Properties of the one-phonon MSS in ^{140}Ba from an α-transfer reaction

G. Rainovski[a], J. Leske[b], C. Bauer[b], L. Coquard[b], A. Damyanova[a], M. Danchev[a], K. Gladnishki[a], I. Kojouharov[c], Th. Kroell[b], N. Pietralla[b], S.Pietri[c], H. Schaffner[c]

[a] University of Sofia, BG-1164, Sofia, Bulgaria
[b] TU Darmstadt, D-64289, Darmstadt, Germany
[c] Gesellschaft für Schwerionenforschung, D-64220, Darmstadt, Germany

1 Introduction

Atomic nuclei are examples of mesoscopic two-fluid quantum systems. The physics of these systems is determined by three main properties: the many-body aspect, the quantum nature, and the two-fluid character. Nuclear phenomena that reflect these three properties are collectivity, shell structure, and the isospin degrees of freedom. The Quadrupole-collective isovector valence-shell excitations, so-called mixed-symmetry states (MSSs) [1, 2], represent a unique quantum laboratory in which the balance and interplay between the nuclear collectivity, the shell structures, and the isospin degree of freedom can be studied. A special type of MSSs, the 1^+ scissors mode, was first discovered in nuclei in electron scattering experiments at the TU Darmstadt [3] and subsequently found or suggested to exist in Bose-Einstein condensates [4] and metallic clusters [5]. In this respect, the impact of a deeper understanding of the structure of these states is beyond the field of nuclear structure physics. **The main aim of the present proposal is to identify the one-phonon MSS in the unstable N=84 nucleus ^{140}Ba on the solid ground of measured absolute M1 transition rates.**

States with proton-neutron mixed symmetry have been defined [1] in the framework of the interacting boson model with proton-neutron degree of freedom (IBM-2). The structure and the characteristics of these states are determined by the effective p-n correlations in the valence shell of collective nuclei. Their excitation energies are directly related to the proton-neutron symmetry energy in the valence shell. This fact is obvious in the IBM where the excitation energies of MSSs determine the parameters of the Majorana interaction to which p-n symmetric states are insensitive [1, 2].

The concept of proton-neutron mixed symmetry is formalized by the F-spin quantum number [7], which is the isospin analogue for bosons. Within this concept the fully symmetric states have $F = F_{max} = (N_\pi + N_\nu)/2$ ($N_{\pi,\nu}$ denote the proton/neutron boson numbers), while MSSs are those states with $F = F_{max} - 1$[7]. In other words, the F-spin quantum number counts the number of protons and neutrons pairs which are in phase in the quantum state. The IBM-2 states with maximum F-spin quantum number are called Full Symmetry States (FSSs). The F-spin is an approximate quantum number for low-lying collective states of heavy nuclei. The lowest states in a given nucleus are those formed by the FSSs. The M1 transitions between these states are forbidden and indeed they are observed to be small on an absolute, single-particle scale. With little modifications due to symmetry restrictions, the MSSs in the IBM-2 repeat the multiplet structure observed for the FSSs albeit at higher energy and with different decay properties. The energy difference between the FS and MS states with the same phonon number is determined by the size of the Majorana interaction in the IBM-2 [1]. The most distinct feature of MSSs (those with $F = F_{max} - 1$) is the existence of allowed F-vector ($\Delta F = 1$) M1 transitions to FSSs. This is of importance because the M1 transitions are forbidden between FSSs and can, thus, very well serve as a unique signature for MSSs.

The fundamental MSS in weakly collective vibrational nuclei, is the one-quadrupole phonon $2^+_{1,ms}$ state [1] which is the lowest-energy isovector quadrupole excitation in the valence shell. Its close relation to the 2^+_1 state is evident in the Q-phonon scheme for MSSs [9], where the wave functions of the one-quadrupole phonon excitations are well approximated by the expressions:

$$|2^+_1\rangle \propto [Q_\pi + Q\nu]|0^+_1\rangle \equiv Q_S|0^+_1\rangle \qquad F = F_{max}$$
$$|2^+_{1,ms}\rangle \propto [(Q_\pi/N_\pi) - (Q\nu/N_\pi)]|0^+_1\rangle \equiv Q_m|0^+_1\rangle \qquad F = F_{max} - 1$$

where $Q_{\pi,\nu}$ denote the proton and neutron quadrupole operators and $|0^+_1\rangle$ is the ground state of a collective even-even nucleus. Within the framework of this model the following signature for one-phonon MSSs in vibrational nuclei can be expected:

- The one-phonon $2^+_{1,ms}$ state should be the lowest-lying MSS.
- The $2^+_{1,ms}$ state should decay to the 2^+_1 by a strong M1 transition with an absolute matrix element of about 1 μ_N.
- Since the $2^+_{1,ms}$ state is a one-phonon excitation it should have collective E2 matrix elements to the ground state for both, protons and neutrons, however, with opposite signs, which might lead to partial cancellation in the total $\langle 0^+\|E2\|2^+_{1,ms}\rangle$ matrix element. Thus, a small-to-weakly-collective ($\leq$ a few W.u.) E2 transition from the $2^+_{1,ms}$ state to the ground state can be expected.
- All MSSs must be expected to be very short lived, typically a few hundred femtoseconds or less, because of the strong M1 matrix elements and typical transition energies ≈ 1 MeV in vibrational nuclei.

From the above fingerprints its is obvious that the MSSs can be identified experimentally by their unique decay to the low-lying FSSs [1, 9]. This however, comprises a major experimental challenge because it requires full spectroscopic information, i.e. the spin-parities of these highly excited non-yrast states, their lifetimes and the branching and multipole mixing ratios of their γ-decay have to be determined. For more detailed insight in the structure of these states, information on their magnetic moments is also necessary. Until recently obtaining all this information was possible for a hand-full of stable nuclei only. **No MSSs have ever been solidly identified in unstable nuclei on the basis of large absolute M1 transition rates.**

2 Physics case – MSSs in the mass A≈130-140 region

Despite their important role for understanding the effective proton-neutron interaction in collective valence shell excitations the experimental information on MSSs is relatively scarce. Available information on MSSs of vibrational nuclei has recently been summarized in a review article [9]. Due to the experimental challenges, MSSs have been observed so far in stable nuclei only. The best examples are found in the mass A≈90 regions [9, 10, 11, 12, 13, 14, 15, 16, 17]. Until recently only a few cases have been known in mass A≈130-140 region [18, 19, 20, 21, 22]. In the last few years, however a tremendous progress on the study of MSSs in mass A≈130 region has been made. Using Coulomb excitation reactions MSSs have been identified in several low-abundant stable nuclei, namely ^{138}Ce [23], ^{136}Ce [24], ^{134}Xe [25] and ^{132}Xe [26]. This extensive experimental information reveals several interesting physics phenomena. It has been shown [23] that in contrast to the neighboring even-even isotone ^{136}Ba, the $2^+_{1,ms}$ state in ^{138}Ce is strongly mixed with a nearby 2^+ fully symmetric state with a mixing matrix element of $V_{mix} = 44(3) keV$ first measured directly for a MSS. This experimental observation led to the hypothesis that the microscopic structure can have a dramatic influence on the properties of these states. In fact, for low-collective vibrational nuclei the single-particle structure of the wave functions can be the most important factor for preserving or fragmenting the MSSs. The observed mixing in ^{138}Ce is attributed to the lack of **shell stabilization** at the proton $1g_{7/2}$ subshell closure. The evolution of the MSSs from ^{136}Ba to ^{138}Ce shows for the first time that the strength concentration of collective-isovector excitations in the valence shell reflects the underlying single-particle structure. This hypothesis was partially confirmed experimentally by observing a fragmented one-phonon MS state in ^{136}Ce [24] and a single isolated MSS in ^{134}Xe [25]. These experimental facts have inspired an extended microscopic calculations of the structures of the MSSs of the N=80 isotones [27] within the framework of the quasiparticle-phonon model [28]. The QPM calculations demonstrate that a simultaneous description of the properties of the MSSs in the N = 80 isotonic chain, including the fragmentation of the one-phonon MSS in ^{138}Ce, can be achieved by slight increase of the energy of the $\pi 2d_{5/2}$ orbital with respect to the $\pi 1g_{7/2}$ orbital. This correction weakens the effect of pairing showing that the shell stabilization is a genuine shell effect [27]. Furthermore the evolution of the MSSs in the N = 80 isotonic chain allows the relative proton-neutron interaction to be derived [25] for first time form the properties of both symmetric and mixed-symmetry states in a simple semi-empirical way as suggested in Ref [29].

Besides the insight in the nature of the MSSs the new physics effects, observed in the N = 80 isotopic chain, also rise some new questions. The generic nature of the shell stabilization mechanism is not apparent. In the N = 80 isotones the proton excitations are realized in the space above Z = 50 (mostly in the $1g_{7/2}$ and $2d_{5/2}$ orbitals) and have particle nature. On the other hand the available neutron space is much smaller; the Fermi level for neutrons is just on the top on the $\nu 1h_{11/2}$ orbital making the neutron excitations hole-like with respect to the N = 82 shell closure. Hence, the collective excitations in N = 80 isotopes have mostly proton particle-like character while the neutrons form a constant contribution. The easiest way to check whether the effect of shell stabilization manifests itself in a similar way under different conditions is to study the properties of MSSs in the N = 84 isotopes. For these nuclei both proton and neutron excitations are particle-like and develop in configuration spaces with similar sizes. Candidates for MSSs of ^{140}Ba, ^{142}Ce and ^{144}Nd vibrational nuclei have been first suggested by Hamilton et al. [30] based on the small E2/M1 multipole mixing ratios. Later on, this unsafe assignment was confirmed in the cases of ^{142}Ce and ^{144}Nd on the basis of Coulomb excitation [31] and lifetime (DSAM-NIS) measurements [32]. This measurements show that the 2_3^+ state of ^{142}Ce at 2004.9 keV, initially suggested by Hamilton et al. [30] as the $2_{1,ms}^+$, decays by a strong M1 transition of $0.23(2)\mu_N^2$ to the 2_1^+ state and by a weakly collective E2 transition of 2.5(2) W.u. to the ground state. However, those experiments also showed the existence of another short-lived 2^+ state of ^{142}Ce at excitation energy of 2365 keV. This state, which is the 2_4^+ state of ^{142}Ce, behaves similarly to the 2_3^+ state and also exhibits the signatures for the $2_{1,ms}^+$ state – it decays by a strong M1 transition of $0.36(5)\mu_N^2$ to the 2_1^+ state and by a weakly collective E2 transition of 2.6(4) W.u. to the ground state [32]. This finding has been interpreted [32] as a fragmentation of the $2_{1,ms}^+$ state over these two close-lying experimental $2_{3,4}^+$ states, a situation quite similar to the ^{138}Ce [23]. It has to be noted, however that the total M1 strength in ^{142}Ce is about three times larger than M1 strength in ^{138}Ce [23]. In the case of ^{142}Ce the mixing calculations, suggested in Ref. [23], result in a mixing matrix element of $V_{mix} = 177(46) keV$, again about three times larger than the one deduced in the case of ^{138}Ce [23]. The situation in ^{144}Nd is similar: the $2_{1,ms}^+$ is fragmented over two close-lying $2_{3,4}^+$ experimental states at 2072 keV and 2369 keV, respectively. These two states decay by strong M1 transitions to the 2_1^+ state but in this case the mixing matrix is only 70(27) keV.

There are several nuclei from the N = 80 and 82 isotonic chains for which the experimental data on MSSs allow estimations of the mixing-matrix elements between fully-symmetric and mixed-symmetry states. This information is summarized in Fig. 1. Even though the data suggest some increase in the mixing-matrix element at Z = 58, which corresponds to the $\pi 1g_{7/2}$ sub-shell closure, no definitive conclusion which confirms or rejects the mechanism of shell stabilization can be made. This is due primarily to the lack of experimental data for MSSs in ^{140}Ba and ^{140}Nd. In ^{140}Ba the 2_3^+ state is suggested as the $2_{1,ms}^+$ [30]. As we already mentioned this assignment is based only on the small multipole mixing ratio of the $2_3^+ \rightarrow 2_1^+$ transition [30]. The crucial experimental information, namely the lifetime of this level is still missing. This information will allow for extraction of the absolute M1 transition strength, which provides the basis for a safe identification of MSSs. Furthermore, it is important to check whether the MSS in ^{140}Ba is fragmented like the MSSs in ^{142}Ce and ^{144}Nd, or it is a single isolated state like the MSS in ^{136}Ba. In the former case it is also important to check whether the resulting mixing-matrix element indicates the presents of the shell stabilization effect (see Fig. 1).

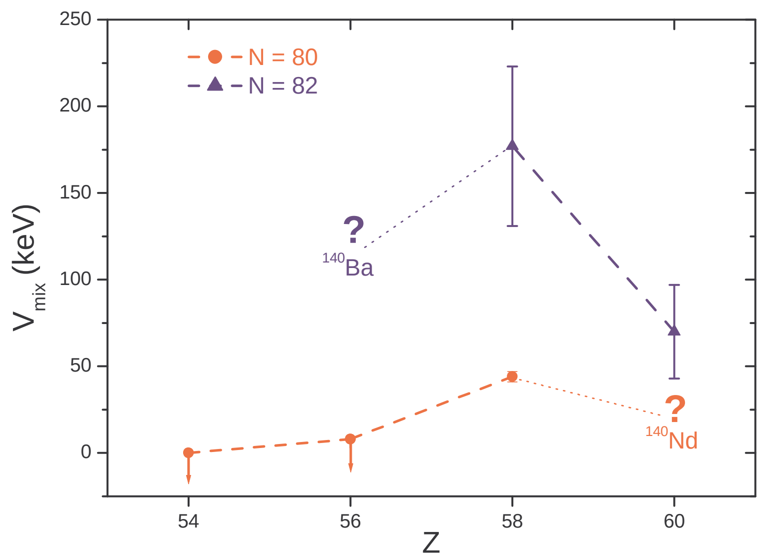

Figure 1: *Evolution of the mixing-matrix elements between fully symmetric and mixed symmetry states in the N = 80 and 82 isotopic chains. The experimental data are taken from Ref. [9]. In the case ^{134}Xe a vanishing mixing-matrix element is assumed because no fragmentation of the $2^+_{1,ms}$ is observed [25]. The dashed lines are drawn to guide the eye. The dotted lines represent the expected behavior if the mechanism of shell stabilization is present.*

Another important piece of experimental information is related to the magnetic moments of one-phonon symmetric and mixed-symmetry states. These magnetic moments are sensitive to the proton and neutron contributions to the structure of the one-phonon states. It has been shown [33] that a well isolated mixed-symmetry state can be expected when the proton and neutron excitations contribute equally to the total structure of MSSs. The unbalanced proton-neutron content in the structure of the one-phonon states of the N = 80 implies breaking of the F-spin [11] due to the fact that neutron excitations are hole like and can develop in a relative small configuration space compared to the proton configuration space. In contrast, the sizes of the proton and the neutron configurations spaces for the N = 82 isotones are comparable. Therefore, it can be expected that the F-spin is a good quantum number for these nuclei. This leads to enhanced M1 transition strength and to small and equal magnetic moments of one-phonon symmetric and mixed-symmetry states. This hypothesis can well be tested in the case of ^{140}Ba if the lifetime measurements are combined with extraction of the magnetic moments.

In general, the neutron rich even-even Ba isotopes exhibit a trend to stronger quadrupol deformation and increasing collectivity with increasing neutron number which is also reflected in increasing $B(E2; 0_1^+ \rightarrow 2_1^+)$ values from Monte-Carlo shell model calculations [38]. Since information on the detailed composition of the 2_1^+ wavefunction in the Ba isotopes is expected to elucidate the mystery of the anomalous behaviour of the E2 transition probabilities in neutron deficient even-A Sn isotopes and ^{136}Te in particular the measurement of the unknown $g(2_1^+)$ factor in ^{140}Ba will be of importance for the investigation of the N=80 isotopes in this mass region. For the even-A Ba isotopes with A larger than 144 the shell model calculation suggests a more or less constant behaviour of the magnetic moments and therefore the domination of collective degrees of freedom. Between N = 80 and N = 90 the proximity to the magic N = 82 shell closure is leading to a stronger influence of single particle configurations. In semi-magic ^{138}Ba the wavefunction is dominated by positive $g_{7/2}$ proton components while in ^{140}Ba the influence of $f_{7/2}$ neutron configurations with their corresponding Schmidt value of $\nu g_{Schmidt}$ = - 0.547 will significantly lower the corresponding $g(2_1^+)$ factor (see fig. 2).

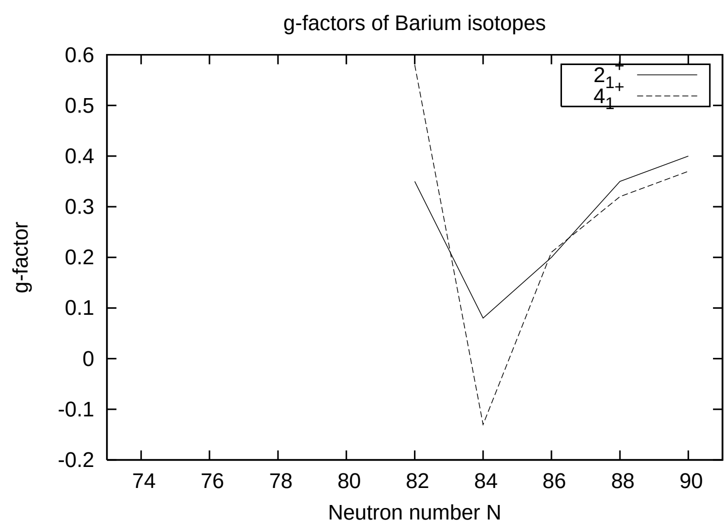

Figure 2: *Monte-Carlo shell model predictions for the magnetic moments of the first 2^+ and 4^+ states in even-A Ba isotopes (taken from [38])*

Finally, it has to be noted that to study further the properties of MSSs in vibrational nuclei, such states have to be identified in unstable radioactive nuclei. No MSSs have ever been unambiguously identified in unstable nuclei on the basis of large absolute M1 transition rates. The main reason for this comes from the fact that the determination of the lifetimes of these highly excited, off-yrast states comprises a real experimental challenge. In this respect, developing new methods for population of MSSs, in particular, those that could potentially be applied to radioactive isotopes, is extremely important. Recently, it has been shown [34] that α-transfer reactions may be an efficient way to populate MSSs, in particular in spherical nuclei. In Ref. [34] analytical expressions for α-transfer cross-sections have been derived for the SU(3) and U(5) dynamical limits of IBM. It turned up that the α-transfer intensities to the zero-, one- and two-phonon states depend in a unique way on the total boson number. This opens the possibility to identify MSSs by measuring the population cross-sections of excited states in α-transfer reactions. The ^{12}C(^{136}Xe,2α)^{140}Ba reaction has been considerd as the most favorable case for testing these predictions [34]. Note that this is the same reaction we are proposing. The one-phonon MSS in ^{140}Ba will be identified on the basis of lifetime measurements but simultaneously we will be able to deduce the α-transfer intensities to the excited states in ^{140}Ba which will allow to check whether and to what extent the α-transfer cross-sections can be used as a new signature for the assignment of mixed-symmetry character to particular excited nuclear state.

3 Expected results

The excited states of ^{140}Ba will be populated in the α-transfer reaction ^{12}C(^{136}Xe,2α)^{140}Ba. The α-transfer intensities to the excited states in ^{140}Ba will be measured. The lifetimes and the magnetic moments of the excited states in ^{140}Ba will be determined by a DSA method and Transient Magnetic Fields (TF) method. This experimental information will allow to:

- Identify the one-phonon mixed-symmetry state in ^{140}Ba on the solid ground of measured absolute M1 transition rates;
- Check whether the mechanism of shell stabilization manifests for the N = 82 isotones;
- Reveal to what extent the balance between proton and neutron excitations influences the properties of the MSSs;
- Check whether the α-transfer cross-sections can be used as a new signature for the assignment of mixed-symmetry character to particular excited nuclear state;

4 Experimental method

We propose to apply the well established technique of Transient Magnetic Fields (TF) in inverse kinematics [36] for the measurement of the magnetic moments of the 2_1^+ and, if possible, the $2_{1,ms}^+$ states in ^{140}Ba. The slowing down of the excited ions in the rather thick targets of about 10 mg/cm^2 required by this technique will allow to deduce the lifetimes simultaneously, using the Doppler-Shift-Attenuation-Method (DSAM). The one-phonon MSS in ^{140}Ba is expected to have a lifetime ranging from 50 to 100 femtoseconds which is therefore still accessible with the DSAM technique as we could demonstrate for the short-lived 4_1^+ state in ^{20}Ne with $\tau = 93(4)fs$ (see fig. 3). Since the α transfer reaction also occurs below the Coulomb barrier ^{136}Xe ions will be accelerated to 4 MeV/u which would correspond to the Coulomb barrier from Xe on carbon at 542 MeV. The multilayered target will consist of a carbon layer enabling the transfer reaction and simultaneous Coulomb

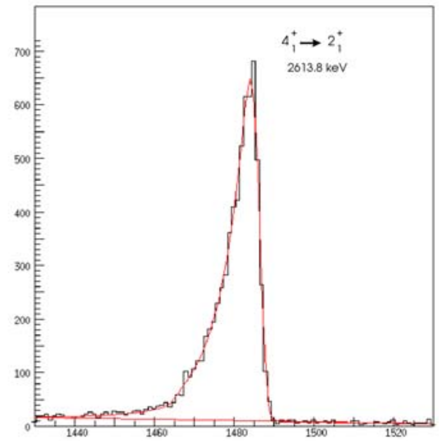

Figure 3: *DSAM fit to the lineshape of the* $(4^+_1 \rightarrow 2^+_1)$*-Transition in* ^{20}Ne *with* $\tau(4^+_1) = 93(4)fs$ *at a decay velocity of approximately 0.05c. [35]*

excitation of the xenon ions, followed by an externaly magnetized gadolinium layer where excited ions precess in their different nuclear states under influence of the transient fields and a backing made of copper which serves as hyperfine interaction free environment where the ions will finally be stopped and decay. The scattered carbon ions as well as the alpha particles emerging from the decay of the residual ^{8}Be from the α transfer will be detected in a Si array consisting of two PIN diodes of 2cm×2cm, one above and one below the beam axis, in coincidence with the de-excitation γ rays. This configuration will ensure the maximum nuclear spin alignment when the γ detectors are placed in a plane perpendicular to the particle detector. Four EUROBALL cluster detectors with an absolute γ efficiency of 1% will be placed upstream and downstream at ±65 degrees with respect to the beam axis for the measurement of the nuclear spin precession and particle-γ angular correlation, respectively.

The TF technique in inverse kinematics will combine high detection efficiency due to the kinematic focussing of the scattered target ions and a high sensitivity to the nuclear spin precession as a consequence of the large nuclear spin alignment in the particle-γ angular correlation. In addition high velocities of the recoiling Xe and Ba ions will provide large transient fields as well as favourable conditions for the DSAM analysis. As a by-product the known lifetimes and magnetic moments in ^{136}Xe will be remeasured which will allows to exclude systematic uncertainties. The combination of α transfer and transient field technique in heavy nuclei was already succesfully applied in the UNILAC experiment U234 in 2008 for stable beams of ^{112,114,116}Sn and in transfer reactions created ^{116,118,120}Te in 2008 [37] which was, to our best knowledge, the first experimental observation of a sub-coulomb barrier α transfer in a mass region above $A \sim 100$. Since the transfer reaction is highly selective for low spin states basically background free γ spectra could be obtained (see fig. 4).

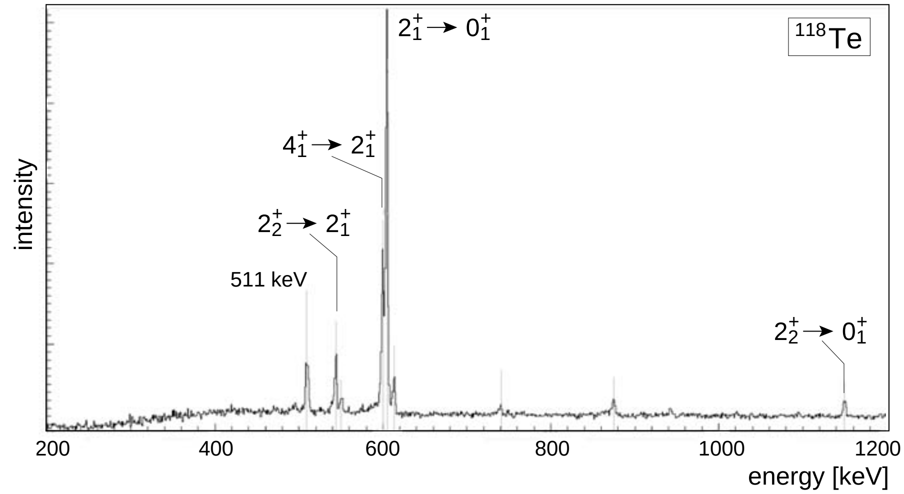

Figure 4: *γ coincidence spectrum of excited ^{118}Te from UNILAC experiment U234 after the α transfer reaction $^{12}C(^{114}Sn, 2\alpha)^{118}Te$*

5 Beamtime estimate

The beamtime estimate is based on the following assumptions and will be scaled to rates and efficiency from experiment U234 which was done with the proposed set-up under similar experimental conditions:

- Target : 0.2 mg/cm^2 C + 8 mg/cm^2 Gd + 1 mg/cm^2 Ta +5 mg/cm^2 Cu

- Beam : ^{136}Xe at 4 MeV/u

- Beam intensity : 1pnA

- absolute gamma efficiency of 1% for 4 EUROBALL cluster detectors
- the cross section of ^{12}C(^{136}Xe,2α)^{140}Ba is approximately 1/3 of the Coulex cross section ^{12}C(^{136}Xe,^{136}Xe*)^{12}C with $\sigma_{tot} = 0.006 b/sr$ for the proposed set-up

- according to [34] the one-phonon MSS is expected to have 1/3 of the strength from the first 2^+ state

From the calculated and estimated cross sections and the given set-up one would expect to have

- 0.4 cts/s or 1440 cts/h for ^{136}Xe($2_1^+ \rightarrow 0_1^+$)
- 0.13 cts/s or 480 cts/h for ^{140}Ba($2_1^+ \rightarrow 0_1^+$)
- 0.04 cts/s or 160 cts/h for ^{140}Ba($2_{1,ms}^+ \rightarrow 0_1^+$)

In order to reach the optimum statistics for the lineshape analysis of the ($2_{1,ms}^+ \rightarrow 0_1^+$) transition, a total number of 10000 counts will be required corresponding to 5 days of beam on target (with 0.5% absolute γ efficiency at the sensitive angles). Assuming g factors of $g(2_1^+) = +\ 0.2$ [38] and $|g(2_{1,ms}^+)| = 0.5$ in ^{140}Ba for the given beam intensity and known slopes of the particle-γ angular correlation for α-transfer reactions of $|S| \approx 0.4 mrad^{-1}$ and the calculated and measured slope for a ($2_1^+ \rightarrow 0_1^+$) transition for this configuration, 33 hours of beam on target are required to reach an accuracy of 20% for the $g(2_1^+)$ and 5 days will be necessary for a 50% accuracy of the one-phonon MSS.

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