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EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
Proposal to the ISOLDE and Neutron Time-of-Flight Committee

Spectroscopy of ^{8}Be: Search for Rotational Bands Above 16 MeV

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Abstract

Recent advances in nuclear theory allow the consideration of the spectrum of light nuclei at excitation energy as high as 20 MeV. In particular for Be isotopes, ab-initio no core shell model (NCSM) and the newly proposed cluster shell model (CSM) predict the occurrence of high lying rotational bands above 16 MeV. We propose to use ^{7}Be beams from HIE-ISOLDE to measure the d(^{7}Be,p) reaction at 12 MeV/u, detecting the protons with the ISOLDE Solenoidal Spectrometer (ISS) operating at 1.5 Tesla, to measure the spectroscopy of ^{8}Be around 22 MeV. We propose to measure the scattered protons in the backward angles, in coincidence with the decay product of the excited ^{8}Be* in the forward angles (^{7}Li, ^{7}Be or alpha-particle). Angular distributions of the observed protons will be measured for all possible states over the angular range of 10° - 40°, to elucidate spin parity of the excited states in ^{8}Be at 21.50 - 23.0 MeV. Specifically, we propose to measure the spin and parity of four states in ^{8}Be at 21.50, 22.05, 22.63 and at 22.98 MeV. The first one was originally listed in the TUNL(2004) A=8 compilation as a $J^{\pi} = 3^{(+)}$, but recent *R*-matrix analysis of existing data suggests a 3^{-} state. The other states are with unknown spin-parity, but one of the three states (most likely the 22.98 MeV) is predicted to be a 3^{+}. These two 3^{-} and 3^{+} states, if confirmed, will allow us to firmly identify the $K^{\pi} = 2^{-}$ and 1^{+} rotational bands predicted by the CSM, and in addition to the already observed $K^{\pi} = 2^{+}$ band, it will confirm the newly predicted particle-hole CSM structure in ^{8}Be.

Requested shifts: 15 shifts
Beamline: ISOLDE Solenoidal Spectrometer

Introduction

With the advent of nuclear theory, extensive calculations of light nuclei become possible. In particular, the nuclei ^{8}Be and ^{12}C are recognized as good testing grounds of ab-initio nuclear structure theories, such as the ab-initio no-core shell model (NCSM) calculation [1] and Quantum Monte Carlo theories [2]. On the other hand, ^{8}Be is perhaps the best example of alpha-clustering. As such the algebraic cluster model (ACM) of Bijker and Iachello [3] was recently developed and applied to light nuclei. This new cluster model considers geometrical symmetries of nuclear molecular configurations, and it predicts the most unusual ground state band in ^{12}C including the spin sequence of $J^{\pi} = 0^{+}, 2^{+}, 3^{-}, 4^{\pm}$ and 5^{-}, which was recently observed by the Birmingham-UConn collaboration [4], including the predicted parity doublet: 4^{-} at 13.35 and 4^{+} at 14.08 MeV in ^{12}C. Such rotational bands including parity doublets are commonly observed in molecules.

The ACM was recently extended by Della Rocca and Iachello to ^{9}Be and ^{9}B to describe single particle motion in the field of the two alpha-particles molecular configurations of ^{8}Be [5]. This cluster shell model (CSM) is an extension of the shell model to molecular configuration, much like the Nilsson model is an extension of the shell model to the deformed mean field of heavy nuclei. Furthermore, the rotational bands in ^{9}Be and ^{9}B are predicted by the CSM to be closely related to the g.s. band in ^{8}Be, as observed [5]. One important prediction of the CSM, is the occurrence of parity doublet, much like for octupole deformation in heavy nuclei [6,7]. In both models the intrinsic state is not reflection symmetric, hence parity is only preserved as a good quantum number in the lab frame, where the nucleus rotates.

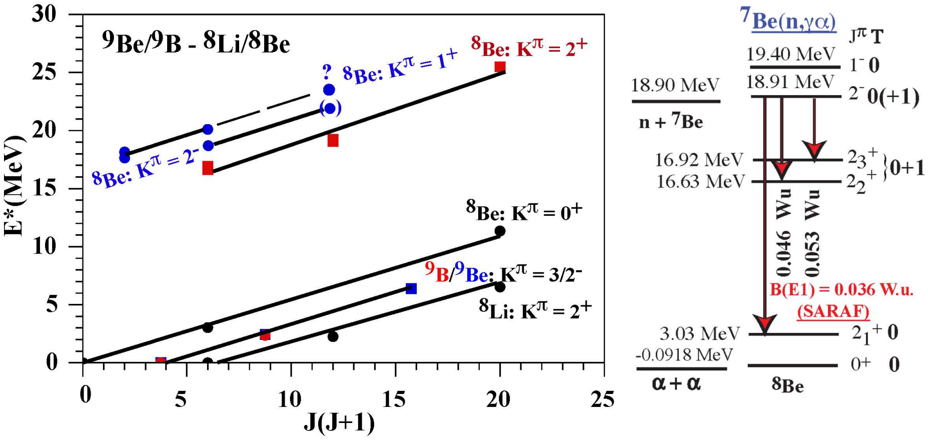

Fig 1: Left: the observed rotational bands in ^{8}Be [8], and the analog band in ^{8}Li, and the corresponding bands in ^{9}Be and ^{9}B. Right: the B(E1) (red) measured at the SARAF, Israel, in ^{8}Be [9,10].

We propose to test for the first time the phenomenology of CSM particle-hole (p-h) high lying states in ^{8}Be at energies above 16 MeV. It was shown by Gai [8] that all observed states below 19.5 MeV in ^{8}Be (T = 0 and 1: $2^{+}, 1^{+}, 2^{-}$ and 1^{-}), correspond to the predicted CSM p-h states. The recent SARAF measurement of the strong $B(E1: 2^{-} \rightarrow 2^{+}_{1}) = 0.039 \pm 0.013$ W.u. [9,10,11], is quite similar to the known ($\Delta T = 1$) $B(E1: 2^{-} \rightarrow 2^{+}_{2}) = 0.053 \pm 0.02$ W.u. and $B(E1: 2^{-} \rightarrow 2^{+}_{3}) = 0.046 \pm 0.02$ W.u. as shown in Fig. 1. The similarity of these strong B(E1)s suggests that the structure of the 2^{-}, 2^{+}_{2} and 2^{+}_{3}, states at 18.91, 16.626 and 16.922 MeV, respectively, is similar to the $\alpha + \alpha$ structure of the of 2^{+}_{1}, at 3.03 MeV in ^{8}Be. Since the CSM p-h states are deformed, they are predicted [5] to be the band head of rotational bands. Furthermore, these rotational bands above

16 MeV in ^{8}Be, are predicted to be closely related to the g.s. band in ^{8}Be with similar moment of inertia and B(Eλ)s. In this sense, the predictions of the CSM differ from the prediction of the ab-initio NCSM, where a search for high lying rotational bands in beryllium isotopes revealed high lying rotational bands in ^{10,12}Be, but not in ^{8}Be [1].

We propose a “complete" spectroscopic study of ^{8}Be at the high excitation of 21-23 MeV, in search for high lying rotational structure in ^{8}Be. Currently we already observe the $K^{\pi}=2^{+}$ band built on top of the iso-spin mixed 2^{+} states at 16.63 and 16.92 MeV in ^{8}Be [8]. Hints of the other $K^{\pi} = 2^{-}$ and 1^{+} rotational bands are also observed, as shown in Fig. 1. The moment of inertia of the CSM particle-hole bands is predicted to be similar to that of the g.s. band in ^{8}Be, as observed in Fig. 1, and the electromagnetic transitions are related by Clebsch Gordon coefficients, to the measured B(E2: $4^{+} \rightarrow 2^{+}$) in the g.s. bands of ^{8}Be (and ^{9}Be) [5].

<u>The goals of this measurement are:</u>
1) Confirm the negative parity of the J = 3 state at 21.50 MeV proposed in [12].
2) Measure the spin-parity of the (narrow) well resolved states at 22.2, 22.6 and 22.98 MeV.

A confirmation of the negative parity of the J = 3 state at 21.5 MeV, and a discovery of a 3^{+} state around 23 MeV in ^{8}Be, will allow us to firmly establish the newly predicted rotational structure of: $K^{\pi} = 2^{+}$, 1^{+} and 2^{-}, CSM particle-hole bands in ^{8}Be, as shown in Fig. 1.

Experimental Setup

We propose to use ^{7}Be from HIE-ISOLDE together with the ISOLDE Solenoidal Spectrometer (ISS) to measure the d(^{7}Be,p) reaction at 12 MeV/u. We intend to use the same setup that was already successfully used by the ISS collaboration, to measure the d(^{28,30}Mg,p)^{29,31}Mg [13], and d(^{206}Hg,p)^{207}Hg reactions [13], including the recoil detector placed at the forward angles. The 12 MeV/u ^{7}Be beam extracted from HIE-ISOLDE, we anticipate will be available after the LS2 [15] (due to the low A/Q of ^{7}Be). We assume a HIE-ISOLDE ^{7}Be beam intensity of 5 x 10^{6} pps [16,17], which will also preserve the 100 - 200 μg/cm^{2} deuterated polypropylene target [14].

A valid proton event will require a signal in the ISS hexagonal proton detector placed in the backward angles, in coincidence with the recoil detector placed in the forward angles. The recoil detector is a QQQ1 Micron Semiconductor Ltd, double sided 65 micron followed by 500 micron thick, E-ΔE detector. The QQQ1 strip detector is arranged in four quadrant circular geometry, with outer diameter of 10 cm and a 1.8 cm hole in the center, for beam passage. It will be placed at 18 cm downstream from the target and subtend the angular range of 2.9° - 15.5°. The area of the hole in the center amounts to only 3.2% of the total area, leading to a high efficiency for detecting charged particles that are emitted in the forward angles up to 15°. The recoil E-ΔE detector will be used to detect either an alpha-particle, ^{7}Li or ^{7}Be, from the decay of the high lying states in ^{8}Be. The beam intensity will be monitored using a separate detector that measures the recoil deuterons that are bent by the magnetic field around the recoil detector.

The ISS magnet will be operated at 1.5 Tesla and the resultant proton kinematics in the ISS is shown in Fig. 2. The low value of the magnetic field is required to assure measurements of angular distributions over the angular range of 10° - 40° for ^{8}Be* = 21 - 23, which is our region of interest. This angular range is the same as measured in the previous ISS experiment with ^{206}Hg beam 14].

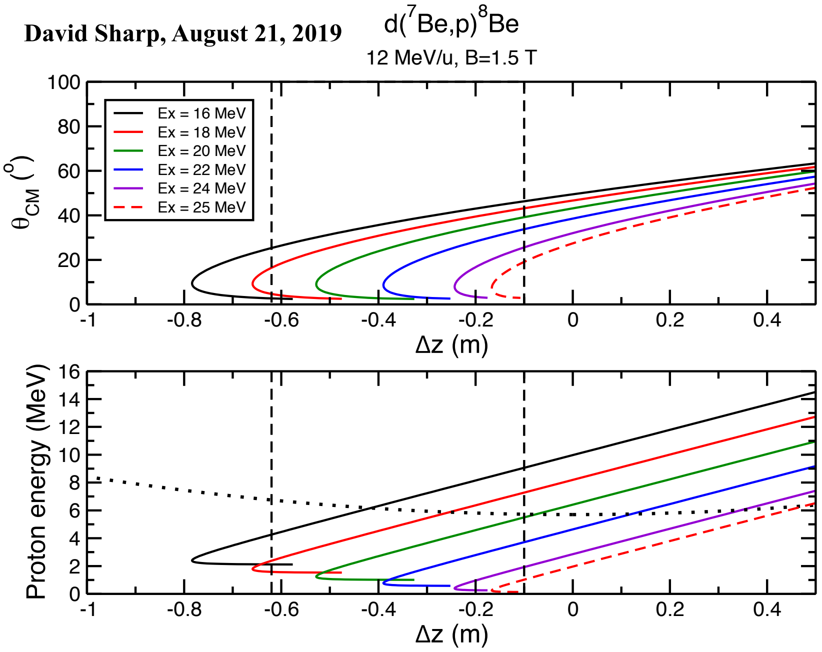

Fig 2: The kinematics of proton detection in the ISS leading to the measured center of mass angles of 10° to 40°.

For example, for 84 MeV ^{7}Be beam, at θ_{cm} = 30° we obtain for the d(^{7}Be,^{8}B*(22 MeV)) reaction, E_3[^{8}B*(22 MeV)] = 75.5 MeV, and θ_3[^{8}B*(22 MeV)] = 4.1°. The 75.5 ^{8}Be*(22 MeV) may decay to: 1) two alpha-particles confined to a cone with an opening angle of 33°, wrt to the recoiling ^{8}Be*(22 MeV). 2) To p + ^{7}Li with the protons confined to a cone of 42° and the ^{7}Li confined to a cone of < 5°. 3) To neutron + ^{7}Be, with similar kinematics as for p +^{7}Li.

The efficiency for detecting in the recoil detector, the ^{7}Li or ^{7}Be (confined to less than 10°), was evaluated using Monte Carlo simulation to be 84% and for the alpha particle it is considerably smaller, 28%, due to the limited angular range covered by the recoil detector. We note that the alpha-particle efficiency depends on the angular distribution of the emitted alpha-particles (which depends on the unknown spin of ^{8}Be* states). We expand our Monte Carlo simulation to include effects of the angular distribution of the emitted recoil particles. With this geometry, we will be able to tag with ^{7}Li or ^{7}Be with high efficiency (84%), all ^{8}Be*states of interest that decay to p+^{7}Li or n+^{7}Be.

Angular Distributions

Recent advances in Continuum Discretized Coupled-Channel (CDCC) calculations of transfer reactions into the continuum as applied for example to the ^{9}Li(d,p)^{10}Li reaction [18], will allow us to extract the l-transfer of the (d,p) reaction into levels above the proton and neutron thresholds. In Fig. 3 we show the angular distributions predicted for l = 1, 2 and 3 neutron (hole) transfer in the ^{7}Be(d,p) reaction, for a nominal state at 21.5 MeV in ^{8}Be. The top left panel corresponds to DWBA calculations and the top right to CDCC calculations, with two optical potentials, CH89 and Koning-Delaroche using Johnson-Soper potential for the d-7Be channel. The bottom panel compares DWBA and CDCC calculations.

The calculations shown in Fig. 3 allow us to determine the needed sensitivity to for example distinguish a 3^- state (l = 2) from a 3^+ state (l=3), which is predicted to be the most demanding case. The l = 2 transfer and l = 3 transfer exhibit slightly different slopes, and in order to distinguish them at the 5σ level, we need to measure each of the data point (at 10° - 40°) with better than 5% precision, hence at least 400 counts per measured angle, considerably less than the design goal sensitivity of our proposed measurement, which is discussed below. The preliminary CDCC calculations presented in Fig. 3 are being improved, by for example using three body wave function (calculated by Dr. Casal). The calculations will be fine-tuned ("calibrated") by measuring the angular distributions of the known states in ^{8}Be, shown in Fig. 4.

Mario Gomez-Ramos, Septemebr 21, 2020

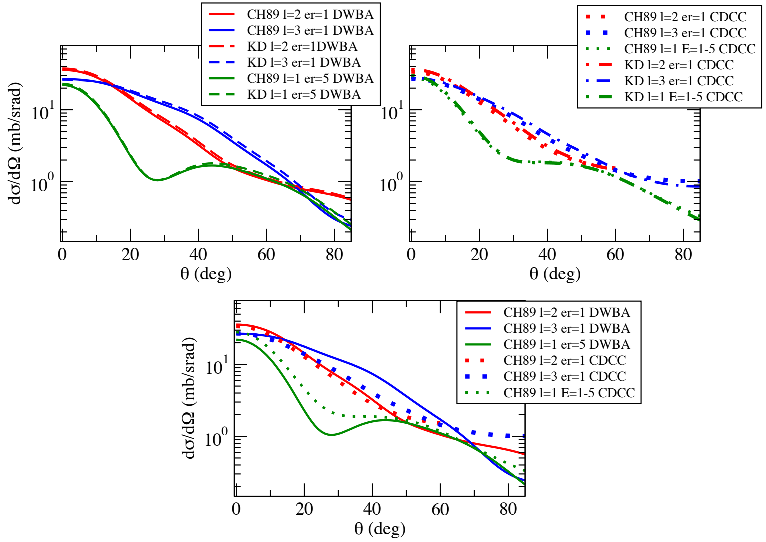

Fig. 3: DWBA (top) and CDCC (bottom) calculations for l = 1 (green), 2 (red) and 3 (grey) neutron (hole) transfer in the ^{7}Be(d,p) reaction, for a nominal state at 21.5 MeV, as discussed in the text.

Liam Gaffney, September 21, 2020

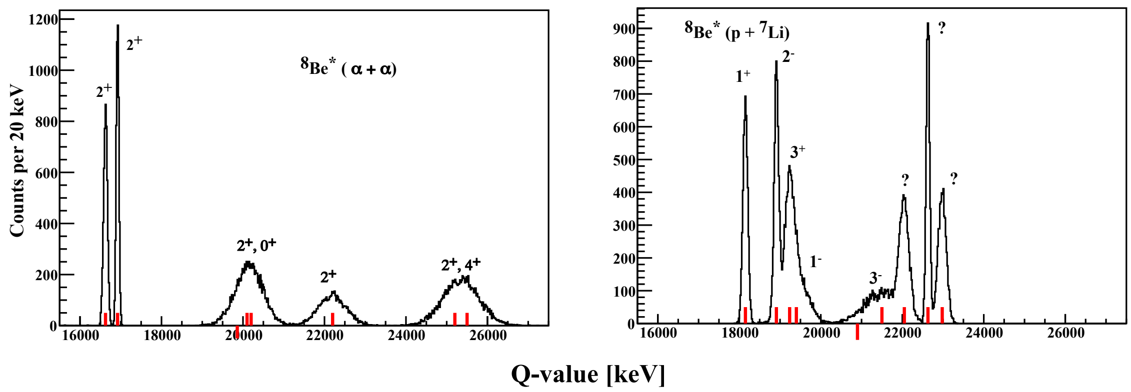

Fig. 4: Simulated proton spectra in coincidence with alpha-particle (left) and ^{7}Li (right).

In Fig. 5 we show a portion of the simulated ISS proton spectrum, measured in coincidence with the ^{7}Li decay product that are detected in the recoil detector. The ISS resolution has been ignored, since it is considerably smaller than the natural width of the shown states. T=1 isobaric analog states in ^{8}Be and states without known neutron width, cannot be populated by the ^{7}Be(d,p) reaction, and are not included in Fig. 4 (they are shown in Fig. 4 with downward red tick mark). In this simulation each known state contributes 5,000 counts, and we show in Fig. 5 the result of six

Gaussian fits of the known states to the simulated spectrum. The narrow states with known spin-parity will be used to calibrate the silicon detector in the ISS, as well as to fine tune ("calibrate") the DWBA and CCDC calculations.

Due to Boson symmetry only the $J^\pi = 0^+$, 2^+ and 4^+ can decay to $\alpha + \alpha$, as shown in Fig. 4. The large difference of for example, 17.3469 MeV between the Q-values for $\alpha + \alpha$ decay and the p + ^{7}Li decay, leads to large differences of the penetrabilities, hence the $J^\pi = 0^+$, 2^+ and 4^+ states are expected to preferentially decay to two alpha-particles. Indeed the 2^+ state at 20.1 MeV is listed with branching ratio for proton decay of only 18%.

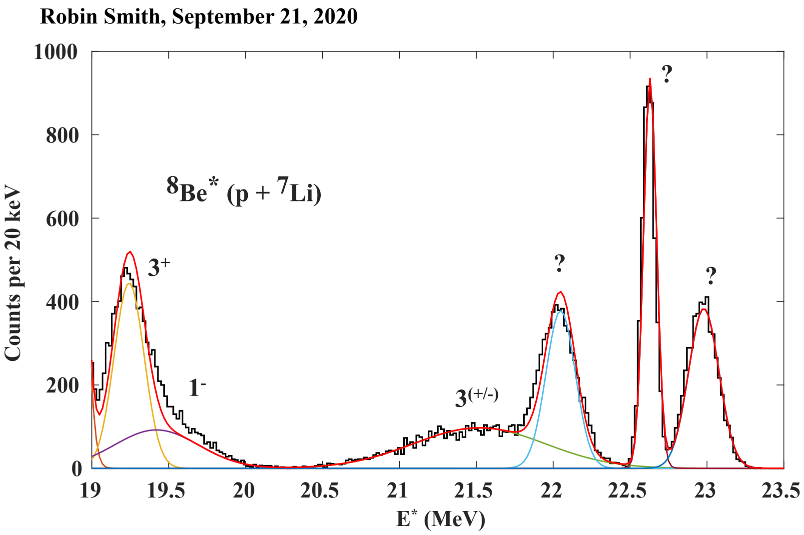

Fig. 5: Simulated proton spectrum (from $E^* = 19 – 23.5$ MeV states in ^{8}Be) in coincidence with ^{7}Li, with 5,000 counts per state and the obtained six Gaussian fits. The states of interest are at 21.5, 22.2, 22.6 and 22.98 MeV.

Design Goal

In an angular distribution measured over $\theta_{cm} = 10° - 40°$, of the d(^{7}Be,p) reaction at 12 MeV/u, for a nominal state at 22 MeV, the protons are emitted with 4.5 - 1.4 MeV, at angles of 90° - 138°, respectively, as shown in Fig. 2. Hence the protons are detected with a solid angle of 4.66 Sr. We assume a cross section over that angular range $d\sigma/d\Omega \sim 1$ mb/Sr (at the lower end of the predicted cross section shown in Fig. 3), hence $d\sigma = 4.66$ mb. As discussed before, the recoil efficiency for detecting ^{7}Li is quite large (84%). A $(CD_2)_n$ target with areal density of 100-200 μg/cm^2 ($\Delta E \sim$ 100 keV), and 5 x 10^6 pps ^{7}Be beam extracted from the HIE-ISOLDE, leads to the luminosity of 5.6 x 10^{25} /sec/cm^2, hence a day long integrated luminosity of 4.9 μb^{-1}. The cross section of 4.66 mb leads to 22,647 counts per day for each state. The design goal of collecting 100,000 protons per state, will be achieved in 5 days, hence 15 shifts.

Summary of requested shifts:

Requesting 15 shifts in one continuous measurement, with 12 MeV/u ^{7}Be beam, and intensity of 5 Mpps, from HIE-ISOLDE, delivered to the ISS beam line.

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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
ISOLDE Solenoidal Spectrometer	☒ Existing	☒ To be used without any modification
[Part 1 of experiment/ equipment]	☐ Existing	☐ To be used without any modification ☐ To be modified
	☐ New	☐ Standard equipment supplied by a manufacturer ☐ CERN/collaboration responsible for the design and/or manufacturing
[Part 2 experiment/ equipment]	☐ Existing	☐ To be used without any modification ☐ To be modified
	☐ New	☐ Standard equipment supplied by a manufacturer ☐ 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 [MINIBALL + only CD, MINIBALL + T-REX] 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	[pressure][Bar], [volume][l]		
Vacuum			
Temperature	[temperature] [K]		
Heat transfer			
Thermal properties of materials			
Cryogenic fluid	[fluid], [pressure][Bar], [volume][l]		
Electrical and electromagnetic			
Electricity	[voltage] [V], [current][A]		
Static electricity			
Magnetic field	1.5 T		
Batteries	☐		
Capacitors	☐		
Ionizing radiation			
Target material	Deuterated polyethylene (100-200 μg/cm^2)		
Beam particle type (e, p, ions, etc)	^{7}Be		
Beam intensity	5 E+6 pps		
Beam energy	12 MeV/u		
Cooling liquids	[liquid]		
Gases	[gas]		
Calibration sources:	☒		

• Open source	☒ α-calibration sources 4236 RP		
• Sealed source	☐ [ISO standard]		
• Isotope	^{148}Gd, ^{239}Pu, ^{241}Am, ^{244}Cm		
• Activity	1 kBq, 1 kBq, 1 kBq, 1 kBq, 4 kBq		
Use of activated material:			
• Description			
• Dose rate on contact and in 10 cm distance	[dose][mSV]		
• Isotope			
• Activity			

Non-ionizing radiation

Laser			
UV light			
Microwaves (300MHz-30 GHz)			
Radiofrequency (1-300MHz)			

Chemical

Toxic	[chemical agent], [quantity]		
Harmful	[chemical agent], [quantity]		
CMR (carcinogens, mutagens and substances toxic to reproduction)	[chemical agent], [quantity]		
Corrosive	[chemical agent], [quantity]		
Irritant	[chemical agent], [quantity]		
Flammable	[chemical agent], [quantity]		
Oxidizing	[chemical agent], [quantity]		
Explosiveness	[chemical agent], [quantity]		
Asphyxiant	[chemical agent], [quantity]		
Dangerous for the environment	[chemical agent], [quantity]		

Mechanical

Physical impact or mechanical energy (moving parts)	[location]		
Mechanical properties (Sharp, rough, slippery)	[location]		
Vibration	[location]		
Vehicles and Means of Transport	[location]		

Noise

Frequency	[frequency],[Hz]		
Intensity			

Physical

Confined spaces	[location]		
High workplaces	[location]		
Access to high workplaces	[location]		
Obstructions in passageways	[location]		
Manual handling	[location]		
Poor ergonomics	[location]		