Optical Materials 42 (2015) 430-434

Contents lists available at ScienceDirect

Optical Materials

journal homepage: www.elsevier.com/locate/optmat



Luminescent properties of Pb₂MoO₅ single crystals

D.A. Spassky^{a,b,*}, V.N. Shlegel^c, N.V. Ivannikova^c, A.P. Yelisseyev^d, A.N. Belsky^e

^a Institute of Physics, University of Tartu, 50411 Tartu, Estonia

^b Skobeltsyn Institute of Nuclear Physics, Moscow State University, 119991 Moscow, Russia

^c Nikolaev Institute of Inorganic Chemistry, SB RAS, Novosibirsk 630090, Russia

^d Sobolev Institute of Geology and Mineralogy, SB RAS, Novosibirsk 630090, Russia

^e Institute of Light and Matter, CNRS, University Lyon1, Villeurbanne 69622, France

ARTICLE INFO

Article history: Received 20 November 2014 Received in revised form 16 January 2015 Accepted 21 January 2015 Available online 16 February 2015

Keywords: Pb₂MoO₅ Luminescence Thermostimulated luminescence Scintillating bolometers

1. Introduction

The phase diagram of the PbO-MoO₃ contains two congruently melting compounds - PbMoO₄ and Pb₂MoO₅. In contrast to the well-known scheelite type PbMoO₄ crystals, the properties of lanarkite type Pb₂MoO₅ crystals, which belong to the monoclinic space group C2/m [1,2] are poorly studied. The crystal is known as a promising material for acousto-optical application [3–5], while its luminescent properties are almost unstudied. Molybdates now attract enhanced attention because of the potential application in cryogenic scintillation bolometers [6]. Properties of PbMoO₄ have been already studied, demonstrating that lead containing molybdates are promising for this application [7]. Pb_2MoO_5 is a dense (7.1 g/cm^3) crystal, which also may be a perspective scintillator. The first results on the luminescence spectra, excitation spectra as well as on the band structure calculations of Pb₂MoO₅ are presented in [8,9]. However these papers contain controversy data on the luminescent properties of Pb₂MoO₅ that might be connected with the different quality and purity of the studied samples. The aim of this work is to perform the study of the luminescent properties of high quality Pb₂MoO₅ single crystals in order to obtain the data, which will allow to estimate its applicability for low-temperature experiments.

E-mail address: deris2002@mail.ru (D.A. Spassky).

ABSTRACT

Lanarkite type Pb_2MoO_5 single crystals were grown using low temperature gradient Czochralski technique and their optical and luminescent properties were studied. The luminescence band at 590–600 nm was observed under UV and X-ray excitations and ascribed to emission of self-trapped excitons. The band is thermally quenched at T > 15 K with the activation energy of process, $E_{act} = 11$ meV. The measurements of thermostimulated luminescence demonstrated the presence of shallow traps, which adversely influence the energy transfer to the emission centers.

© 2015 Elsevier B.V. All rights reserved.

2. Experimental details

The single crystals of Pb₂MoO₅ were grown from the stoichiometric melt using the low temperature gradient Czochralski (LTG CZ) technique. The feature of method is the extremely low temperature gradient 0.1–1.0 K/cm in the melt in comparison to conventional Czochralski technique with the temperature gradient 10–100 K/cm. The single crystals were grown in the direction, perpendicular to the cleavage plane with the growth rate 1.5–2.5 mm/ h. The growth procedure has been described in more details in [10]. It is worth noting that the crystals of Pb₂MoO₅, which were studied in [8,9] has been obtained in form of polycrystalline powder samples prepared by conventional solid state reactions [8] or in form of single crystals grown by the conventional Czochralski technique [9]. The LTG CZ method allows growing the crystals of superior optical quality as it has been shown, e.g. for zinc molybdate crystals [11].

As a result, Pb_2MoO_5 single crystals up to 100 mm long and 50 mm in diameter and up to 700 g in mass were obtained (Fig. 1). According to [12] the presence of microinclusions of other phases is the problem of the Pb_2MoO_5 single crystals growth of large dimensions. The crystals grown using the LTG CZ technique were free from the inclusions of other phases. Impurities concentration in the investigated Pb_2MoO_5 was analyzed by means of ionization mass spectrometry analysis. The measurements were performed using a laser mass-spectrometer EMAL-2. The traces of Ca (0.1 ppm) Ag (0.8 ppm) and W (100 ppm) were detected while the concentration of other elements was below 0.1 ppm.



Optical Materia

^{*} Corresponding author at: Institute of Physics, University of Tartu, 50411 Tartu, Estonia.

Transmission spectra were recorded in the visible to near IR spectral range using a Shimadzu spectrometer UV-2501PC. The working planes of samples were parallel to the perfect-cleavage plane (201). Luminescence spectra and decay curves were measured under UV-excitation at the laboratory setup in the temperature region 7–100 K. The luminescence spectra were corrected for the spectral sensitivity of registration channel. The measurements of X-ray excited luminescence, TSL glow curves and spectra were carried out at the Institute of Light and Matter of Claude Bernard Lyon University (France). An X-ray source with a tungsten anode operating at U = 30 kV was used as an excitation source.

3. Results and discussion

The transmission spectra were recorded for a polished Pb₂MoO₅ plates 2.5 and 16 mm thickness. The crystal is transparent starting from 365 nm on the 5% transmission level. The transmission is about 72% in the visible and near infra-red regions. The transmission cutoff is shifted to longer wavelength region in comparison to the data presented in [13] – 336 nm. We suppose that the shift is due to the different thickness of samples – 2.5 mm in our experiments and 0.15 mm in [13]. The absorption band is observed in the transparency region of crystal at 400–480 nm and is connected with the absorption of intrinsic defects, probably with the oxygen vacancies (Fig. 2, curve 2). The band is observed only for the thick sample (16 mm) and responsible for the yellowish coloration of crystal (Fig. 1).

An intensive emission band was observed under UV and X-ray excitation at 10 K (Fig. 3). The maximum of emission band is located at 590 nm for UV excitation and it slightly shifts (\sim 10 nm) to the long-wavelength region in the case of X-ray excitation. The excitation spectrum demonstrates a broad band with a maximum at 320 nm. According to [8] the crystal demonstrates the broad emission band with maximum at 525 nm with the excitation band peaking at 345 nm at *T* = 4.2 K. Another result is presented in [9] where the emission band has maximum at 600 nm with the excitation band registered by us well corresponds to that presented in [9], while the result obtained in [8] is not confirmed with the present data.

The edge of excitation spectrum in the long wavelength region corresponds to the fundamental absorption edge of crystal (Fig. 3, curve 4). The observed slight mismatch of the edges is due to the different temperature of measurements of the excitation (10 K)



Fig. 1. Pb₂MoO₅ single crystal grown by the low temperature gradient Czochralski technique.



Fig. 2. Transmission spectra for the Pb₂MoO₅ plates 2.5 (1) and 16 mm (2) thick, T = 300 K. In the inset: Absorption spectra calculated from transmission spectra of the plate 2.5 mm thick measured at 300 K (3) and 80 K (4).



Fig. 3. Luminescence spectra of Pb₂MoO₅ measured under X-ray (1) and UV, $\lambda_{ex} = 340 \text{ nm}$ (2) excitation and luminescence excitation spectrum, $\lambda_{em} = 590 \text{ nm}$ (3), T = 10 K. Curve 4 represents the absorption edge of Pb₂MoO₅ at T = 80 K. In the inset – enlarged luminescence spectrum at $\lambda_{ex} = 340 \text{ nm}$ in the short wavelength region.

and absorption (80 K) spectra. Fundamental absorption edge shifts to the long-wavelength region with the increase of temperature (see inset in Fig. 2) following the Urbach rule [14] and the edge in excitation spectrum will follow this shift in case when the luminescence is excited via the interband electron transitions. The presence of broad emission band, which is excited starting from the edge of fundamental absorption region is common for the molybdates. The band is ascribed to the emission of excitons, which are self-trapped at MoO₄ complexes. The position of STE emission band depends on the crystal structure of a given molybdate. In crystals with the scheelite crystal structure (CaMoO₄, PbMoO₄, SrMoO₄, BaMoO₄) the self-trapped excitons (STE) emission band is peaking around 480-530 nm [15]. The band shifts to the long wavelength region for molybdates, which crystal structure differs from scheelite, e.g. 540 nm in MgMoO₄ [16], 580 nm in Li₂MoO₄ [17], 640 nm in ZnMoO₄ [11], etc. Though the crystal structure of these molybdates is different, all of them are characterized by the presence of isolated tetrahedral MoO₄ complexes, which are responsible for the self-trapping of excitons. The crystal structure of Pb₂MoO₅ is also characterized by the presence of tetrahedral MoO₄ complexes. The position of the broad emission band in Pb₂-MoO₅ correspond to the spectral region of the STE emission in molybdates and the excitation of the luminescence starts in the region of the absorption edge of crystal. It allows to attribute the observed luminescence band in Pb₂MoO₅ to the emission of STE.

The complex character of the emission band in Pb₂MoO₅ has been supposed in [9] because a shoulder to the main emission band has been observed at 580 nm. Our experiments did not confirm the complex structure of the band. We have measured decay curves in the region of the maximum of STE band as well as at the short-wavelength and long-wavelength slopes of STE band (Fig. 4). The curves are similar, i.e. the decay times of the components and their relative amplitudes do not depend on the wavelength. This observation confirms that the emission band is elementary. Decay curves can be fitted with a sum of two exponents with decay times $8.2 \pm 0.2 \mu s$ and $25.0 \pm 1.4 \mu s$. Presence and origin of several decay components in the emission of molybdates is a complicated question. The studies of the emission decay kinetics as well as its temperature dependence have been performed earlier for several molybdates including PbMoO₄ [7,18–20], CaMoO₄ [21–24], $MgMoO_4$ [21], CdMoO_4 [25]. Several decay components with decay times varying from units to tens of µs have been observed frequently for the emission of STE indicating the presence of several excited energy levels or different configurations of the MoO₄ complexes, which are responsible for the radiative transitions. Some of these results have been obtained under irradiation by X or γ rays or high-energy particles [7,22,23]. In such cases, the decay curves deviate from an exponential behavior in their initial part because of the interaction between excitons created at high densities in the ends of secondary electron tracks as it was shown for CdWO₄ [26]. Therefore, a complex decay kinetics of the STE emission under high-energy excitation does not necessary provide the evidence of the availability of several excited energy levels. The results obtained by using selective excitation with conventional sources in the UV spectral region should give more direct information, however contradictory data have been obtained even in this case. The measurements of decay curves in a wide temperature region have demonstrated the presence of a single component or several decay components in the triplet STE emission of $PbMoO_4$ ([19,18], respectively) and also in that of $CaMoO_4$ ([24.21], respectively). Time-resolved spectroscopy has also been used for the determination of the spectral composition of the STE emission in CdMoO₄. It has demonstrated the presence of a single band [25] or several emission bands attributed to the emission from different MoO₄ excited states split by the Jahn–Teller effect [27]. The contradictory results indicate the difficulties in preparation of high-quality crystals as well as the absence of a clear understanding of the origin of a complex emission decay in molybdates.



Fig. 4. Decay curves of Pb_2MoO_5 at λ_{em} = 650 nm, 580 nm, 500 nm (1–3) and 400 nm (4) under λ_{ex} = 340 nm, *T* = 10 K.

The results obtained by us agree, e.g. with those obtained for $CdMoO_4$ [25] and for PbMoO_4 [18] where slower and faster components with decay times of few and tens of μ s are observed at low temperatures. We suppose that a three level scheme of a triplet exciton proposed as a model of an emission center is valid also for the emission of triplet STE observed in Pb₂MoO₅. It explains the availability of two components in the decay of triplet exciton emission by the non-equilibrium initial population of the emitting and metastable states of the triplet at low temperatures.

It is worth noting that the additional low-intensity band peaking at 390 nm has been also observed in the luminescence spectrum under UV-excitation (see inset in Fig. 3). The decay curve of this band coincides with the shape of excitation pulse that implies that the decay time of the band is less than 10^{-7} s (Fig. 4, curve 4). Recently the short-wavelength emission band with decay time of several ns has been detected in some molybdates, e.g. in PbMoO₄ and CaMoO₄ [9,20,21]. The band was ascribed to the singlet STE, viz to the transitions from the singlet states ${}^{1}T_{1}$ and ${}^{1}T_{2}$ of the lowest excited configuration of MoO₄ complex to ${}^{1}A_{1}$. Similar mechanism may be proposed for the short-wavelength band in Pb₂MoO₅.

The temperature dependence of the intensity of STE emission band is presented in Fig. 5. Under UV excitation the dependence has plateau in the region 9–15 K and the thermal quenching starts at T > 15 K (Fig. 5a). The temperature dependence can be fitted using Mott formula with the activation energy E_{act} = 11 meV. The temperature dependence of STE emission intensity under X-ray excitation slightly differs from that, measured under UV-excitation (Fig. 5b). The main differences in the dependence measured under X-ray excitation are the following: (I) the presence of the bend at 28 K; (II) the thermal quenching starts at T > 20 K and (III) at T < 15 K the intensity is decreased by 10%. These features are connected with the influence of trapping effect on the efficiency of STE creation from separated electron-hole pairs, which are created under X-ray excitation. The TSL curve is presented in Fig. 6, which reveals the presence of strong peak at 25 K followed by the lowintensity peak at 54 K. The luminescence spectra measured in these peaks coincide with the intrinsic emission of Pb₂MoO₅ (see



Fig. 5. (a) Temperature dependence of STE emission intensity at λ_{ex} = 340 nm (circles) and its fitting using Mott formula with E_{act} = 11 meV. (b) Temperature dependence of STE emission intensity under X-ray excitation.



Fig. 6. TSL curve of Pb_2MoO_5 after irradiation with X-rays at T = 10 K. In the inset – TSL spectra in peaks at 25 K (1) and 54 K (2).

inset in Fig. 6). The presence of strong TSL peak at 25 K results in the decrease of STE emission intensity by 10% with the cooling of sample down to 10 K. Similar effect has been observed for PbMoO₄ were the strong TSL peak has been observed at 43 K and the STE emission decreased by \sim 30% with the cooling of sample down to T = 10 K [28]. The TSL peak has been attributed to the thermal release of self-trapped electrons in PbMoO₄. Existence of holes, self-trapped by MoO₄ complexes has been also detected in molybdates [28]. However, the self-trapped holes have not been observed in PbMoO₄ because of the presence of Pb 6s states at the very top of the valence band. The stabilization of self-trapped holes is improbable in such case due to their possible migration over the lead states. The band structures of PbMoO₄ and Pb₂MoO₅ are similar in the vicinity of bandgap [9]. Therefore we tentatively ascribe the strong peak at 25 K in Pb₂MoO₅ to the self-trapped electrons while the self-trapped holes are not expected to be revealed in TSL.

Trapping should negatively influence the light yield of cryogenic scintillator because some part of created charge carriers will be captured by shallow traps. In order to estimate the applicability of Pb_2MoO_5 as a cryogenic scintillator we compared its luminescence intensity under X-ray excitation with the luminescence intensity of $PbMoO_4$ and Li_2MOO_4 , which are promising crystals for cryogenic scintillating bolometers [7,29]. The luminescence intensity of Pb_2MoO_5 is comparable to that observed in $PbMoO_4$ and it is one order of magnitude higher than the luminescence intensity of Li_2MoO_4 . Taking into account that the light yield of $PbMoO_4$ crystal has been estimated as ~5500 ph/MeV [28] one can expect the comparable value of light yield also for the Pb_2MoO_5 crystals. It allows to consider Pb_2MoO_5 as a promising crystal for cryogenic scintillation bolometers.

4. Conclusions

The Pb₂MoO₅ single crystals of high optical quality were grown by the LTG CZ technique and their optical and luminescent properties were studied. The broad elementary emission band peaking at 600 nm is ascribed to the emission of triplet STE. The decay of STE emission is characterized by the presence of two components with decay times $8.2 \pm 0.2 \mu$ s and $25.0 \pm 1.4 \mu$ s at T = 10 K. The thermal quenching of STE emission starts at T > 15 K, the activation energy of quenching process is calculated as $E_{act} = 11$ meV. The TSL curve reveals the presence of two peaks at 25 and 54 K. The trapping process is responsible for the decrease of the intensity of STE emission at T < 15 K under X-ray excitation and it is expected to worsen the scintillation properties of crystal at low temperatures. The emission intensity under X-ray excitation is comparable to that of the promising cryogenic scintillator PbMoO₄ that allows to consider the Pb₂MoO₅ crystals for this application as well.

Acknowledgements

This work was supported by Institutional Research Funding IUT (IUT02-26) of the Estonian Ministry of Education and Research and RFBR 14-08-00527 grant. The financial support from Mobilitas European Social Fund (ESF) program (grant MTT83) is also gratefully acknowledged.

References

- [1] B.F. Mentzen, A. Latrach, J. Bouix, A.W. Hewat, The crystal structures of PbO.PbXO 4 (X = S, Cr, Mo) at 5k by neutron powder profile refinement, Mater. Res. Bull. 19 (1984) 549–554.
- [2] S. Miyazawa, H. Iwasaki, Single crystal growth of Pb₂MoO₅, J. Cryst. Growth 8 (1971) 359–362.
- Y. Ohmachi, N. Uchida, Acoustic and acousto-optical properties of Pb₂MoO₅ single crystal, J. Appl. Phys. 42 (1971).
- [4] A. Tchernyatin, E. Nazarova, Acousto-optic diffraction in biaxial crystals possessing considerable optic dispersion, Eur. Phys. J. Spec. Top. 154 (2008) 217–220.
- [5] M.G. Mil'kova, M.D. Volnyanskii, A.M. Antonenko, V.B. Voloshinov, Acoustic properties of biaxial crystal of double lead molybdate Pb₂MoO₅, Acoust. Phys. 58 (2012) 172–179.
- [6] F.A. Danevich, Development of crystal scintillators from enriched isotopes for double β decay experiments, IEEE Trans. Nucl. Sci. 59 (2012) 2207–2213.
- [7] F.A. Danevich, B.V. Grinyov, S. Henry, M.B. Kosmyna, H. Kraus, N. Krutyak, V.M. Kudovbenko, V.B. Mikhailik, L.L. Nagornaya, B.P. Nazarenko, A.S. Nikolaiko, O.G. Polischuk, V.M. Puzikov, A.N. Shekhovtsov, V.I. Tretyak, Yu.Ya. Vostretsov, Feasibility study of PbWO₄ and PbMO₄ crystal scintillators for cryogenic rare events experiments, Nucl. Inst. Meth. Phys. Res. A 622 (2010) 608–613.
- [8] H.F. Folkerts, J. Zuidema, G. Blasse, The luminescence of Pb²⁺ in lead compounds with one-dimensional chains, Solid State Commun. 99 (1996) 655–658.
- [9] S. Nedilko, V. Chornii, Yu. Hizhnyi, M. Trubitsyn, I. Volnyanskaya, Luminescence spectroscopy and electronic structure of the PbMoO₄ and Pb₂MoO₅ single crystals, Opt. Mater. 36 (2014) 1754–1759.
- [10] E.N. Galashev, T.M. Denisova, I.M. Ivanov, E.P. Makarov, V.N. Mamontov, V.N. Shlegel, Yu.G. Stenin, Ya.V. Vasiliev, V.N. Zhdankov, Growing of ¹⁰⁶CdWO₄, ZnWO₄, and ZnMOO₄ scintillation crystals for rare events search by low thermal gradient Czochralski technique, Funct. Mater. 17 (2010) 504–508.
- [11] D.A. Spassky, V.V. Mikhailin, A.E. Savon, E.N. Galashov, V.N. Shlegel, Ya.V. Vasiliev, Low temperature luminescence of ZnMoO₄ single crystals grown by low temperature gradient Czochralski technique, Opt. Mater. 34 (2012) 1804– 1810.
- [12] D.D. Nihtianova, S.S. Angelova, L.K. Djonev, Ts.S. Zheleva, E.A. Tsukeva, K.P. Petrov, Phase inhomogeneity of Pb₂MoO₅ single crystals, J. Cryst. Growth 148 (1995) 148–154.
- [13] N. Uchida, S. Miyazawa, K. Ninomiya, Refractive indices of Pb₂MoO₅ single crystal, J. Opt. Soc. Am. 60 (1970) 1375–1377.
- [14] K.S. Song, R.T. Williams, in: Self-Trapped Excitons, Springer Ser. Solid-State Sci., second ed., vol. 105, Springer-Verlag, Berlin, 1996.
- [15] D. Spassky, S. Ivanov, I. Kitaeva, V. Kolobanov, V. Mikhailin, L. Ivleva, I. Voronina, Optical and luminescent properties of a series of molybdate single crystals of scheelite crystal structure, Phys. State Solid (c) 2 (2005) 65–68.
- [16] D.A. Spasskii, V.N. Kolobanov, V.V. Mikhailin, L.Yu Berezovskaya, L.I. Ivleva, I.S. Voronina, Luminescence peculiarities and optical properties of MgMoO₄ and MgMoO₄: Yb crystals, Opt. Spectrosc. 106 (2009) 556–563.
- [17] D.A. Spassky, V. Nagirnyi, E. Aleksanyan, A.E. Savon, O.P. Barinova, S.V. Kirsanova, V.D. Grigorieva, N.V. Ivannikova, V.N. Shlegel, A.N. Belsky, A.P. Yelisseyev, Low temperature luminescence and energy transfer in a cryogenic scintillator Li₂MoO₄, J. Lumin. (submitted for publication).
- [18] W. van Loo, Luminescence decay of lead molybdate and lead tungstate a descriptive model, J. Lumin. 10 (1975) 221–235.
- [19] V. Babin, P. Bohacek, E. Bender, A. Krasnikov, E. Mihokova, M. Nikl, N. Senguttuvan, A. Stolovis, Y. Usuki, S. Zazubovich, Decay kinetics of the green emission in tungstates and molybdates, Radiat. Meas. 38 (2004) 533–537.
- [20] T. Kajitani, M. Itoh, Time-resolved composite nature of the self-trapped exciton luminescence in PbMoO₄, Phys. State Solid (c) 8 (2011) 108–111.
- [21] V. Mikhailik, H. Kraus, M. Itoh, D. Iri, M. Uchida, Radiative decay of self-trapped excitons in CaMoO₄ and MgMoO₄ crystals, J. Phys.: Condens. Mater. 17 (2005) 7209–7218.
- [22] V.B. Mikhailik, S. Henry, H. Kraus, I. Solskii, Temperature dependence of CaMoO₄ scintillation properties, Nucl. Inst. Method Phys. Res. A 583 (2007) 350–355.
- [23] A.N. Annenkov, O.A. Buzanov, F.A. Danevich, A.Sh. Georgadze, S.K. Kim, H.J. Kim, Y.D. Kim, V.V. Kobychev, V.N. Kornoukhov, M. Korzhik, J.I. Lee, O. Missevitch, V.M. Mokina, S.S. Nagorny, A.S. Nikolaiko, D.V. Poda, R.B. Podviyanuk, D.J. Sedlak, O.G. Shkulkova, J.H. So, I.M. Solsky, V.I. Tretyak, S.S. Yurchenko, Development of CaMoO₄ crystal scintillators for a double beta

decay experiment with ¹⁰⁰Mo, Nucl. Inst. Method Phys. Res. A 584 (2008) 334-345.

- 345.
 [24] J.A. Groenink, C. Hakfoort, G. Blasse, The luminescence of calcium molybdate, Phys. State Solid (a) 54 (1979) 329–336.
 [25] A. Kotlov, L. Jönsson, H. Kraus, V. Mikhailik, V. Nagirnyi, G. Svensson, B.I. Zadneprovski, Excited states of molybdenum oxyanion in scheelite and wolframite structures, Radiat. Meas. 42 (2007) 767–770.
- [26] R. Laasner, N. Fedorov, R. Grigonis, S. Guizard, M. Kirm, V. Makhov, S. Markov, V. Nagirnyi, V. Sirutkaitis, A. Vasil'ev, S. Vielhauer, I.A. Tupitsyna, Band tail absorption saturation in CdWO₄ with 100 fs laser pulses, J. Phys.: Condens. Mater. 25 (24) (2013) 245901-245911.
- [27] M. Itoh, Luminescence study of self-trapped excitons in CdMoO₄, J. Lumin. 132 (2012) 645-651.
- (2012) 045-051.
 [28] D.A. Spassky, V. Nagirnyi, V.V. Mikhailin, A.E. Savon, A.N. Belsky, V.V. Laguta, M. Buryi, E.N. Galashov, V.N. Shlegel, I.S. Voronina, B.I. Zadneprovski, Trap centers in molybdates, Opt. Mater. 35 (2013) 2465–2472.
 [29] L. Cardani, N. Casali, S. Nagorny, L. Pattavina, G. Piperno, O.P. Barinova, J.W. Beeman, F. Bellini, F.A. Danevich, S. Di Domizio, L. Gironi, S.V. Kirsanova, F.
- Orio, G. Pessina, S. Pirro, C. Rusconi, C. Tomei, V.I. Tretyak, M. Vignati, Development of a Li₂MoO₄ scintillating bolometer for low background physics, J. Instrum. 8P10002 (2013).