



# R&D tellurium-loaded liquid scintillator

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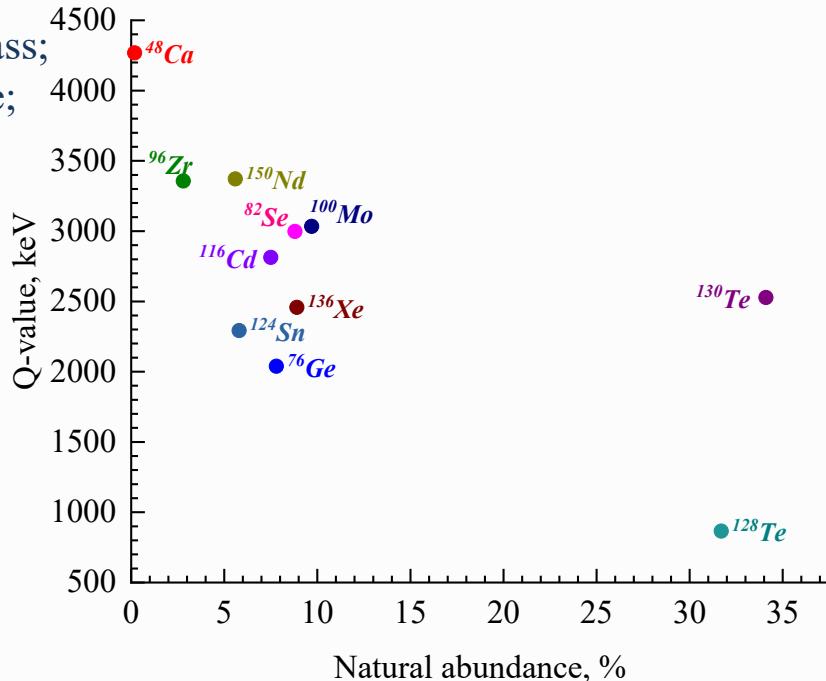
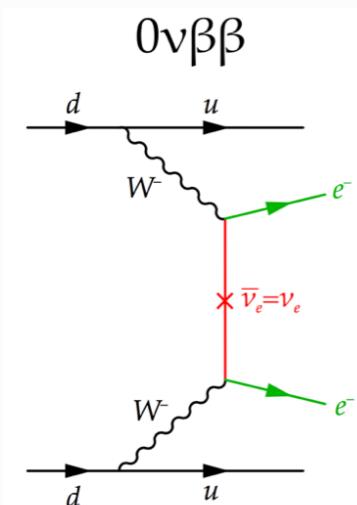
XXVI International Scientific Conference of  
Young Scientists and Specialists

# Neutrinoless double $\beta$ -decay



Observation of  $0\nu\beta\beta$  decay would imply:

- lepton number violation;
- presence of a Majorana term for the neutrino mass;
- constraints on neutrino mass hierarchy and scale;
- hint on origin of matter/anti-matter asymmetry.



1. Shimizu I. and Chen M. (2019) Double Beta Decay Experiments With Loaded Liquid Scintillator. *Front. Phys.* 7:33.

# Element-loaded liquid scintillators for searching $0\nu\beta\beta$



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| Element/isotope, concentration         | Scintillation base       | Element-containing additive  | Light yield <sup>4</sup> |
|--|--------------------------|--|--------------------------|
| Nd, up to 6.5 g/l [2]                  | PC <sup>1</sup>          | 2-Methylvalerate   | 80%                      |
| <sup>150</sup> Nd, [3]<br>up to 20 g/l | PC <sup>1</sup>          | Tris(trimethylhexanoate)   | 90%                      |
| up to 2 g/l                            | PC <sup>1</sup>          | Complexes with fluorinated $\beta$ -diketonates                        | 62%                      |
| Nd, 0.32% [4]                          | LAB <sup>2</sup>         | 4-Methyloctanoate  | 64%                      |
| Mo, 0.027 – 0.43% [5]                  | Toluene                  | Nanoparticles of AMoO <sub>4</sub> (A= Ca, Sr, Ba)                     | –                        |
| Sn, 32.6%, [6]                         | PC                       | Tetramethyltin   | 57%                      |
| Sn, 0.5 – 10% [7]                      | LAB                      | Tetrabutyltin  | 96% – 55%                |
| Cd, 1.5% [8]                           | LAB + TBP <sup>3</sup>   | Chloride   | 47%                      |
| Zr, 1.4% [9]                           | Anisole                  | Tetrakis(isopropylacetato)acetate                                      | 30 – 40%                 |
| Zr, up to 2.5 g/l [10]                 | PC <sup>1</sup>          | Dipivaloylmethanate  | 63%                      |
| Zr, 0.33% [11]                         | Toluene                  | Nanoparticles of ZrO <sub>2</sub>                                      | -                        |
| <sup>136</sup> Xe, $\leq$ 3% [12]      | Decane + PC <sup>1</sup> | Gaseous <sup>136</sup> Xe  | -                        |
| Te, 0.5% [13]<br>[14]                  | LAB                      | Complex of telluric acid with butanediol<br>+ N,N-dimethyldodecylamine | 64%<br>67%               |

<sup>1</sup> Pseudocumene; <sup>2</sup>Linear alkylbenzene; <sup>3</sup>Tributylphosphate; <sup>4</sup> Relative to unloaded LS

2. I.R. Barabanov, et al., Instruments and Experimental Techniques. 55 (2012) 545–550.

3. I.R. Barabanov, et al., Physics of Atomic Nuclei. 82 (2019) 89–97.

4. I.B. Nemchenok, et al., Bulletin of the Russian Academy of Sciences: Physics. 75 (2011) 1007.

5. S. Arai, et al., Journal of the Ceramic Society of Japan. 127(2019).

6. M.J. Hwang, et al., NIM A. 570 (2007) 454–458..

7. O. Chkvorets, et al., Journal of Physics: Conference Series. 1342 (2020) 12112.

8. I.B. Nemchenok, et al., Bulletin of the Russian Academy of Sciences: Physics. 76 (2012) 1187–1190.

9. Y. Fukuda, et al., Journal of Physics: Conference Series. 1342 (2020) 12093.

10. L.B. Bezrukov, et al., Russian Journal of Inorganic Chemistry. 66 (2021) 421–426.

11. A. Watanabe, et al., Nanomaterials. 11 (2021).

12. Y. Gando, (2019). <http://arxiv.org/abs/1904.06655> (accessed September 24, 2021).

13. S. Biller, S. Manecki, Journal of Physics: Conference Series. 888 (2017) 12084.

14. Patent CN № 112608263 (B), pub. 2022-05-27. G01T 1/20

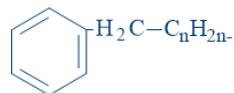


## Scintillation base:

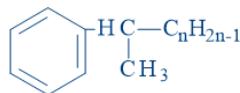
- high boiling point;
- explosion and fire safety, high flash point;
- non-toxicity;
- low corrosive activity in relation to the materials of the detector;
- availability and low cost.

## Linear alkylbenzene:

[15. arXiv:2205.15046](https://arxiv.org/abs/2205.15046)

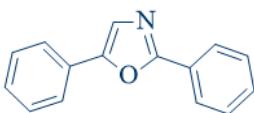


where  $n = 8 - 12$

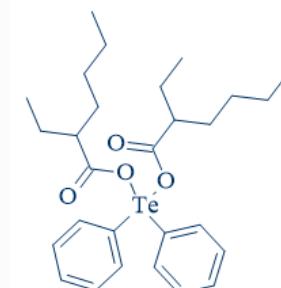


where  $n = 7 - 13$

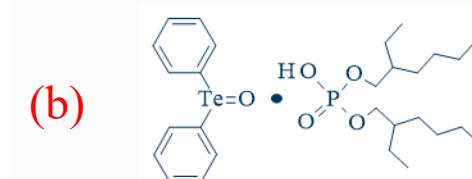
## Scintillation additives:



PPO



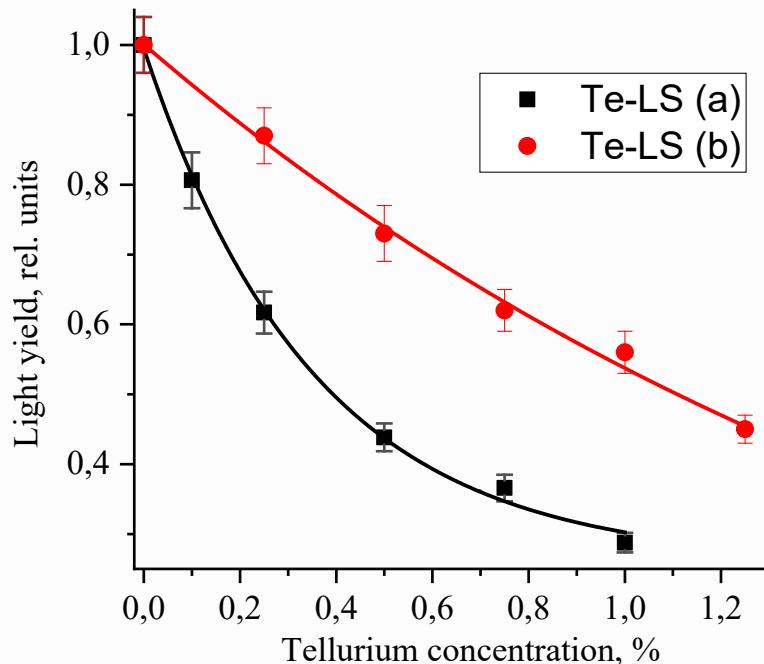
(a)



(b)

Structure formula of diphenyltellurium (a) di-2-ethylhexanoate, (b) oxide with di-(2-ethylhexyl)phosphoric acid (complex)

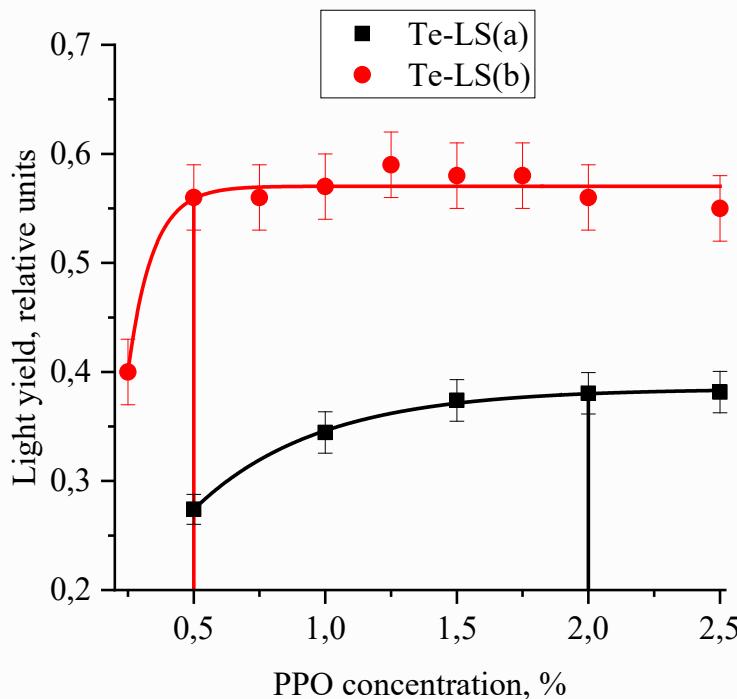
# Scintillation characteristics. Concentration dependency



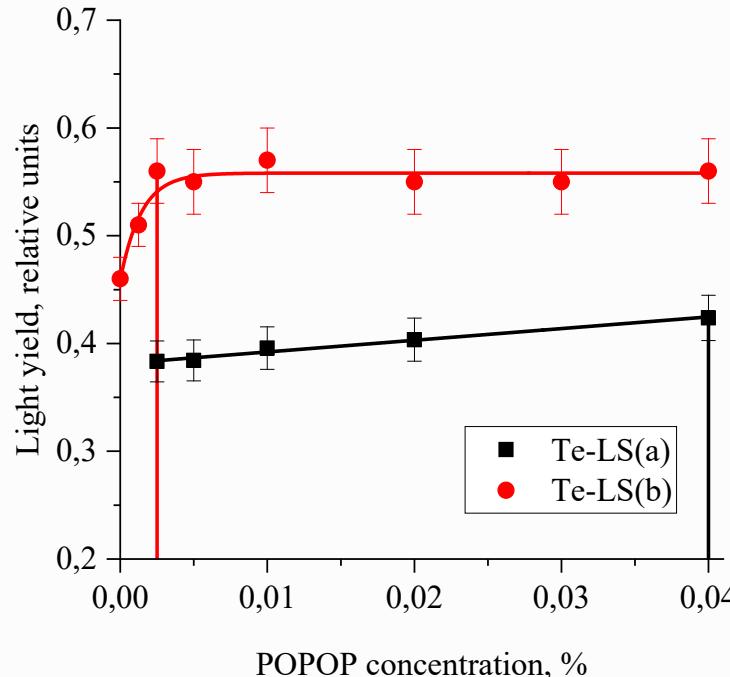
| Te, % | $T_{\lambda=430 \text{ nm}} \pm 1, \%$ |      |
|-------|--|------|
|       | (a)                                    | (b)  |
| 0     | 90.9                                   | 90.9 |
| 0.1   | 90.2                                   | -    |
| 0.25  | 90.3                                   | 87.9 |
| 0.5   | 88.9                                   | 87.1 |
| 0.75  | 88.7                                   | 87.0 |
| 1.0   | 86.2                                   | 85.1 |
| 1.25  | -                                      | 83.8 |

Light yield (relative to unloaded LS) and transparency data at  $\lambda=430 \text{ nm}$  (optical path 10 cm, relative to air) of Te-LS with a (a) diphenyltellurium di-2-ethylhexanoate, (b) complex with constant concentration PPO, POPOP (0.5%, 0.0025%, respectively).

# Scintillation characteristics. Optimization PPO and POPOP



Te-LS light yield as a function of the  
concentration PPO (concentration POPOP – 0,0025%)  
relative to unloaded LS

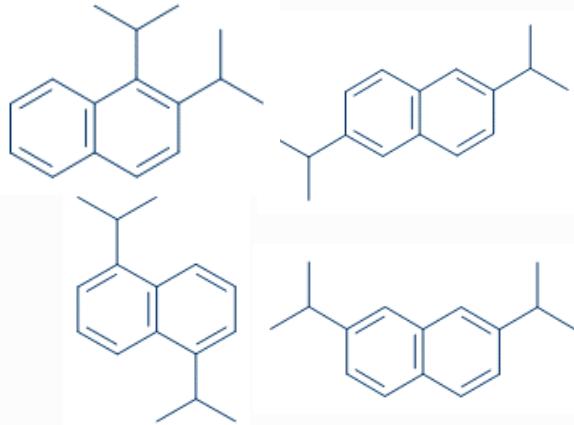


Te-LS light yield as a function of the concentration  
POPOP with a constant concentration PPO (for (a) 2% PPO,  
for (b) 0,5% PPO) relative to unloaded LS

# Scintillation characteristics. Optimization secondary solvent



Te-LS light yield with different concentration  $\text{DIPN}_{\text{mix}}$  with a constant concentration 1% Te,  
PPO, POPOP (for (a) – 2% PPO, 0.04% POPOP; for (b) – 0.5% PPO, 0.0025% POPOP)

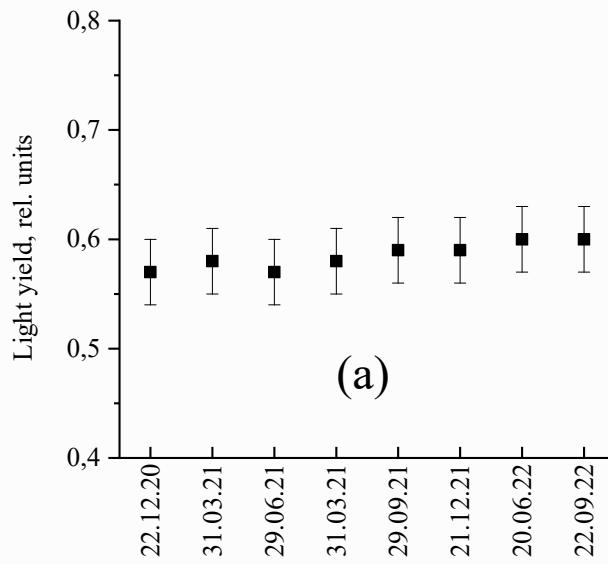


*diisopropylnaphthalene*

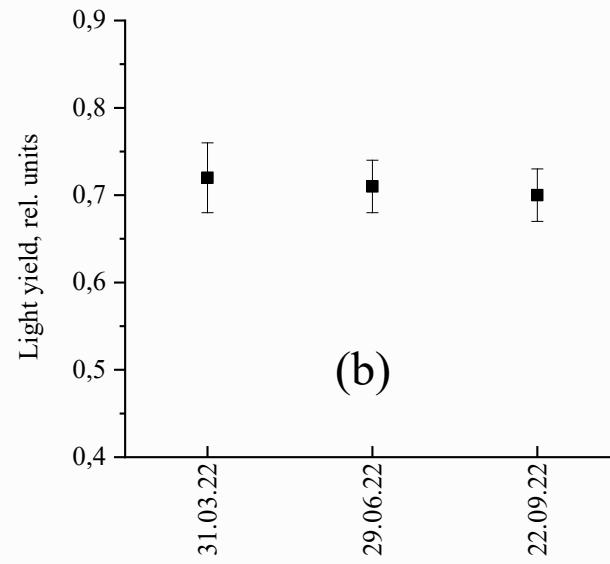
15. arXiv:2205.15046

| $\text{DIPN}_{\text{mix}},$<br>% | Light yield, rel. units |                 | $T_{\lambda=430 \text{ nm}} \pm 1, \%$ |      |
|----------------------------------|-------------------------|-----------------|--|------|
|                                  | (a)                     | (b)             | (a)                                    | (b)  |
| 0                                | $0.42 \pm 0.02$         | $0.55 \pm 0.03$ | 86.6                                   | 85.1 |
| 10                               | $0.50 \pm 0.03$         | $0.60 \pm 0.03$ | 83.1                                   | 82.9 |
| 20                               | $0.55 \pm 0.03$         | $0.67 \pm 0.03$ | 82.9                                   | 82.6 |
| 30                               | $0.57 \pm 0.03$         | $0.71 \pm 0.04$ | 81.0                                   | 80.8 |
| 40                               | -                       | $0.74 \pm 0.04$ | -                                      | 79.9 |
| 50                               | -                       | $0.78 \pm 0.04$ | -                                      | 79.0 |
| 60                               | -                       | $0.88 \pm 0.04$ | -                                      | 77.1 |
| 70                               | -                       | $0.88 \pm 0.04$ | -                                      | 74.0 |

# Scintillation characteristics. Stability



(a)



(b)

| Date     | $T_{\lambda=430 \text{ nm}} \pm 1, \%$ |      |
|----------|--|------|
|          | (a)                                    | (b)  |
| 22.12.20 | 81.0                                   | -    |
| 31.03.21 | 81.0                                   | -    |
| 29.06.21 | 81.2                                   | -    |
| 29.09.21 | 82.3                                   | -    |
| 21.12.21 | 80.4                                   | -    |
| 31.03.22 | 80.9                                   | 80.9 |
| 20.06.22 | 82.6                                   | 79.9 |
| 22.09.22 | 81.7                                   | 79.7 |

Stability of light yield and transparency for Te-LS samples of following composition:

- (a) 1%Te (in form of diphenyltellurium di-2-ethylhexanoate), 2%PPO, 0.04%POPOP, 30% DIPN<sub>mix</sub>;
- (b) 1%Te (in form of complex), 0.5%PPO, 0.0025%POPOP, 30% DIPN<sub>mix</sub>.

# Scintillation characteristics. Comparison with other Te-LS



| Te-LS sample                              | Scintillation composition                               | Light yield <sup>1</sup> ,<br>relative units |
|---|---|--|
| Our research (a)                          | 0.5% Te, 1% PPO, 0.04%POPOP, 30% DIPN <sub>mix</sub>    | 0.72±0.03                                    |
| Our research (a)                          | 1% Te, 2% PPO, 0.04%POPOP, 30% DIPN <sub>mix</sub>      | 0.58±0.03                                    |
| Our research (b)                          | 0.5% Te, 0.5% PPO, 0.0025%POPOP                         | 0.73±0.04                                    |
| Our research (b)                          | 1% Te, 0.5% PPO, 0.0025% POPOP, 30% DIPN <sub>mix</sub> | 0.71±0.03                                    |
| Patent CN 112608263 (B) <sup>2</sup> [14] | 0.5% Te, 2.5 g/L PPO, 3 mg/L bis-MSB                    | ~0.67  |
| SNO+ <sup>2</sup> [16]                    | 1% Te, 6 g/L PPO  | ~0.65  |

<sup>1</sup>Relative to unloaded LS

<sup>2</sup>Tellurium in form of complex telluric acid with butanediol-1,2 and N,N-dimethyldodecylamine

14. Patent CN № 112608263 (B), pub. 2022-05-27. G01T 1/20

16. T. Kroupova, Water phase results and  $0\nu\beta\beta$  prospects of the SNO+ experiment, in: Proceedings of European Physical Society Conference on High Energy Physics — PoS(EPS-HEP2019), Sissa Medialab, Trieste, Italy, (2020)

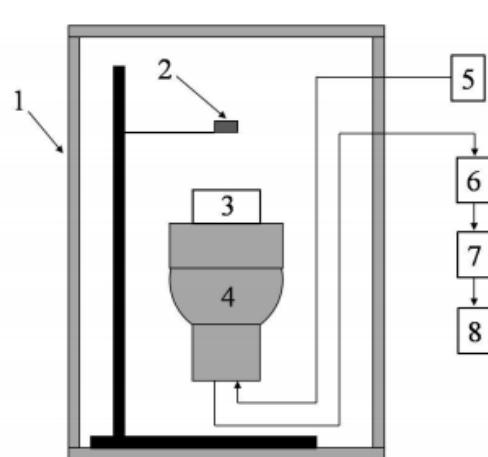


1. The samples of the new liquid scintillators with a tellurium concentration more than 1% and good light yield were obtained.
2. Different class of tellurium compounds – (a) diphenyltellurium dicarboxylates and (b) complex of diphenyltellurium oxide with di-(2-ethylhexyl)phosphoric acid have been tested.
3. In aim to improve the light yield of the new scintillator:
  - scintillation additives concentration have been optimized;
  - diisopropynaphthalene as secondary solvent has been proposed;
4. Long-term stability of properties of the new Te-LS's has been demonstrated.



# Backup

## Light yield:



## Experimental conditions:

- teflon cuvette with uviol glass;
- volume – 40 ml, height – 2 cm;
- $^{207}\text{Bi}$  A=2.5 kBq;
- difference measurement method

Block diagram of the installation for measuring the light yield and energy resolution of the LS: 1 - light-protective box; 2 - radioactive source; 3 – cell with LS; 4 - PMT; 5 – high voltage source; 6 - preamplifier; 7 - amplifier; 8 - signal converter

**UV-VIS spectra:** UNICO UV 2804 in a 10 cm cuvette relative to air at a wavelength of 390 to 600 nm.

**Tellurium-containing additives:** UV-VIS, IR, Raman-spectroscopy, elemental analysis (C, H, Te), Differential Scanning Calorimetry (melting point), ICP-AES (MS) (in plans)

# Scintillation characteristics. Absolute light yield



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| LS sample   | Scintillation composition                            | Absolute LY,<br>photons/MeV | Evaluation method               |
|-------------|--|-----------------------------|---------------------------------|
| unloaded-LS | 0.5% PPO, 0.0025%POPOP                               | 8646±400                    | Relative to EJ-309 <sup>2</sup> |
| Te-LS       | 0.5% Te <sup>1</sup> , 1% PPO, 0.04% POPOP, 30% DIPN | 6399±320                    | Relative to EJ-309              |
| Te-LS       | 1% Te <sup>1</sup> , 2% PPO, 0.04% POPOP, 30% DIPN   | 5128±256                    | Relative to EJ-309              |
| RENO        | 0.3% PPO, 0.0030% bis-MSB                            | ~8000                       | Relative to anthracene          |
| Daya Bay    | 0.3% PPO, 0.0015% bis-MSB                            | 8700                        | Relative to anthracene          |
| Stereo      | 0.3% PPO, 0.0020% bis-MSB                            | 8400                        | Quantum efficiency of PMT       |

<sup>1</sup>in form di-2-ethylhexanoate diphenyltellurium

<sup>2</sup>LS based on diisopropylnaphthalene with light yield 12.300 photons/ 1 MeV e<sup>-</sup>

# Synthesis of diphenyltellurium derivatives

