26th International Symposium on Spin Physics
A Century of Spin

A proposal to search for T-violating muon polarization in $K^+ \rightarrow \pi^0 \mu^+ \nu$ decay using stopped positive kaons

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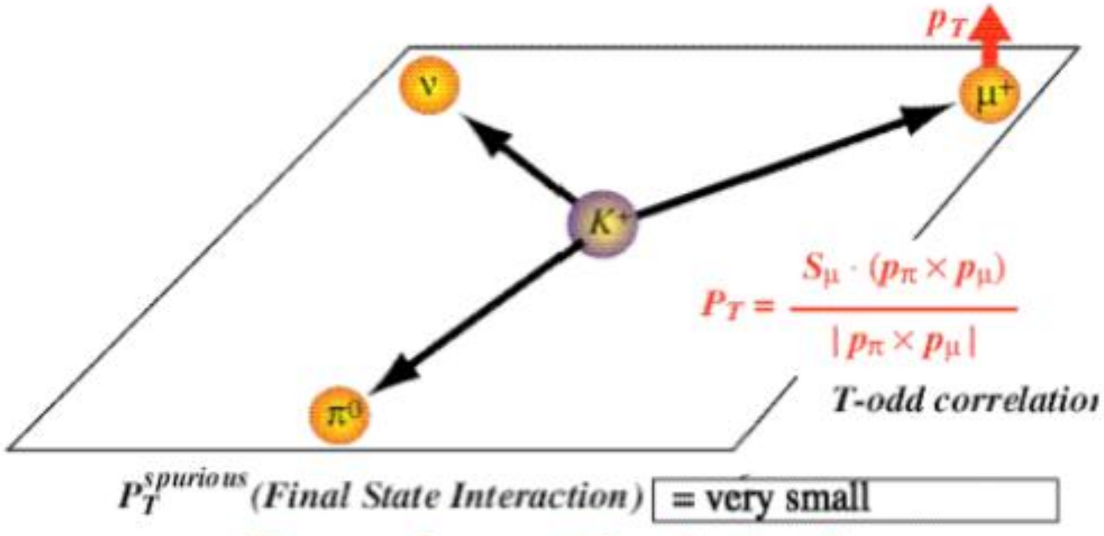
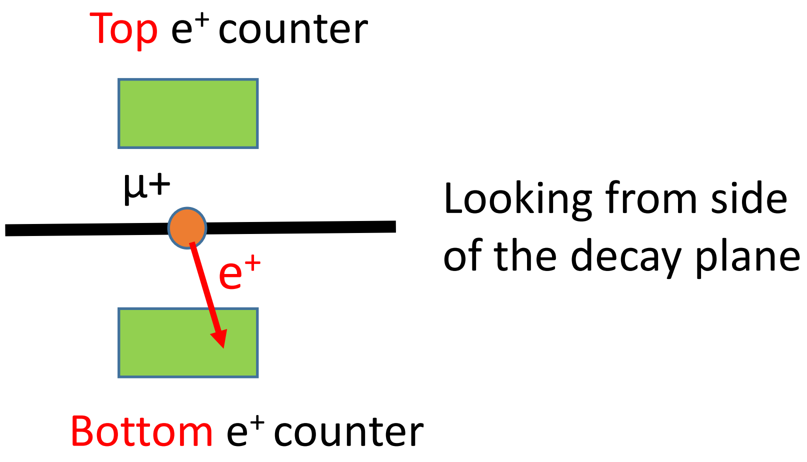
Transverse muon polarization in $K^+ \to \pi^0 \mu^+ \nu$ ($K_{\mu 3}$)



$P_T \neq 0 \rightarrow$ T-violation



- Small final state interaction in $K_{\mu 3}^+$ $P_T \sim 10^{-5}$
- Standard Model $< 10^{-6}$
- Important clues to new Physics beyond the Standard Model

  3 multi Higgs doublet model $< 10^{-3}$

  SUSY with R parity violation $< 10^{-3}$

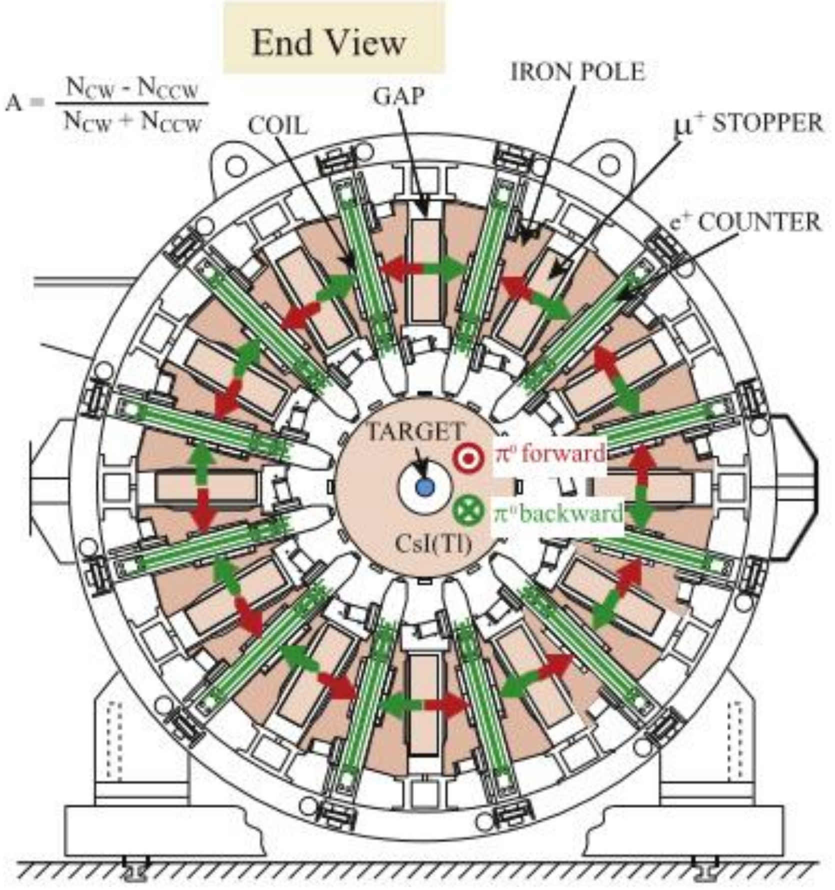
  Lepto-quark model $< 10^{-2}$

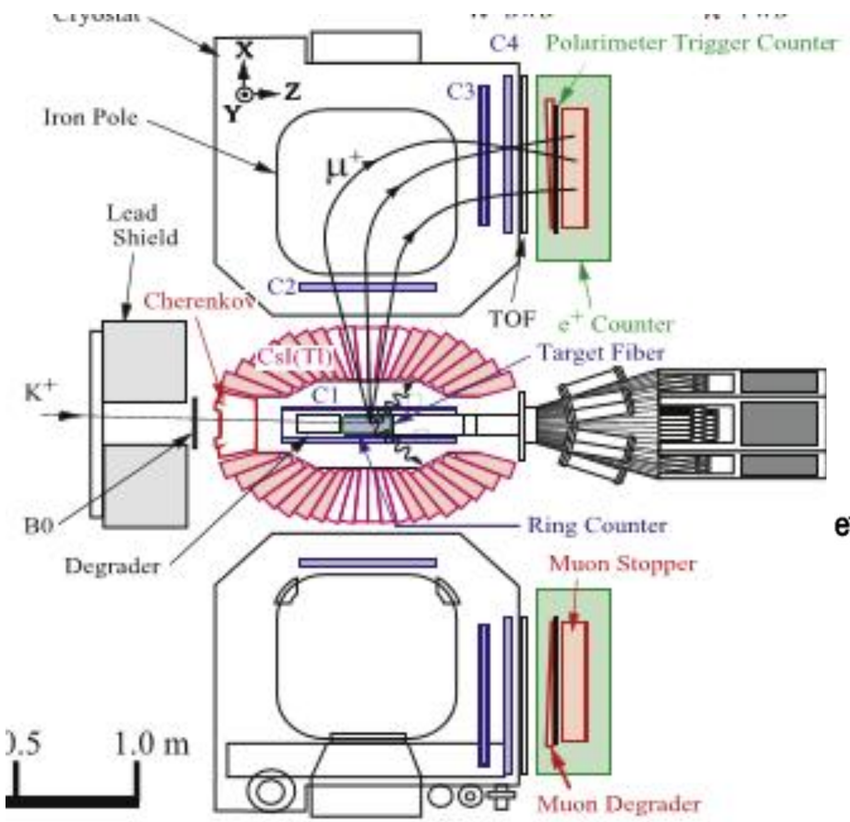
- $P_T = s_\mu \cdot (P_\mu \times P_\pi)$, $P_L = s_\mu \cdot P_\mu$
- Co-existence of the P_T and P_L components indicates T-violation.
- Setting e^+ counters top and bottom of the decay plane, the e^+ counting rates are measured.
- If we will find the difference, it will be a great discovery!

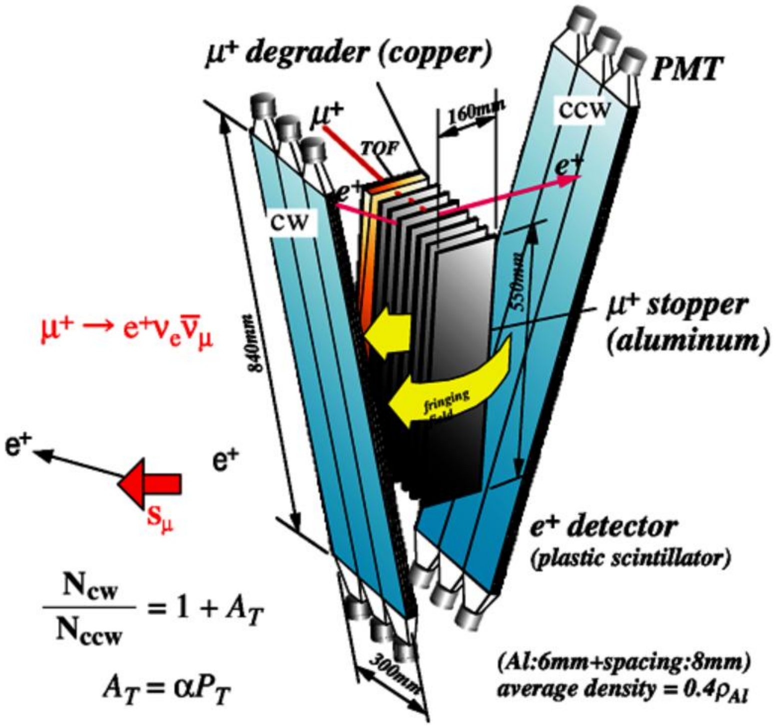
μ^+ polarization measurement in KEK-PS E246

- $K^+ \to \pi^0\mu^+\nu\ (K_{\mu3})$ with $\mu^+ \to e^+\nu\bar{\nu}$ and $\pi^0 \to \gamma\gamma$ decays
- Stopped K^+ method. Large solid angle and high resolution of the Toroidal spectrometer and CsI(Tl) calorimeter were used for the muon and photon measurement.

$$A_T = \frac{N_{cw} - N_{ccw}}{N_{cw} + N_{ccw}} = \frac{1 + \alpha P_T}{1 - \alpha P_T}$$

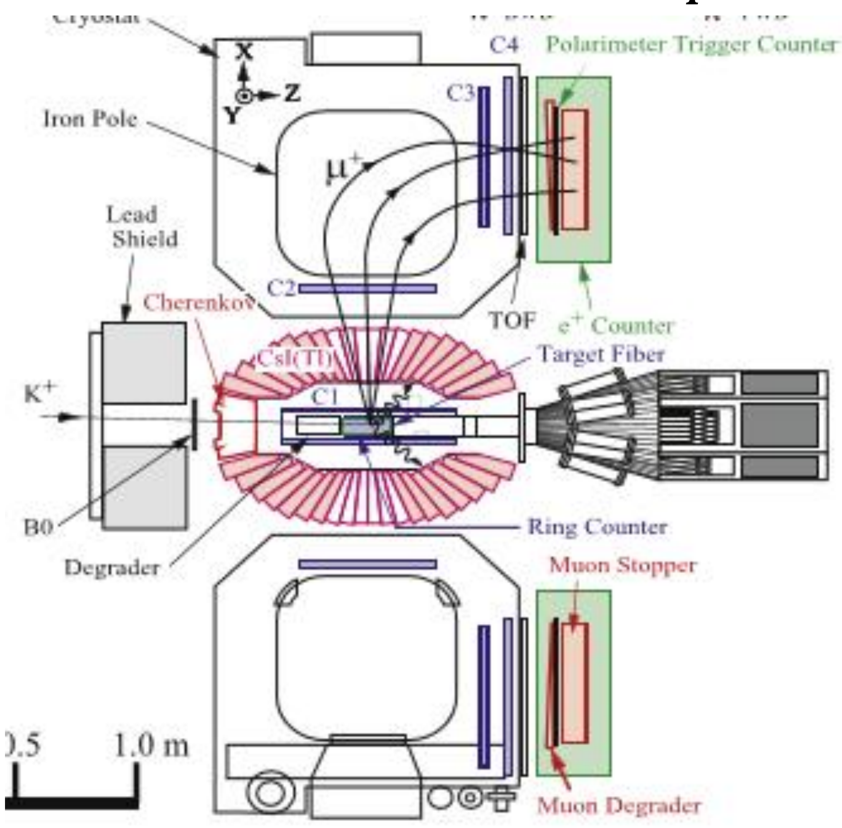






μ^+ polarization measurement in KEK-PS E246

- Well-designed detector to suppress systematic uncertainties
  - Integration of e^+ asymmetry $A_T = (N_{cw} - N_{ccw})/(N_{cw} + N_{ccw})$ with fwd- and bwd- going π^0s , $\frac{[A_T]_{fwd}}{[A_T]_{bwd}} = \frac{1+2\alpha P_T}{1-2\alpha P_T}$
- Results of E246: P_T=0.0017±0.0023±0.0017, $\Delta P_T \sim 10^{-3}$

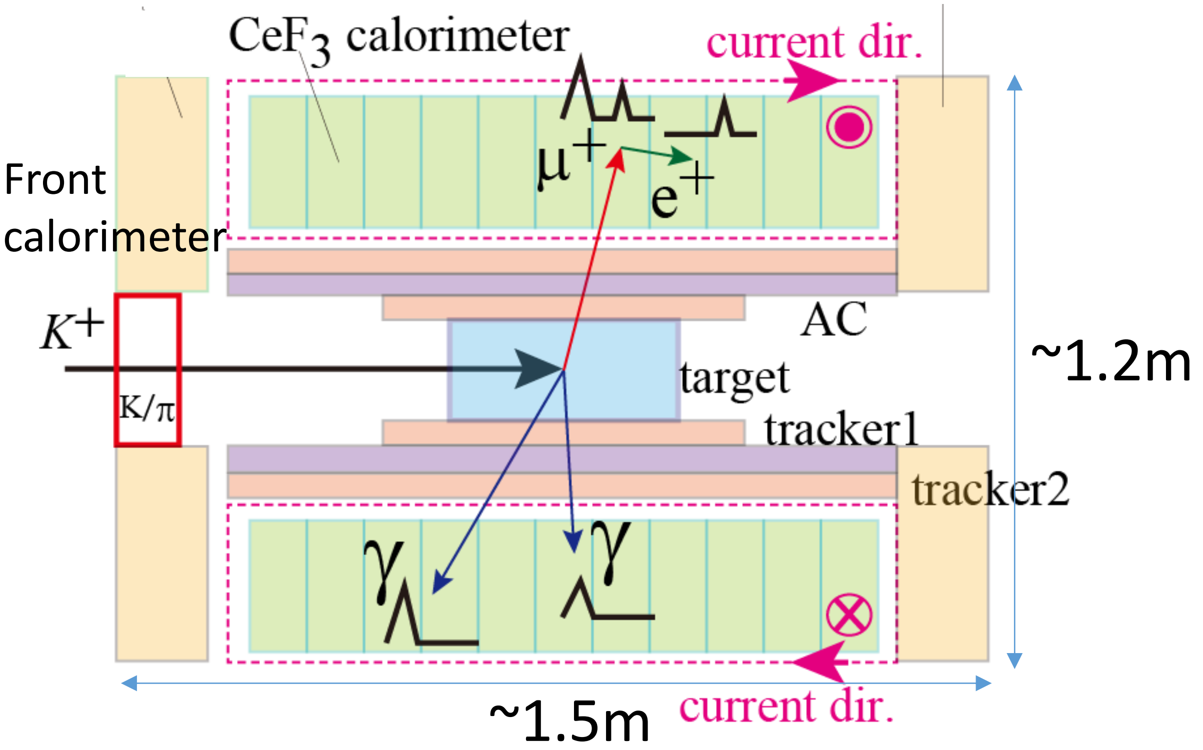


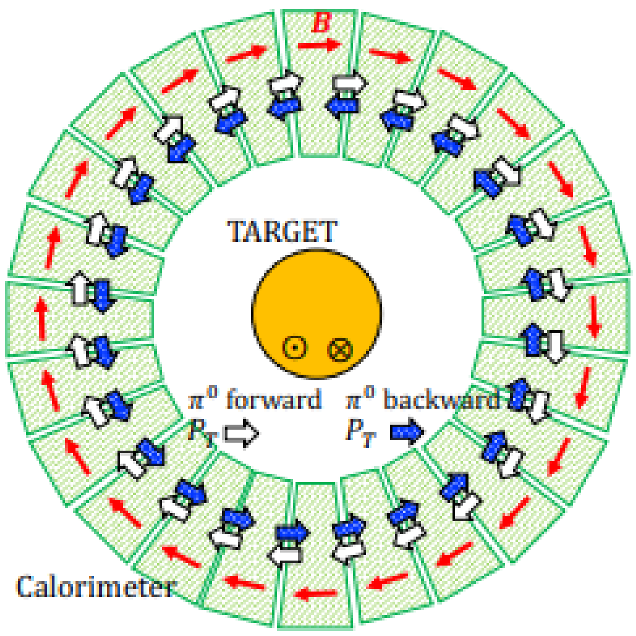
M. Abe et al., Phys. Rev. D40 (2006) 072005

J.A. Macdonald et al., NIM A 506 (2003) 60

- It was very difficult to improve the $K_{\mu 3}$ statistical uncertainty using the E246 setup
  - the finite acceptance of the magnetic spectrometer
  - the small momentum window of the magnetic spectrometer
  - the finite solid angle of the e^+ measurement

Proposal: New T-violation experiment at J-PARC





S. Shimizu et al.,
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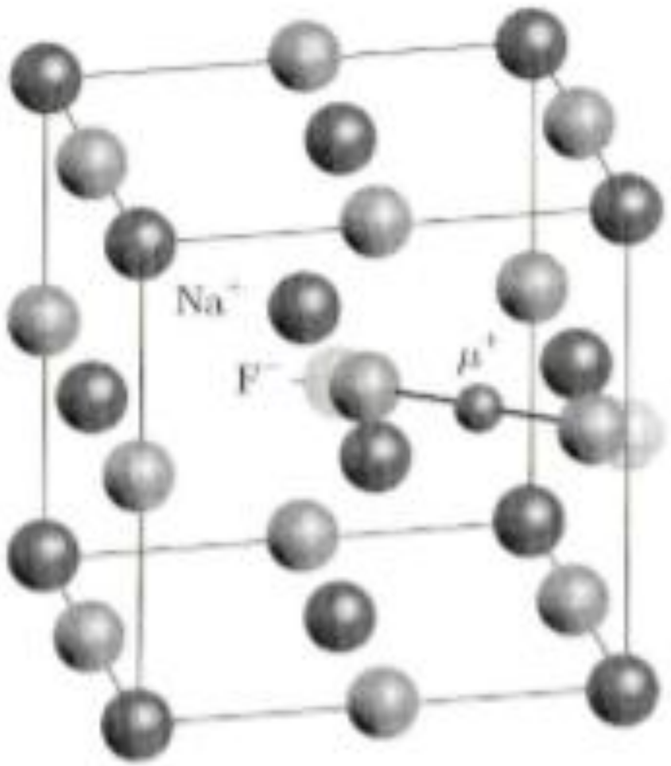
A 945 (2019) 162587

- Muon momentum, muon polarization, and π^0 momentum are determined by the same electro-magnetic calorimeter using a stopped K^+ beam.
- We aim at achieving $\Delta\ P_T \sim 10^{-5}$ level in this experiment by keeping the cancellation mechanism to reduce systematic uncertainties with 1000 times higher acceptance.
- A scintillating material which can preserve the μ^+ polarization **at room temperature**.

Muon behavior in Fluorine compounds

- The μ^+ polarization in alkali halide such as NaI and CsI is promptly depolarized due to muonium ($\mu^+ e^-$) formation.
- In fluorine compounds, a part of muons create a stable F-μ-F diamagnetic state, which can preserve the μ^+ polarization.
- In zero-field experiments, the μSR signal by the fluorine magnetic moment was actually observed.
- However, the observed μ^+polarization is less than 50% at low temperature.



R. Kadono, Muon Spin Rotation

Measurement of μ^+ polarization in Lanthanoid Fluoride materials

- LaF_3, CeF_3, PrF_3, and NdF_3 crystals with $15 \times 15\ \mathrm{mm}^2$ cross section were used.
- A 100% polarized μ^+ beam was stopped in the samples.
- The time integrated polarization higher than 90% was obtained

K. Horie et al., Nucl. Instrum. Methods A 1037 (2022) 166932

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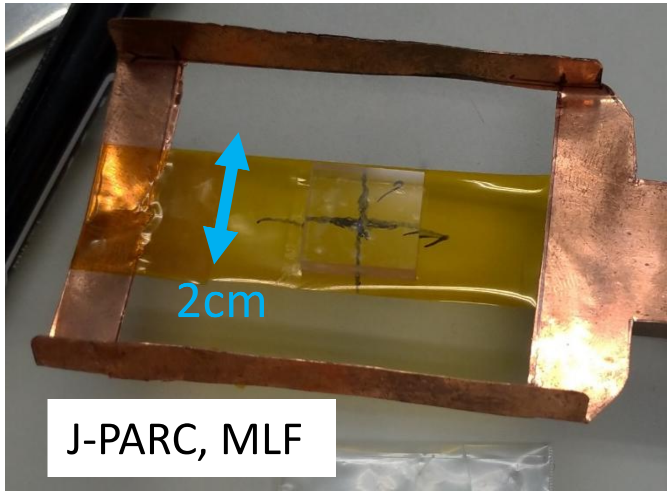
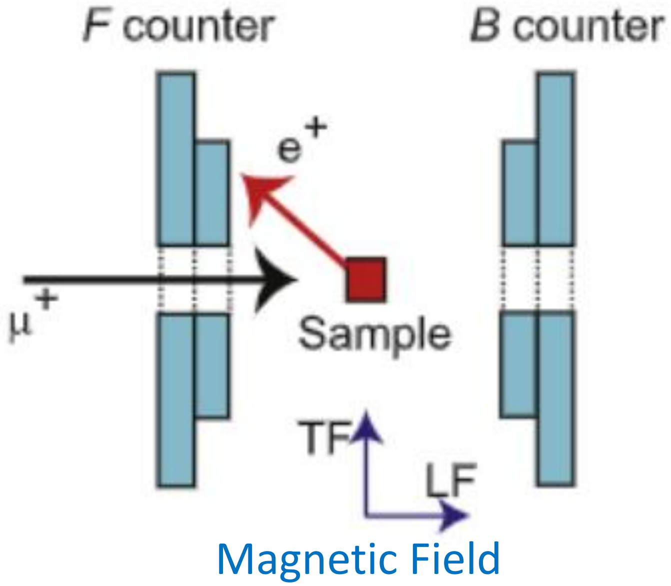
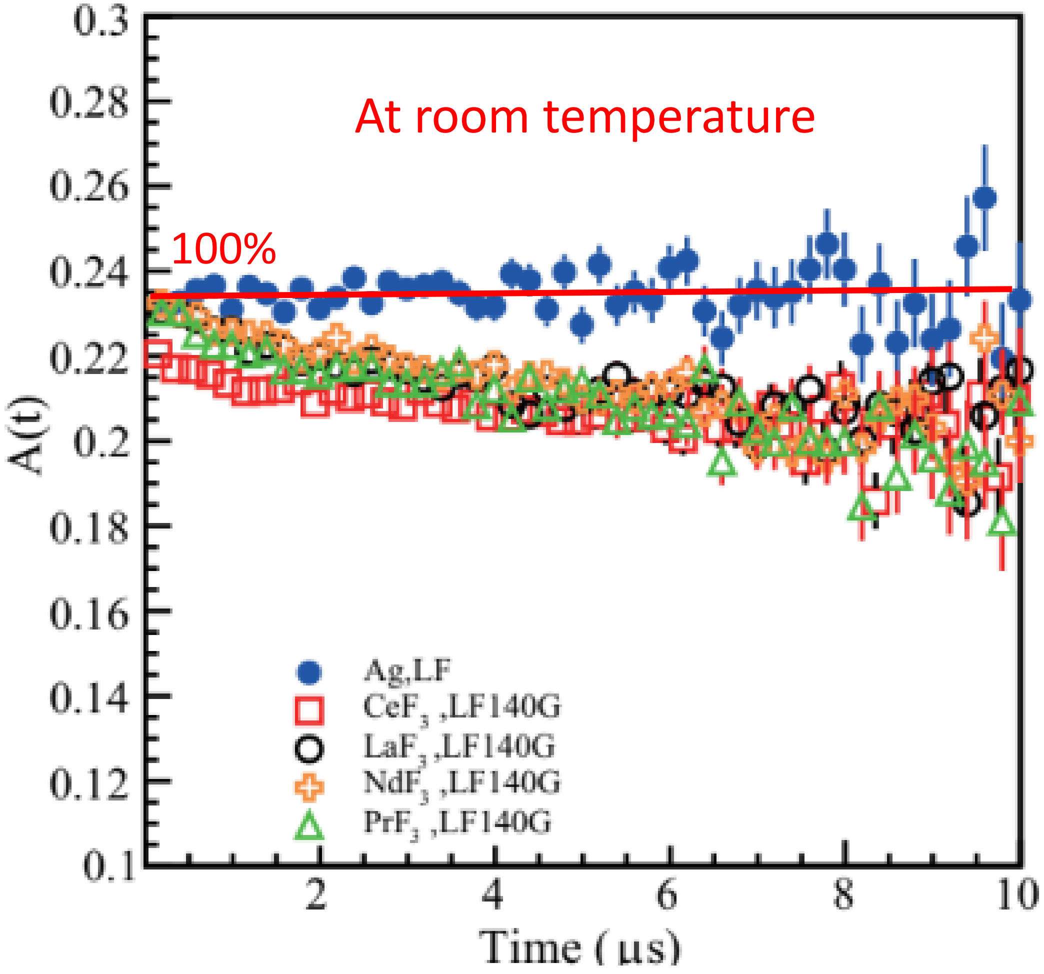
$$A(t) = \frac{N_F(t) - N_B(t)}{N_F(t) + N_B(t)}$$







S. Shimizu et al., Hyperfine Int. (2022) 243

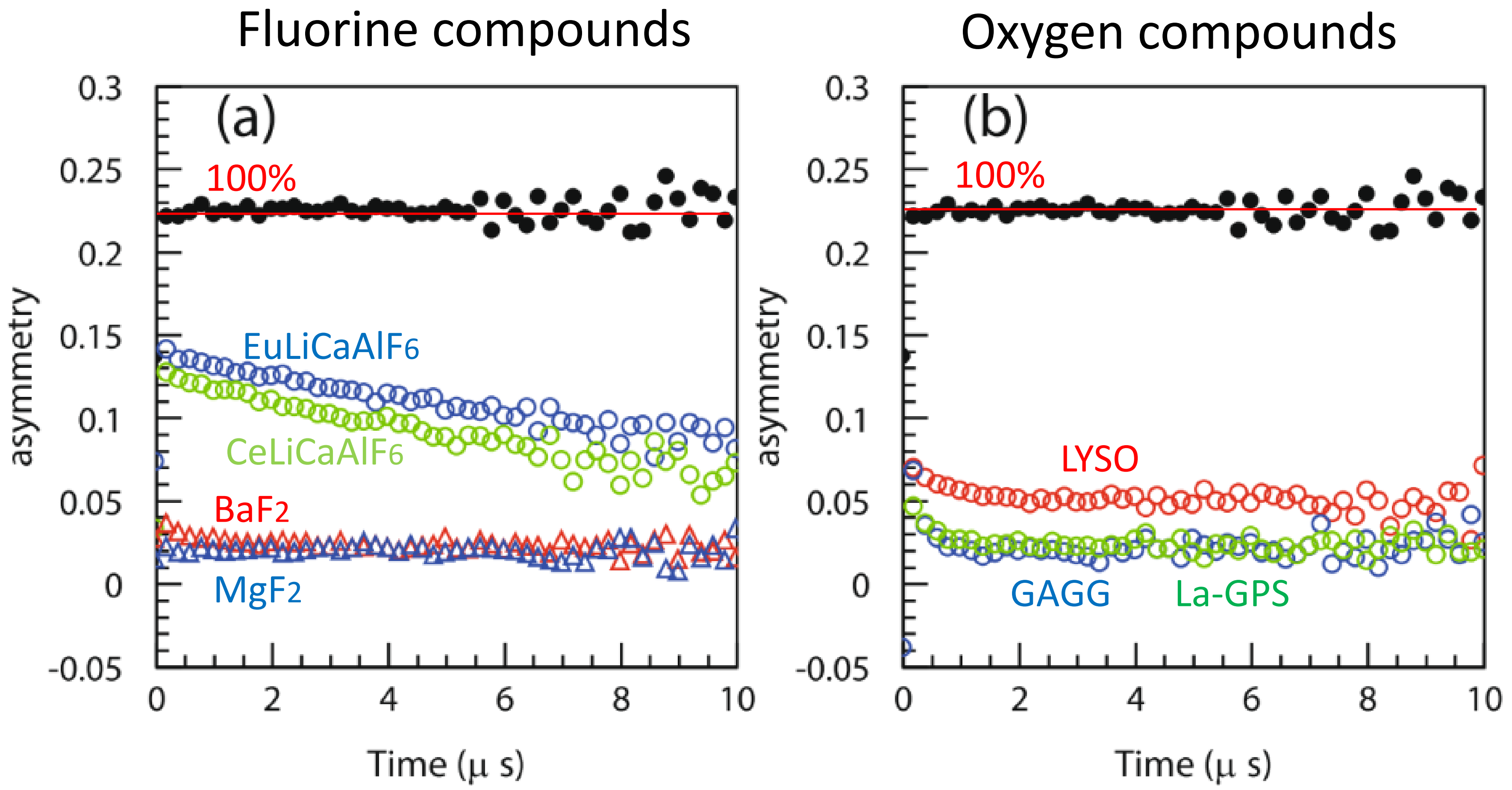
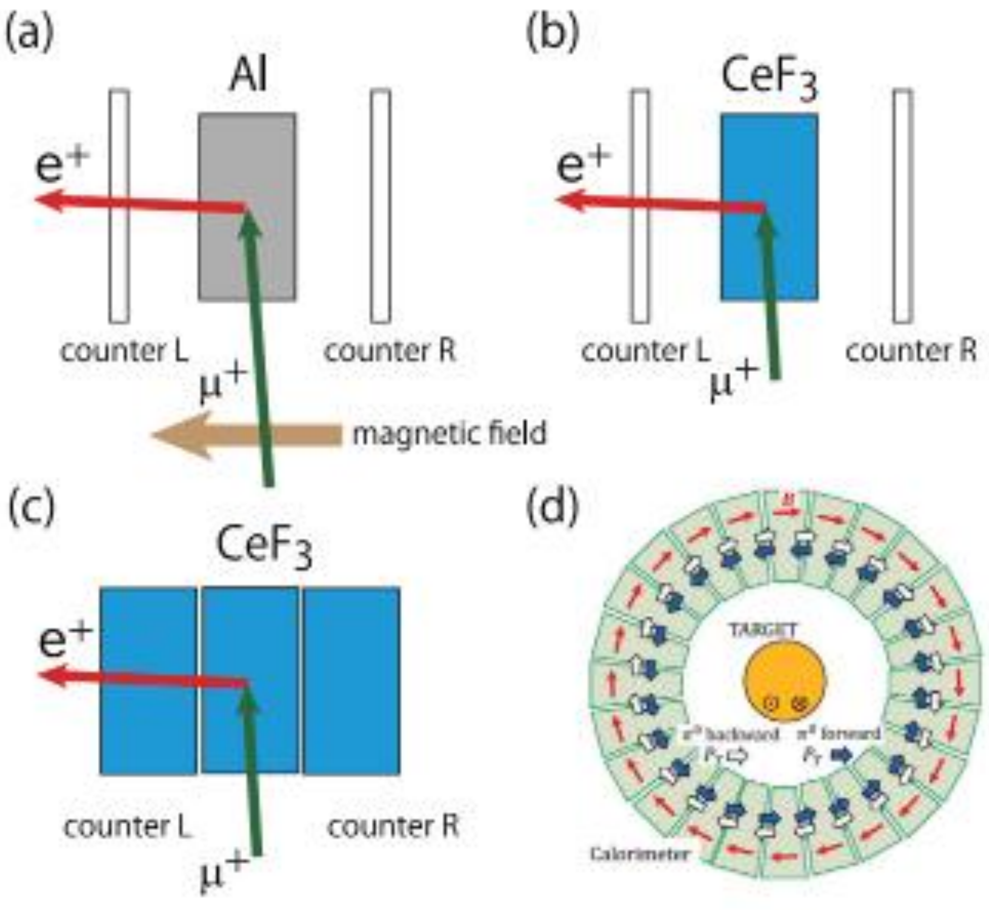


Fig. 4 The μSR spectra in the longitudinal field of 100 Gauss for (a) $EuLiCaAlF_6$ (green), $CeLiCaAlF_6$ (blue-circle), BaF_2 (red), MgF_2 (blue-triangle) and (b) LYSO (red), GAGG(blue), and La-GPS (green). Black dots are the e^+ asymmetry using a Ag material, which corresponds to the 100% level. The diamagnetic fraction in CeF_3, $CeLiCaAlF_6$, and $EuLiCaAlF_6$ at room temperature is significantly higher than that in MgF_2 and BaF_2

Consideration on the new polarimeter system



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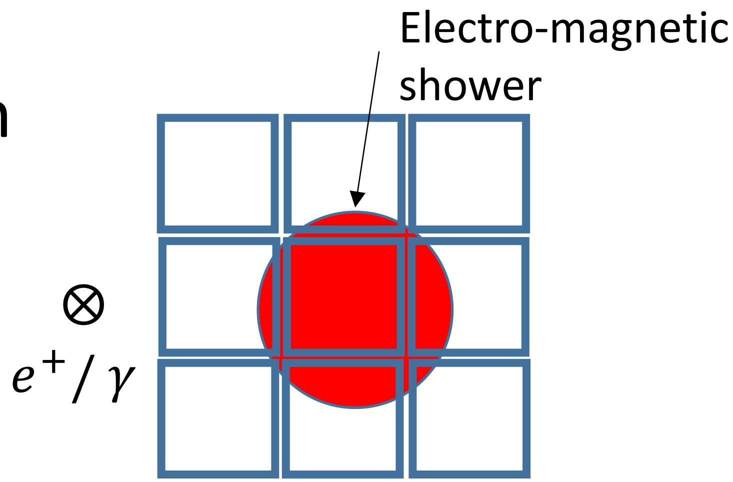
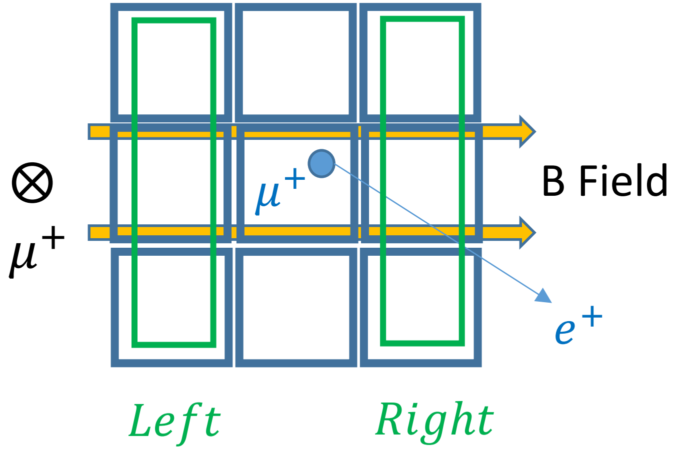
Here, it is worth summarizing the new polarimeter systems and the application to the proposed experiment. Fig. 1(a) shows a schematic view of the standard μ^+ polarimeter using a metal stopper and a magnetic spectrometer. Fig. 1(b) is a new idea to use the CeF_3 scintillator as the μ^+ stopper and for the μ^+ energy measurement. Fig. 1(c) corresponds to a modification from the (b) system, and the e^+ energy and direction are measured using the CeF_3 modules of the μ^+ stop and around the μ^+ stop. Fig. 1(d) is a schematic end view of the new experiment which is further expansion of (c) system to cover any μ^+ directions by the CeF_3 modules, and the e^+ detection efficiencies of each CeF_3 module are canceled out by integrating over all CeF_3 counts. Also, the analyzing power in the μ^+ polarization determination should be improved by measuring the e^+ energy because the magnitude of the e^+

Performance check as an integrated calorimeter and polarimeter

- An integrated calorimeter and polarimeter system with 3x3 or 5x5 modules will be constructed.
  - The design is now going on using a GEANT4 code.
- A test experiment as a calorimeter at Raris
  - $E = \sum E_i$
  - $x = [\sum E_i \cdot \omega_i]/\sum E_i$
  - Energy resolution as a function of the photon energy
  - Timing resolution
- A test experiment as a polarimeter at TRIUMF
  - e^+ asymmetry defined as $\frac{N_R - N_L}{N_R + N_L}$
  - The muon spin is flipped to cancel out detector efficiencies.





Systematic uncertainties

- Various methods to suppress systematic uncertainties cultivated in the E246 will be re-used.
  - The e^+ integration in clockwise and counter-clockwise directions
  - The double ratio measurement for π^0 going forward and backward events
- Spin holding magnetic field
  - In E246, the magnetic field was generated using ion plates
  - In the new experiment, the magnetic field will be generated using air-core coils
  - The field direction can be easily flipped, effects from in-plane component, P_L and P_N can be checked
- The system will be rotated from front to end to change cw and ccw direction in the e^+ asymmetry measurement
- In E06 proposal submitted to J-PARC, methods to reduce the systematic uncertainty less than 10^{-4} carefully discussed

Preparation for the realization toward the T-violation experiment at J-PARC

- Step-by-step ΔP_T improvement
  - Phase 0: $\Delta P_T \sim 10^{-3}$ which is the same level as the KEK-PS E246
  - Phase 1: $\Delta P_T \sim 10^{-4}$, running time is ~1 week
  - Phase 2: $\Delta P_T \sim 10^{-5}$, running time is ~1 year
- Detector upgrade to reduce systematic uncertainties
- Proposal submission
  - By the end of 2026, the proposal for the Phase 1 experiment will be submitted.
  - The experimental feasibility will be verified by test experiments in Japan and Canada
  - Various calculations using Monte Carlo simulation will be performed.
- Collaboration
  - New collaborators are always welcome!

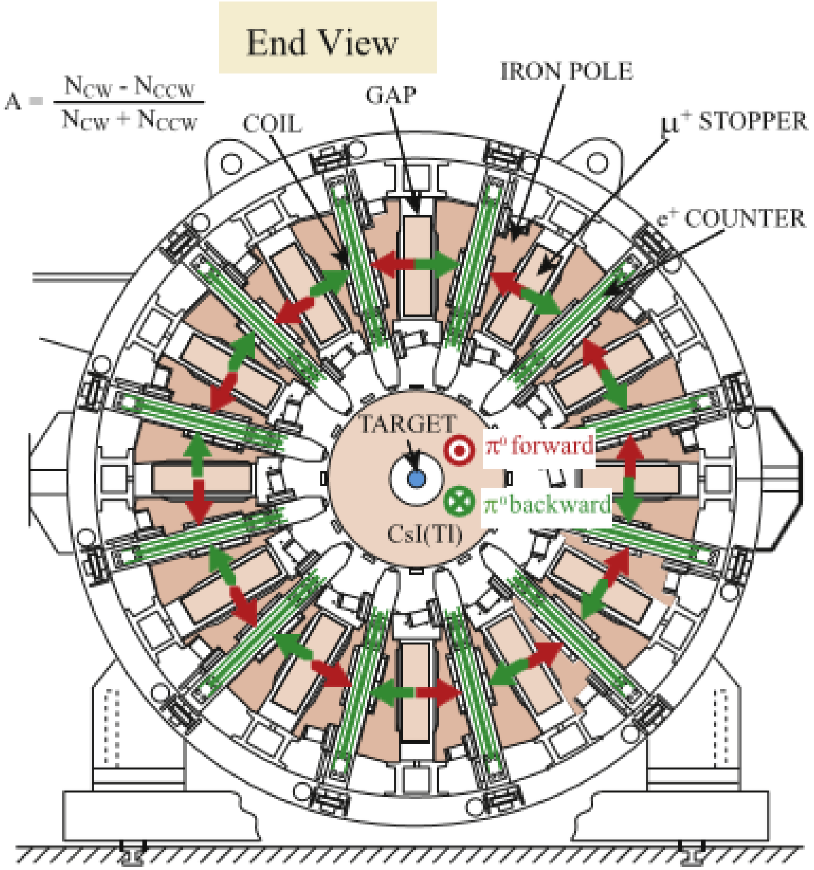
Summary

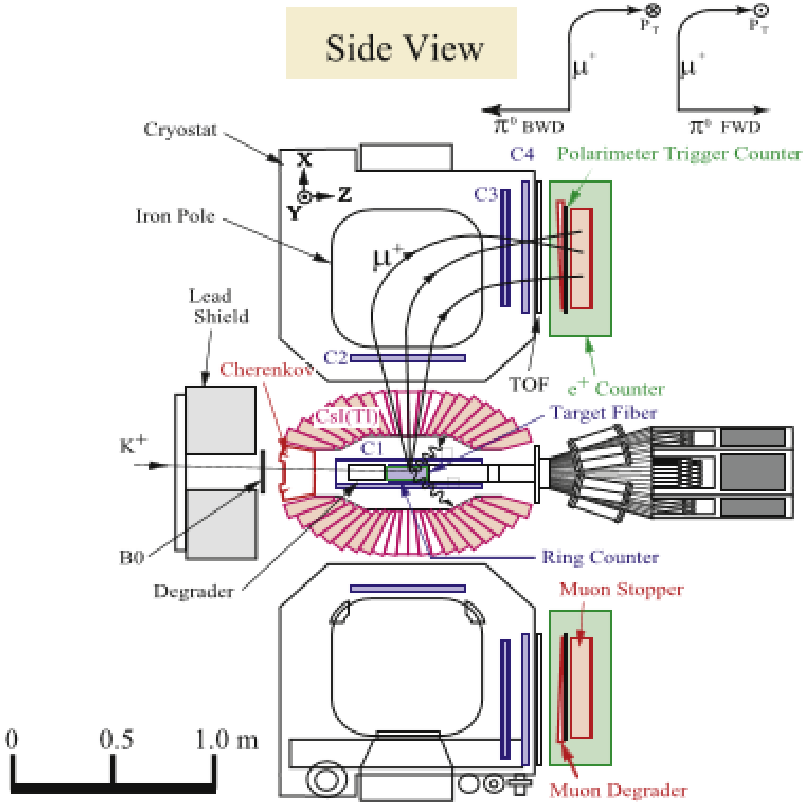
- A new experimental method to search for *T*-violating transverse muon polarization in $K^+ \to \pi^0 \mu^+ \nu$ ($K_{\mu 3}$) decay is proposed.
- In this experiment, the muon momentum, the muon polarization, and the π^0 momentum are determined by the same electro-magnetic calorimeter using a stopped K^+ beam.
- We concluded the μ^+ residual polarization higher than 90% in LaF_3-type crystals is high enough to perform the *T*-violation experiment at J-PARC.
- A test experiment to improve the analyzing power of muon polarization will be performed at TRIUMF (S. Ide talk on 24 Sep).
  - The analyzing power is expected to be highly improved by measuring the e^+ energy.
  - Can CeF3 crystals observe surface muons (kinetic energy of 4 MeV)?
- The μ^+ spin relaxation time in β-YF_3 materials will be measured at J-PARC MLF.

Backup

T-violation search in the KEK-PS E246 experiment

- $K^+ \rightarrow \pi^0 \mu^+ \nu$ ($K_{\mu 3}$) with $\mu^+ \rightarrow e^+ \nu \bar{\nu}$ and $\pi^0 \rightarrow \gamma\gamma$ decays
- Stopped K^+ method. Large solid angle and high resolution of the Toroidal spectrometer and CsI(Tl) calorimeter were used for the muon and photon measurement.
- However, the finite acceptance for μ^+ and e^+, small momentum window for μ^+





Results of E246:

P_T=0.0017±0.0023±0.0017

$\Delta\ P_T \sim 10^{-3}$

M. Abe et al.,
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CeF_3 crystal fabrication for the T-violation experiment

- Large CeF_3 crystal can be fabricated by K. Kamada et al. @Tohoku University.
- It will take a year to produce all of the CeF_3 modules.
- Cost estimation of the CeF_3 calorimeter
  - Calorimeter weight is ~1ton
  - Cost of raw materials is 0.3-0.4 M$

CeF_3の一般的性質

	CeF_3	PWO	CsI(pure)	NaI(Tl)
密度(g/cm^3)	6.16	8.2	4.86	3.67
輻射長(cm)	1.7	0.92	1.86	2.6
光量相対的	4-5	0.26	4	100
光の減衰時間(nsec)	30	15	10～1000	230
発光波長 (nm)	340	430	300～400	415
屈折率	1.68	2.2	1.8	1.85
放射線耐性(rad)	10^6		10^{4-5}	10^3
潮解性	なし	なし	少し	あり

・光量の温度依存性　0.05(%/℃)

・モリエル半径　2.8(cm)

・圧縮強度　3.1×10^9(dyn/cm^2)

・ヤング率　1.1×10^{12}(dyn/cm^2)

・熱膨張率　1.3×10^{-5}(/℃)

Properties of CeF_3 as a scintillating material

Density [g/cm^3]	6.16
Radiation length [cm]	1.68
Molière radius [cm]	2.63
Emission peak [nm]	286,300,340
Melting temperature [℃]	1443

表 1: General properties of CeF_3

	density (g/cm^3)	hygroscopic	λ_{max} (nm)	index refr.	photons /MeV	decay time (ns)
NaI(Tl)	3.67	yes	415	1.85	38,000	230
BaF_2	4.89	no	195,220	1.49	1,800	0.8
			310		10,000	630
BGO	7.13	no	480	2.15	700	60
			480	2.15	7,500	300
CsI(Tl)	4.51	no	540	1.80	59,000	800
					5,400	6,000
CsI(pure)	4.51	no	315	1.80	2,300	16
CeF_3	6.16	no	340	1.62	4,200*	27*
			300		200*	3*

*sample によってことなる.

Discussion

M. Diwan and H. Ma, Int. J. of Modern Phys A, 2441 (2001)

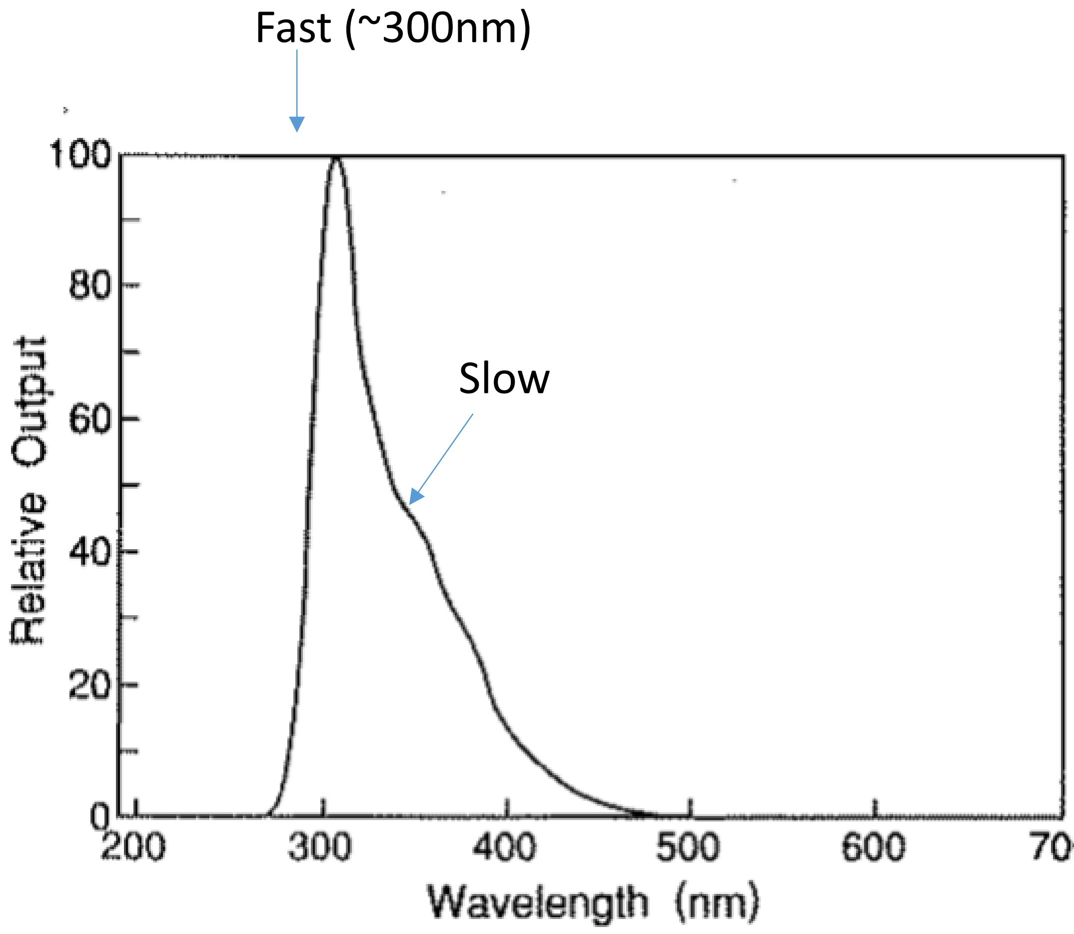
- The transverse μ^+ polarization in $K^+ \to \mu^+ \nu\gamma$ and $K^+ \to \pi^+\mu^+\mu^-$ decay can be measured.
  - Search for T-violation using stopped kaons
  - The data will be simultaneously recorded in the $K_{\mu 3}$ measurement.
- The longitudinal μ^+ polarization in $K_L \to \mu^+\mu^-$ (and $\eta \to \mu^+\mu^-$) decays can be measured.
  - Search for CP-violation using in-flight kaons
  - The polarimeter system will be additionally placed at the end of the existing detector configuration.
- Rare muon decay from polarized muons (Y. Kuno and Y. Okada, PRL 77 434, 1996)
  - Active muon stopper which can preserve the muon polarization

Properties of CeF_3 scintillating material

●結晶特性データ

密度	density	6.16g/cm³
融点	melting point	1443℃
屈折率	refractive index	1.62
放射長	radiation length	1.68～1.7cm
発光波長(ピーク)	wave length	fast=300nm slow=340nm
発光時間（減衰時間）	decay time	fast=5～8ns very fast response
発光量(NaI=100%)	photon yield	4～8.6 (NaI=100%)
モリエル半径	Moliere radius	>2.8cm
潮解性	hygroscopic	不溶 No
ヤング率		$1.1x10^{12}$dyn/cm²
熱膨張係数		$1.3x10^{-5}$

※参考Advatech-UK
※数値はすべて参考です。保証するものではありません。

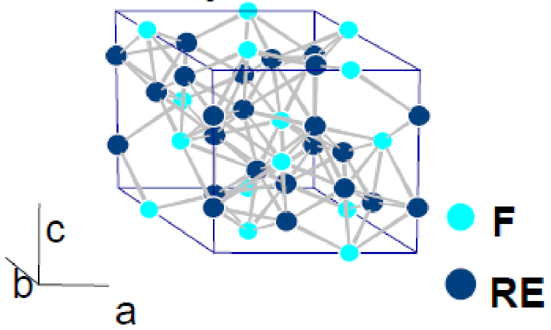


希土類フッ化物の諸性質

	結晶構造	密度, g/cm^3	一次相転位, ℃	融点, ℃
LaF_3	LaF_3-type	5.94		1500
CeF_3	LaF_3-type	6.13		1436
PrF_3	LaF_3-type	6.28		1401
NdF_3	LaF_3-type	6.51		1378
SmF_3	LaF_3-type⇔β-YF_3-type	6.64	480	1309
EuF_3	LaF_3-type⇔β-YF_3-type	6.79	853	1258
GdF_3	LaF_3-type⇔β-YF_3-type	7.06	1065	1235
TbF_3	β-YF_3-type	7.23		1182
DyF_3	β-YF_3-type	7.47		1160
HoF_3	β-YF_3-type	7.64		1147
ErF_3	α-YF_3-type ⇔ β-YF_3-type	7.82	1119	1147
YbF_3	α-YF_3-type ⇔ β-YF_3-type	8.17	986	1172
LuF_3	α-YF_3-type ⇔ β-YF_3-type	8.29	943	1180
YF_3	α-YF_3-type ⇔ β-YF_3-type	5.05	1082	1162

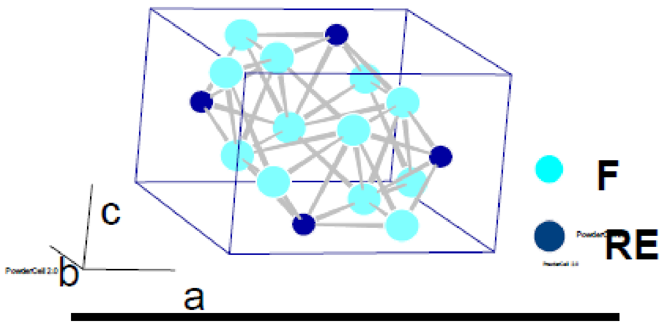
一次相転移のため融液からの単結晶作製が不可能

LaF_3 型構造



結晶構造	hexagonal
空間群	P3cl
陽イオンの配位数	11

β-YF_3型構造



結晶構造	orthorhombic
空間群	Pnma
陽イオンの配位数	8

α-YF_3型構造

結晶構造	hexagonal
空間群	P3m1に近い構造
陽イオンの配位数	8

ref. B.P.Sobolev. Multicomponent crystals based on heavy metal fluorides for radiation detectors. 1994

▼一次相転移のない新規希土類フッ化物単結晶の作製に成功した。

$Gd_{1-x}Y_xF_3$ (x=0.4-0.6)

$Gd_{1-x}Yb_xF_3$(x=0.15-0.45)

$Gd_{1-x}Lu_xF_3$(x=0.2-0.35)

▼ Ce-purterbed 発光の由来はO^{2-}の存在ではないことを見出した。

▼Ce^{3+}→Gd^{3+}→ Ce-perturbedというエネルギー遷移を確認した。

▼既存のPET用シンチレータとの特性比較

	Ce,Ca:$G_{1-x}Y_xF$	CeF_3	Ce:GSO	Ce:LSO	BGO
発光波長 (nm)	**380**	290	440	420	480
蛍光寿命 (ns)	**～30**	30	56	47	300
密度 (g/cm³)	**6.2**	6.16	6.795	**7.395**	**7.13**
PLにおける発光量 (BGO比)	**600**	54	120	**300**	100
融点(°C)	**～1,235**	1,400	1,950	2,150	**1,050**

Muon energy determined by the CsI(Tl) calorimeter

- The μ^+ momentum spectrum was obtained by requiring several cut conditions.
- The gain calibration of all CsI(Tl) modules was successfully performed.
- Distinct π^+ and μ^+ peaks with good separation are observed.
- A tail in the higher energy region is due to imperfect e^+ separation in the fitting.