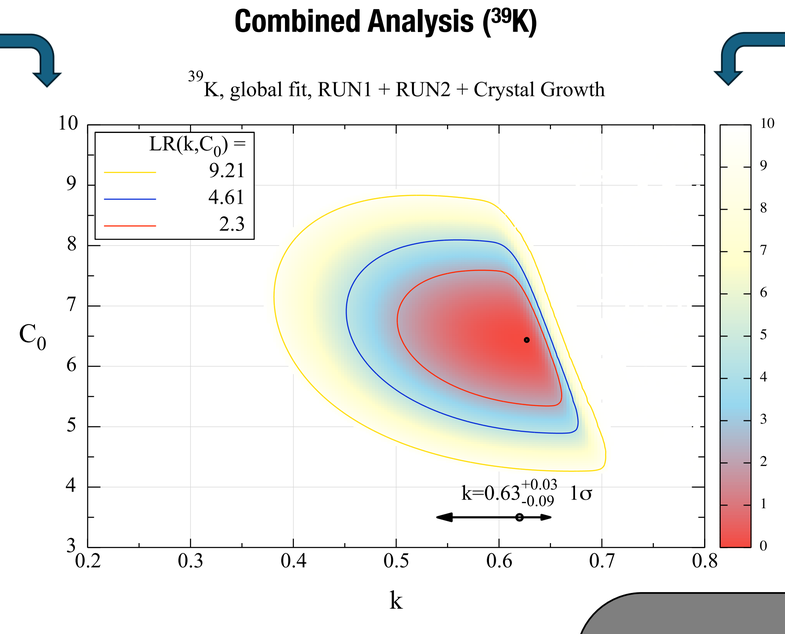
- Five samples in RUN1 and four in RUN2 has been extracted from the refined ingot
- Various contaminants (in particular, $^{39}$K and $^{208}$Pb) have been measured using inductively coupled plasma mass spectrometry (ICP-MS) at Seastar
- Also, 3 samples of the final crystal have been also analyzed
- For each sample, a 20% assumed systematic error was added in quadrature to statystical error
- A maximum likelihood analysis has been performed to extract the initial impurity concentration $C_0$ and the segregation coefficient *k*.

$^{39}$K, W/L=0.2, $N_{pass}$=26, RUN 1

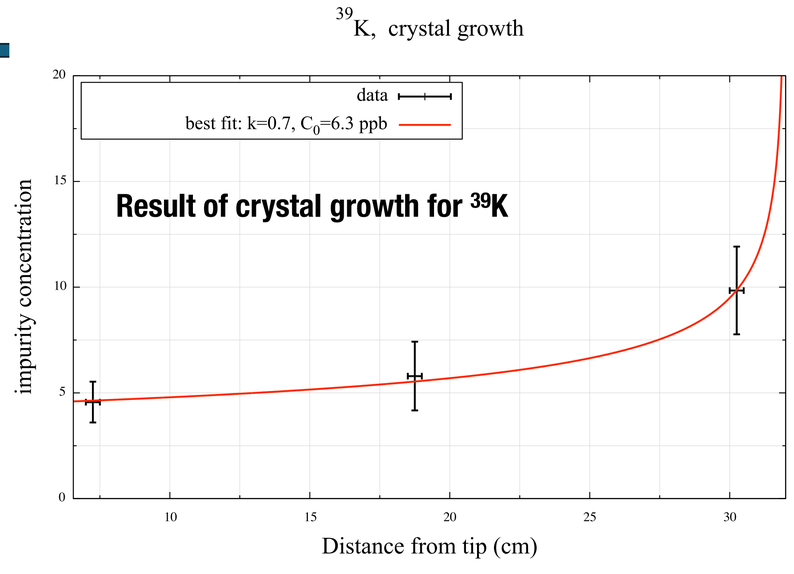



**Combined Analysis ($^{39}$K)**

$^{39}$K, global fit, RUN1 + RUN2 + Crystal Growth




$^{39}$K, crystal growth




| | $^{138}$Ba | $^{44}$Ca | $^{39}$K | $^{24}$Mg | $^{208}$Pb | $^{88}$Sr (RUN2) |
|---|---|---|---|---|---|---|
| $f_{pur}$, best | 0.06 | 1.21 | 0.24 | 1. | 1.1 | 1.23 |
| $k \in 1\sigma$ range | 0.03÷0.14 | 1.20÷1.22 | 0.13÷0.31 | 0.94÷1.04 | 1.08÷1.13 | 1.22÷1.24 |
| $\bar{C}$, best (ppb) | 0.018 | 45.1 | 1.55 | 1.97 | 1.98 | 0.61 |
| $(k, C_0) \in 1\sigma$ allow. | 0.008÷0.036 | 38.6÷51.7 | 0.64÷1.80 | 1.76÷2.0 | 1.78÷2.18 | 0.61÷0.62 |

**Coefficient of purification $f_{pur}=C/C_0$ and coefficient of segregation *k* for 6 selected contaminats for 80% cut of the initial part the ingot**

## Conclusions

Zone-refining has shown to be an efficient method to purify NaI crystals

- Potassium is reduced by factor 5 (but further improvement is achievable). $^{40}$K is the main radioactive background for Dark Matter detection
- Unfortunately, the technique cannot reduce lead contamination since the segregation coefficient for Pb is k≳ 1

➢ More details can be found in the paper arXiv:2601.15998 (submitted to JINST)