

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Addendum to the ISOLDE and Neutron Time-of-Flight Committee
(Addendum to the IS440 Proposal)

Shape effects along the Z=82 line: study of the beta decay of $^{186,188}\text{Pb}$

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A. Algora, B. Rubio, J. L. Taín, E. Estevez, J. Agramunt, E. Valencia, C. Domingo, S. Origo

IFIC, University of Valencia, Valencia, Spain

A. Krasznahorkay, M. Csatos, Zs. Dombrádi, D. Sohler, J. Timár

Institute of Nuclear Research, Debrecen, Hungary

W. Gelletly

University of Surrey, Guildford, UK

P. Sarriguren, M. J. G. Borge, O. Tengblad, E. Nácher, A. Jungclaus

Instituto de Estructura de la Materia, CSIC, Madrid, Spain

L. M. Fraile, O. Moreno

Universidad Complutense de Madrid, Madrid, Spain

V. Fedosseev, B. A. Marsh

EN Department, CERN, Switzerland

D. Fedorov

Petersburg Nuclear Physics Institute, Gatchina, Russia

A. Frank

Instituto de Ciencias Nucleares, UNAM, Mexico

A. N. Andreyev

School of Engineering, University of the West of Scotland, UK

Baki Akkus, Yesim Oktem, Ela Ganioglu, Lidya Susam, R. Burcu Cakirli

Istanbul University, Science Faculty, Istanbul, Turkey

Spokesperson(s): A. Algora (algora@ific.uv.es), B. Rubio (rubio@ific.uv.es), W. Gelletly

(w.gelletly@surrey.ac.uk)



Abstract

This addendum to the IS440 proposal is aimed at the study of the beta decay of the neutron-deficient $^{186,188}\text{Pb}$ nuclei using two different techniques. First, we propose to determine the Gamow-Teller strength distribution in the decay of ^{186}Pb using the Total Absorption Spectrometer (TAS) “*Lucrecia*” as a continuation of our previous studies of IS440. Secondly, we propose to study the beta decay of $^{186,188}\text{Pb}$ nuclei using high-resolution techniques, which are necessary for the analysis of the TAS data. Theoretical results show that from measurements of the Gamow-Teller strength distribution the shapes of the ground states of the decaying Pb nuclei can be inferred. This study offers an independent way to study the phenomenon of shape co-existence in a region of particular interest.

Requested shifts: 19 shifts, (split into 2 runs over 2 years)

1. General motivation

Neutron-deficient Pb nuclei have been the subject of intensive experimental and theoretical research in recent years. The main reason for this interest is the existence in all the even-even Pb isotopes between $A=184$ and $A=194$ of at least one low-lying 0^+ excited state (below 1 MeV) which offers unique opportunities to study shape co-existence [1]. The cases that have attracted most interest recently are the $^{186,188}\text{Pb}$ nuclei where we even find two 0^+ excited states below 700 keV [2]. Theoretically, the existence of the low-lying excited 0^+ states has been interpreted as the result of the combined effect of the proton shell gap at $Z=82$ and the influence of a large number of neutron holes below $N=126$. The role of the magic proton number $Z=82$ is considered fundamental to the structure of these nuclei. All of them, down to ^{182}Pb , are believed to be spherical in their ground states (see for example [3]).

The co-existence of the low-lying excited 0^+ states has been studied in the framework of different models. In a shell model picture, the excited 0^+ states are interpreted as two-quasiparticle and four-quasiparticle configurations [4]. On the other hand model calculations based on phenomenological mean field models and the Strutinsky method predict the existence of several competing minima in the deformation surface of these nuclei [5,6]. Self-consistent mean field calculations [7,8] and calculations including correlations beyond the mean field [9-11] confirm these results. This phenomenon has also been studied in the framework of the interacting boson model [12].

From the perspective of beta decay it has been shown theoretically that the decay properties of unstable nuclei may depend on the shape of the decaying parent nucleus [13,14]. In particular cases the Gamow-Teller strength distribution shows different patterns depending on the shape of the parent nucleus [14]. This property can be used to determine the shape of the ground state of the decaying nucleus if a proper measurement of the Gamow-Teller strength distribution is available. Measurements performed at ISOLDE of the beta decay of the neutron deficient ^{74}Kr and $^{76,78}\text{Sr}$ nuclei using the total absorption spectrometer *Lucrecia* have shown the potential of this method [15,16,17].

In the vicinity of the $Z=82$ region, theoretical calculations [18,19] predict that as in the cases studied in [15,16,17], the Gamow-Teller strength distributions of the $^{184,186,188,190,192,194}\text{Pb}$ isotopes show clearly differing patterns depending on the assumed deformation of the parent state (see Fig.1). This feature can be used to study the shape co-existence phenomenon if the theoretical results are combined with precise measurements of the $B(\text{GT})$ in these nuclei. Precise measurements of the $B(\text{GT})$ in these nuclei are also important to test nuclear models further in the $Z=82$ region.

The theoretical study of [18] is based on a deformed Hartree-Fock mean field calculation, using an effective two-body Skyrme interaction and including pairing correlations in the BCS approximation. The single particle energies, wave functions, and occupation probabilities are generated from this mean field. Two forces were considered in this work: Sk3, the simplest and successful Skyrme interaction and the SG2 force, which is considered successful in the treatment of spin-isospin excitations in spherical and deformed nuclei. In the calculations time reversal and axial symmetry were assumed. For more details on the calculations we direct the reader to refs. [14,18].

One important result of [18] is that the different profiles of the $B(\text{GT})$ obtained for different deformations remain unchanged when the force and/or pairing are changed. This implies that the GT profile is characteristic of the shape and depends little on the details of the two-body forces used. The main difference between the calculations from Sk3 and SG2 is a small shift to lower excitation energies in the case of SG2.

This was the main motivation of the IS440 proposal. The experiment related to this proposal was performed in November 2008. In the run, the beta decays of the $^{188,190,192}\text{Pb}$ isotopes were studied using the TAS technique. The analysis of the $^{188,190,192}\text{Pb}$ decays is part of the thesis of M. E. Estevez, which should be defended in 2011 [20]. In all these cases the electron capture component of the decays was analysed, which was obtained by requiring coincidences of the measured TAS spectra with the characteristic K X-rays of the TI daughter nuclei. The X-rays were measured using a planar detector positioned inside the TAS. A preliminary analysis of the three decays ($^{188,190,192}\text{Pb}$) has been carried out and we are working to obtain an improved theoretical description of the decays using the model described in [18,19].

In the original IS440 proposal 15 shifts were requested, of which 7 were approved to show the feasibility of the study. From the seven shifts six were used in the 2008 experiment and one shift still remains to be used. The goal of this addendum is to continue this line of research with two complementary measurements to the IS440 proposal.

2. Addendum motivation: additional reasons to study the $^{186,188}\text{Pb}$ decays

The analysis of the beta decay of ^{192}Pb from our TAS experiment is presented in Figure 2. The strength distribution deduced from our analysis is compared with the theoretical predictions of [18] in Figure 3. Looking at the values of the total strength our preliminary results are consistent with the assumption of a spherical ground state shape for the ^{192}Pb decaying nucleus. The agreement of the detailed distributions (theory vs. experiment) is not so satisfactory if we compare this result with previous studies [15,16,17]. This issue is currently under study, and may be related to the spherical character of the present cases compared to the well deformed nature of the previously studied nuclei. It is worth mentioning that the theoretical calculations presented in Figure 3 have not been further refined and were taken from the published results in [18]. The calculations for this nucleus can be further improved, since some of the parameters used were not fully optimised because of the lack of experimental data. Similar results were obtained for the decay of ^{190}Pb [20].

The analysis of the TAS data requires solving the $\mathbf{d}=\mathbf{R}(\mathbf{B})\mathbf{f}$ inverse problem. In this equation \mathbf{d} represents the measured spectrum (free of contaminants), $\mathbf{R}(\mathbf{B})$ is the response matrix of the TAS detector, which depends on the branching ratios of the levels in the daughter nucleus (\mathbf{B}) and \mathbf{f} is the feeding distribution. To construct the branching ratio matrix \mathbf{B} the standard procedure is to use high-resolution results for the low-lying levels and to use a statistical model to construct the “unknown” or high-lying part. *One of the main motivations of this addendum is that the analysis of our TAS measurement for the ^{188}Pb decay requires a better knowledge of the levels populated in the daughter from high resolution studies. Presently there is a very poor knowledge of this decay, which makes our TAS analysis for this case more uncertain than for the $^{190,192}\text{Pb}$ cases: indeed only two states are known to be populated in the decay of ^{188}Pb from high resolution measurements, a (1+) state at 185 keV excitation and a (1+) state at 758 keV. Thus we propose to study the decay of ^{188}Pb using a high-resolution setup, to provide a better experimental input for the analysis of the ^{188}Pb TAS decay data and to improve our detailed knowledge of this decay in general.*

From the point of view of the shape-coexistence phenomenon the $^{186,188}\text{Pb}$ are very interesting nuclei. Both $^{186,188}\text{Pb}$ have three co-existing 0+ states at low excitation. They are expected to be spherical in their ground states but with an increasing role for mixing with decreasing neutron number. This phenomenon could be also studied by means of a TAS measurement from the comparison of the deduced B(GT) distribution with theory. *For that reason in this addendum we propose to study the beta decay of ^{186}Pb using both the TAS technique and the high-resolution technique since, to all intents and purpose, the beta decay of ^{186}Pb is unknown.*

Most of the information available on the shape co-existence phenomenon in neutron-deficient Pb nuclei has been obtained from measurements of the α -decay of Po isotopes [21] and in-beam measurements of high-spin states populated in fusion-evaporation reactions, see for example [22,23] and references therein. The method proposed in IS440 and in this addendum is an alternative way to study this phenomenon using β -decay as the source of information. Our studies can be considered an independent way to test the results of [21-24], and can provide new experimental results to test nuclear models in the region.

Confirmation of the spherical character of the ground state of the nuclei studied can serve as solid grounds for further studies of Hg, Po and Pt isotopes in the region [19] where deformation might play a stronger role.

3. Experimental techniques

For the study of the ^{186}Pb decay we plan to use the TAGS *Lucrecia*, installed at ISOLDE (CERN). It consists of a large NaI(Tl) crystal of cylindrical shape ($l=\varnothing=38$ cm) with a cylindrical hole perpendicular to the symmetry axis. The transverse hole allows us to take the activity to the centre of the crystal and it also makes possible the placement of ancillary detectors in close geometry to the sources. The total efficiency of the TAGS has been estimated, using Monte Carlo methods, to be $\sim 90\%$ for mono-energetic gamma rays of 300-3000 keV energy, which gives an approximate 99% total efficiency for gamma cascades.

We propose to use the ISOLDE RILIS resonance ionisation laser ion source [25] for the production of the sources in the same way as in IS440. The separated parent activity will be carried to the centre of the total absorption spectrometer *Lucrecia* by a tape transport system.

Since the calculation of the response function of *Lucrecia* requires a separate treatment of the EC and the β^+ processes, in the ^{186}Pb decay measurement we plan to use a Ge planar detector for the detection of the X-rays and a plastic detector to detect the β^+ particles. Coincidence requirements with these detectors will allow us to tag on the EC and the β^+ processes. Since in this case we will have daughter contamination and contaminations arising from the alpha decay of the parent nucleus, we will use the X-ray detector to isolate the final isotope we want to study. This, as mentioned before, will tag on the EC component only. However, since the EC/ β^+ ratio is a well-known function and the Q_{β^+} -values are well known in this region we can use this ratio to reconstruct the full GT strength. The analysis of the TAS data will be carried out using the methods developed by the Valencia group [26]. The application of these methods will allow one to determine the B(GT) in a reliable way up to the limit of the Q_{EC} as in the earlier cases studied [15,16]. The standard TAS setup

will be combined for the proposed measurements with a particle detector sandwich (E and dE-E detectors) to determine the beta-delayed proton emission probability in $^{186,188}\text{Pb}$ as well. The dE-E telescope will be positioned opposite to the planar detector and has an estimated efficiency of 20 %.

The high-resolution measurements will be performed at LA1/LA2 using a conventional setup composed of two or three Ge detectors in close geometry. A tape station or a windmill system will be used for these measurements depending on the availability of these systems.

Table 1. Relevant experimental data for the IS440 proposal and the present addendum: the half-life values and the EC branches are taken from the last ENSDF and XUNDL database compilations. S_p is the proton separation energy in the corresponding daughter nuclei. S_p and Q_{EC} are taken from Audi et al, Nucl. Phys. A729 (2003) 337.

Isotope	Half life	EC branch (%)	S_p (keV)	Q_{EC} (keV)	Status
^{186}Pb	4.82(3) s	60(8)	1303(185)	5509(185)	proposed
^{188}Pb	25.1(1) s	90.7(8)	1520(40)	4530(30)	to be completed
^{190}Pb	71(1) s	99.6(4)	1990(60)	3920(50)	done
^{192}Pb	3.5(1) min	99.9941(7)	2570(40)	3320(30)	done

4. Beam time request

The beam time request is based on the yields obtained during our measurement in 2008. For the production of the Pb isotopes we propose to use a UCx/graphite target with a W surface ionisation ion source. In order to obtain the Pb sources the use of the RILIS is required [25]. For the TAS measurement of the ^{186}Pb decay we request 6 shifts. Two additional shifts are requested to measure the daughter activity of this decay with the TAS. One shift is also requested for the on-line calibration of the TAS using the ^{24}Na source that should be produced during our experiment. The measurement of the beta delayed particle emission in ^{188}Pb with the TAS in combination with the dE-E telescope requires two additional shifts.

Two additional shifts are required to measure the beta decay of ^{188}Pb using a high-resolution setup, and 6 shifts are requested for the high-resolution measurement of ^{186}Pb . These

measurements are necessary for the analysis of the TAS data and will be performed separately. Accordingly:

- 6 shifts are required for the TAS measurement of the ^{186}Pb isotope (estimated to reach 400000 counts in the EC spectrum with a 3% Pb purity of the beam using RILIS).
- 2 shifts are required for the measurement of the daughter activities of ^{186}Pb (TAS).
- 2 shifts are required for the TAS measurement of the ^{188}Pb isotope (beta delayed p-emission in combination with the TAS).
- 1 shift is required for the on-line calibration using the ^{24}Na (TAS)
- 2 shifts are required for the ^{188}Pb high-resolution measurement.
- 6 shifts are required for the ^{186}Pb high-resolution measurement.

Total number of requested shifts: 19 including the remaining shift of the IS440 proposal

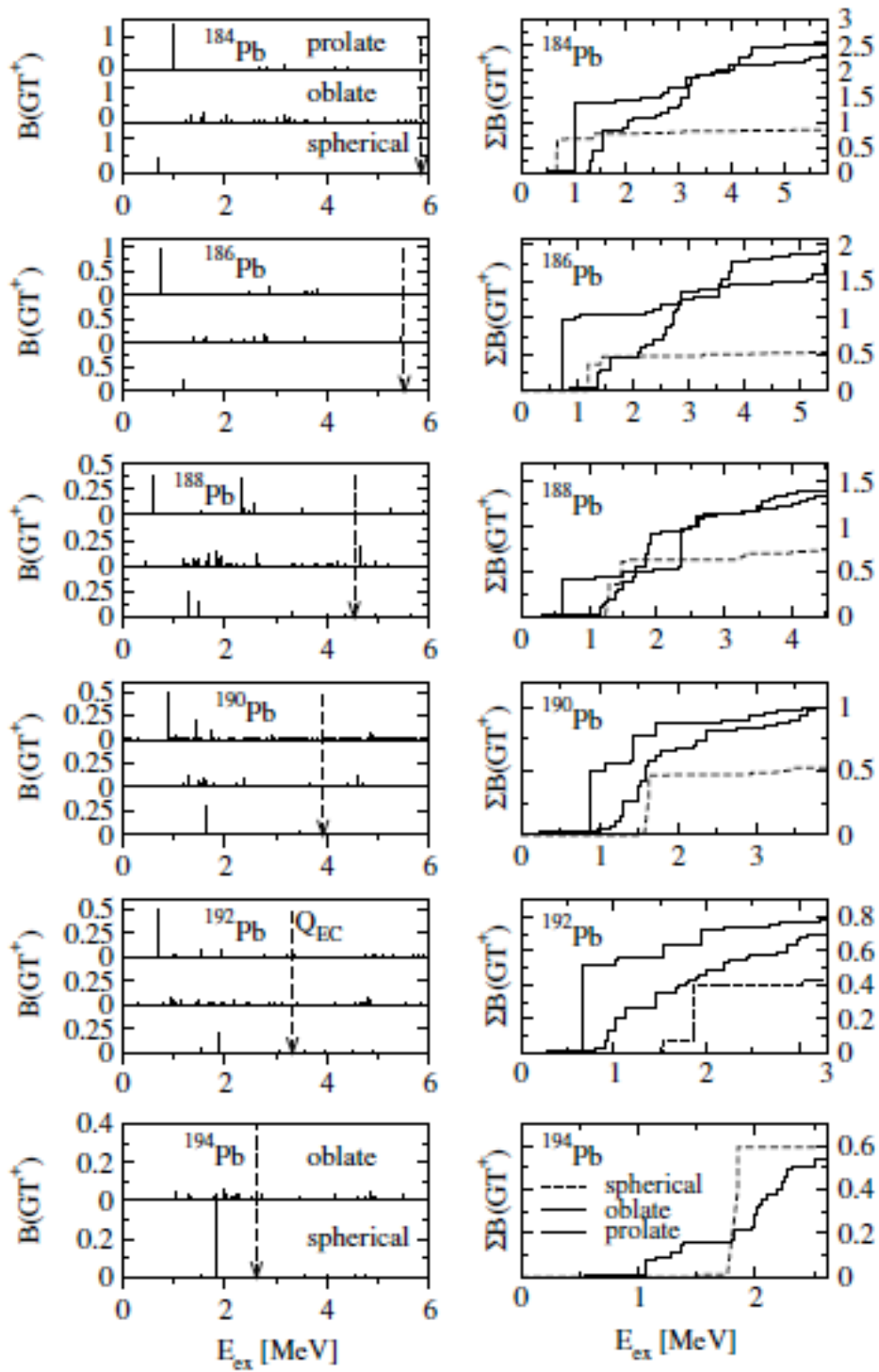


Fig. 1 Gamow-Teller strength distributions in the $^{184-194}\text{Pb}$ isotopes for spherical (left), oblate (middle) and prolate (right) shapes [19].

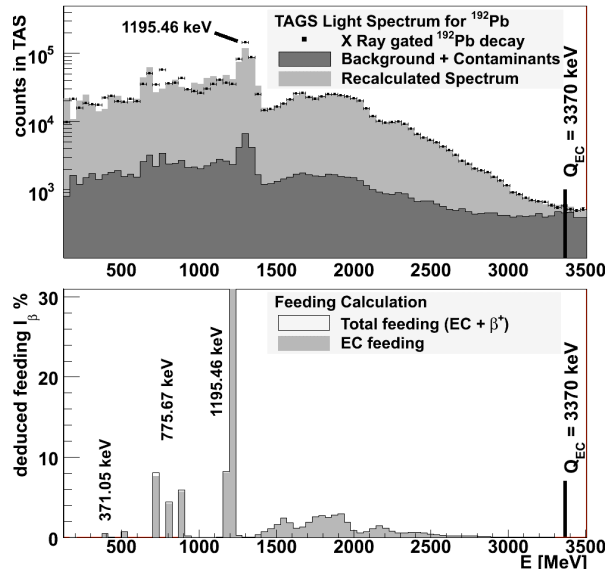


Fig. 2 Results from the preliminary analysis of the ^{192}Pb case [20]: the upper panel shows the comparison of the analysed spectrum with that obtained after the analysis. The lower panel shows the deduced feeding distribution.

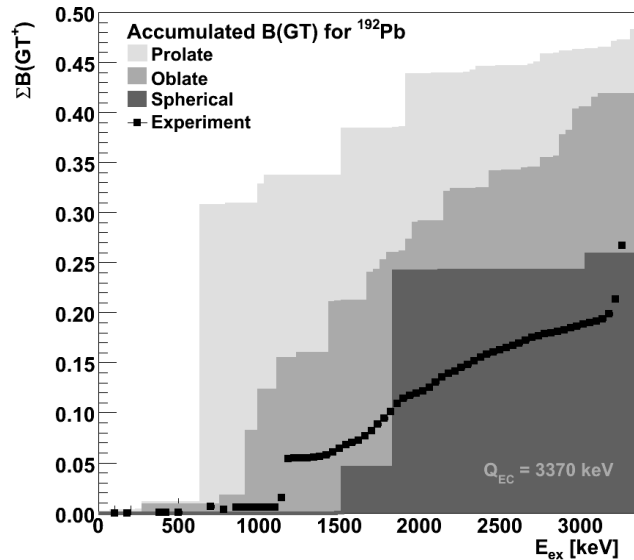


Fig. 3 Comparison of the accumulated experimental strength distribution in the decay of ^{192}Pb with the theoretical calculations of [18,20] assuming different ground state deformations in the ^{192}Pb parent nucleus.

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Appendix

DESCRIPTION OF THE PROPOSED EXPERIMENT

The experimental setup comprises: *(name the fixed-ISOLDE installations, as well as flexible elements of the experiment)*

Part of the Choose an item.	Availability	Design and manufacturing
TAS station and LA1/LA2	<input checked="" type="checkbox"/> Existing	<input type="checkbox"/> To be used without any modification
TAS station (new: combination with a new dE-E detector)	<input checked="" type="checkbox"/> Existing <input checked="" type="checkbox"/> New	<input type="checkbox"/> To be used without any modification <input checked="" type="checkbox"/> To be modified <input type="checkbox"/> Standard equipment supplied by a manufacturer <input checked="" type="checkbox"/> CERN/collaboration responsible for the design and/or manufacturing
High resolution setup at LA1/LA2	<input type="checkbox"/> Existing <input checked="" type="checkbox"/> New	<input type="checkbox"/> To be used without any modification <input type="checkbox"/> To be modified <input type="checkbox"/> Standard equipment supplied by a manufacturer <input checked="" type="checkbox"/> CERN/collaboration responsible for the design and/or manufacturing
[insert lines if needed]		

HAZARDS GENERATED BY THE EXPERIMENT

(if using fixed installation) Hazards named in the document relevant for the fixed [COLLAPS, CRIS, ISOLTRAP, MINIBALL + only CD, MINIBALL + T-REX, NICOLE, SSP-GLM chamber, SSP-GHM chamber, or WITCH] installation.

Additional hazards:

Hazards			
	[Part 1 of the experiment/equipment]	[Part 2 of the experiment/equipment]	[Part 3 of the experiment/equipment]
Thermodynamic and fluidic			
Pressure	Air [2-3 Bar]		
Vacuum	High vacuum	High vacuum	
Temperature	LN2 (77K)	LN2(77K)	
Heat transfer			
Thermal properties of materials			
Cryogenic fluid	LN2	LN2	
Electrical and electromagnetic			
Electricity	4.0 kV (Ge HV supply)	4.0kV (Ge HV supply)	
Static electricity			
Magnetic field			
Batteries			
Capacitors			
Ionizing radiation			
Target material	UCx/grafite ion source with W surface ionisation source with RILIS	UCx/grafite ion source with W surface ionisation source with RILIS	
Beam particle type (e, p, ions,	^{186}Pb (10^4), ^{188}Pb (10^5), ^{24}Na	^{186}Pb (10^4), ^{188}Pb (10^5)	

etc)	(4x10 ³)		
Beam intensity	¹⁸⁶ Pb (10 ⁴), ¹⁸⁸ Pb(10 ⁵), ²⁴ Na (4x10 ³)	¹⁸⁶ Pb (10 ⁴), ¹⁸⁸ Pb(10 ⁵)	
Beam energy	60 keV	60 keV	
Cooling liquids			
Gases			
Calibration sources:	<input checked="" type="checkbox"/>		
• Open source	<input type="checkbox"/>		
• Sealed source	<input checked="" type="checkbox"/> [ISO standard]		
• Isotope	¹⁵² Eu, ¹³³ Ba, ²² Na, ²⁴¹ Am	¹⁵² Eu, ¹³³ Ba, ²² Na, ²⁴¹ Am	
• Activity	10 kBq	10 kBq	
Use of activated material:			
• Description	<input type="checkbox"/>		
• Dose rate on contact and in 10 cm distance	[dose][mSV]		
• Isotope			
• Activity			
Non-ionizing radiation			
Laser	RILIS	RILIS	
UV light			
Microwaves (300MHz-30 GHz)			
Radiofrequency (1-300MHz)			
Chemical			
Toxic			
Harmful			
CMR (carcinogens, mutagens and substances toxic to reproduction)			
Corrosive			
Irritant			
Flammable			
Oxidizing			
Explosiveness			
Asphyxiant			
Dangerous for the environment			
Mechanical			
Physical impact or mechanical energy (moving parts)			
Mechanical properties (Sharp, rough, slippery)			
Vibration			
Vehicles and Means of Transport			
Noise			
Frequency			
Intensity			
Physical			
Confined spaces			
High workplaces			
Access to high workplaces			
Obstructions in passageways			
Manual handling			
Poor ergonomics			

0.1 Hazard identification

3.2 Average electrical power requirements (excluding fixed ISOLDE-installation mentioned above):
(make a rough estimate of the total power consumption of the additional equipment used in the experiment)

2.5 kW