CERN-INTC-2003-003 and INTC-P-166

Proposal to the INTC Committee

Magnetic Moments of Coulomb Excited 2_1^+ States for Radioactive Beams of $^{132,134,136}Te$ and ^{138}Xe Isotopes at REX-ISOLDE

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1 Introduction

Magnetic moments are an indispensable source of information on the microscopic structure of atomic nuclei. It results from the fundamental difference of the spin g factors of protons and neutrons, in *sign* and *magnitude*, $g_S(\pi)= +5.586$ and $g_S(\nu)= -3.826$, which enables to determine the nucleonic components of the wave functions of nuclear states. This behaviour was clearly demonstrated in recent experiments on low-spin states of stable *even-A* Xenon isotopes for which the well-established increase of $g(2_1^+)$ values with increasing neutron number, approaching the $N = 82$ shell closure, exhibits the transition from collective to single particle degrees of freedom with a dominant $1g_{7/2}$ proton configuration for ^{136}Xe [1]. It is a general feature, that nuclei near closed shells, in particular with magic neutron and proton numbers, are characterized by specific single particle components in the wave functions which changes into collective structures when departing from shell closures. The competition between single particle and collective degrees of freedom is sensitively probed by magnetic moments as well as $E2$ transition rates.

For *ps* lifetimes of nuclear states, there is at present only the technique of transient magnetic fields (TF) which provides the necessary field strengths of several $kTesla$, to observe spin precessions with perturbed γ-angular correlations (PAC). The TF are hyperfine fields of the Fermi contact type, which are experienced in fast moving ions during their passage through ferromagnetic materials [2], among which Gd provides the best properties in terms of the polarization of the ions. Its Curie temperature of 298 K, however, requires cooling of the target to liquid nitrogen temperature.

TF have been well studied and described by empirical parametrizations [3] at intermediate ion velocities $v_{ion} \ll Zv_0$ ($v_0 = e^2/\hbar$), whereby the field strength generally increases with velocity reaching a maximum at $v_{ion} = Zv_0$ for single electron ions with its maximum fraction at the 1s electron Bohr velocity [3]. Beyond this velocity the field strength decreases towards zero as the ions become fully stripped [4]. Among the field parametrizations the 'linear' (B_{lin}) and the Rutgers 'rut' (B_{rut}) are the most frequently used parametrizations providing the most reliable g factor results [3].

2 Nuclear structure motivation and expectation

In comparison to the stable *even-A* Te isotopes $^{120-130}Te$, which are collective of vibrational nature with $E(4_1^+)/E(2_1^+) \simeq 2.0$, the structure of the unstable neutron-rich isotopes ^{132}Te, ^{134}Te and ^{136}Te is strongly influenced by the $N = 82$ shell closure and the two protons outside the magic $Z = 50$ shell. This feature becomes evident already from their 2_1^+ excitation energies (Fig. 1a and Fig. 2).

It is also determined by their proximity to doubly-magic ^{132}Sn (Z=50, N=82) and directly relates to neighbouring isotones ^{134}Xe, ^{136}Xe and ^{138}Xe, respectively (Fig. 1b). For stable ^{134}Xe and ^{136}Xe g factors were recently determined for the 2_1^+ and 4_1^+ states clearly exhibiting single proton excitations with dominant $\pi 1g_{7/2}$ configuration [1]:

$$^{134}Xe: \quad g(2_1^+) = +0.354(7) \qquad ^{136}Xe: \quad g(2_1^+) = +0.766(45)$$
$$g(4_1^+) = +0.80(15) \qquad g(4_1^+) = +0.83(14)$$

It is the large and positive g factor of both states in ^{136}Xe and of the 4_1^+ state in ^{134}Xe which unambiguously shows the dominant proton nature whereas the smaller $g(2_1^+)$ value in ^{134}Xe implies additional neutron hole configurations mainly in the $h_{11/2}$ orbit (with its negative Schmidt value, $g(\nu h_{11/2}) = -0.348$). This structure is well confirmed by shell model calculations which in addition yield small admixtures of configurations of neighbouring single particle orbits.

For the isotones ^{132}Te and ^{134}Te we expect for the first 2^+ states similar g factors although the number of protons in the $1g_{7/2}$ orbit is reduced. For ^{136}Te where the $2f_{7/2}$ orbit is occupied by neutrons, its 2_1^+ g factor should be smaller than that of neighbouring semi-magic ^{134}Te. The same behaviour is expected for ^{138}Xe with two neutrons beyond the magic $N = 82$ shell. Shell model calculations predict for ^{136}Te an even negative value emphasizing a dominant neutron component in the nuclear wave function [5]. This scenario is accompanied by an anomalous behaviour of the $B(E2)$ values which consists in an unexpectedly small value for ^{136}Te in comparison to ^{132}Te [6]. In fact its $B(E2)$ is almost equal to that of ^{134}Te (Fig. 2). A measurement of the g factor may shed more light on this unusual behaviour. Terasaki et al. [5] suggested that the origin of this behaviour is related with a reduced neutron pairing gap at ^{136}Te which would cause an increase of the neutron and a decrease of the proton amplitudes in the wave function. On these grounds

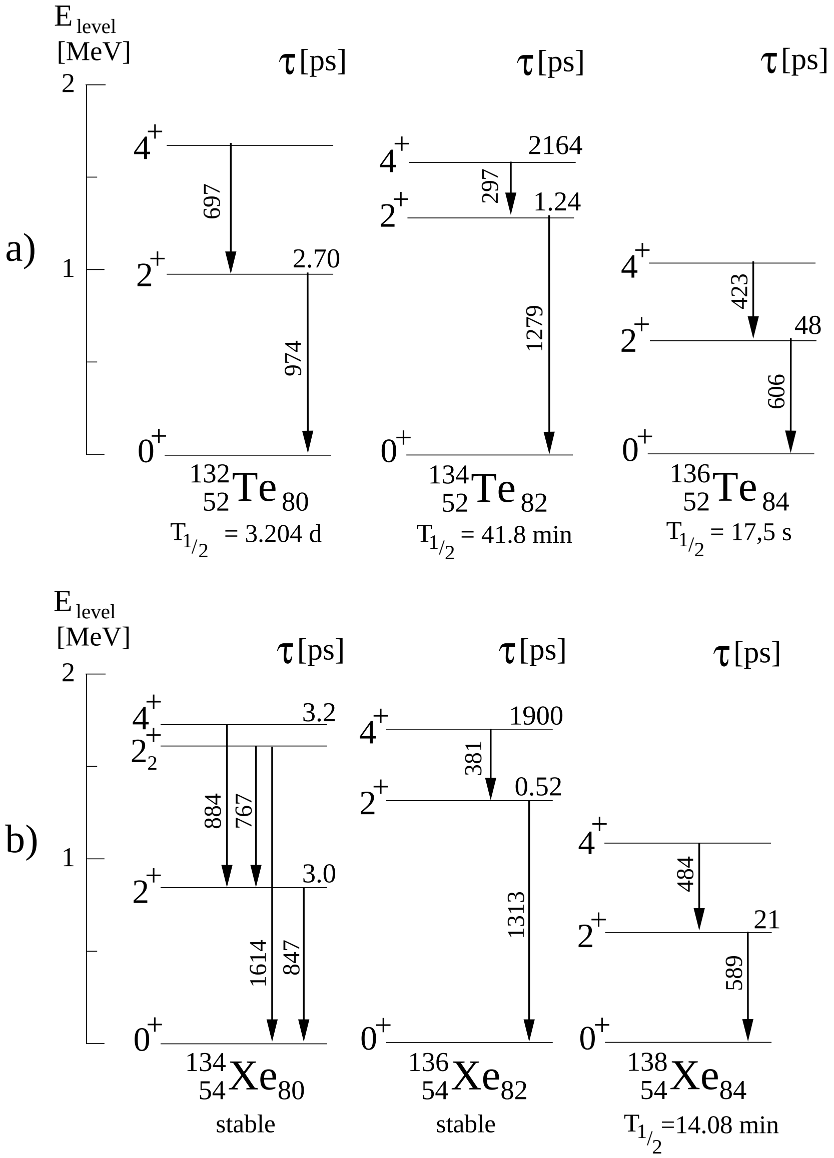

Figure 1: *Low-lying states with relevant γ transitions of even-A (a) unstable Te isotopes and (b) corresponding Xe isotopes. The lifetime quoted for $^{138}Xe(2_1^+)$ corresponds to the calculated $B(E2)$ value [5]*

an even negative $g(2^+)$ value is expected for ^{136}Te which makes the g factor measurement so important (Fig. 2). The same calculations predict for ^{138}Xe a positive but definitely reduced g-factor compared to semi-magic ^{136}Xe.

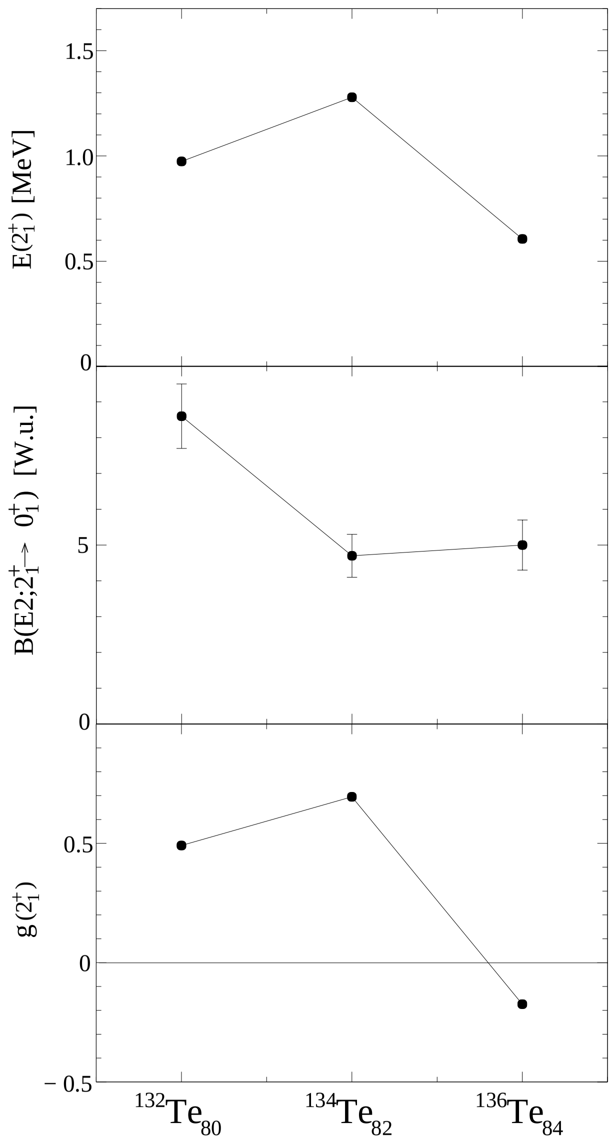

Figure 2: *Experimental $E(2_1^+)$ excitation energies and $B(E2)$ values in Weisskopf units as well as calculated g factors of the 2_1^+ states for $^{132,134,136}Te$ isotopes.*

3 Experimental details

The technique used for the nuclear states of interest, with emphasis on the 2_1^+ states (Fig. 1), is projectile Coulomb excitation in inverse kinematics in combination with TF in ferromagnetic gadolinium. The target consists of (Fig. 3):

$$1.0 \text{ mg/cm}^2\ {}^{48}Ti + 7.0 \text{ mg/cm}^2\ Gd + 1.0 \text{ mg/cm}^2\ Ta + 4.0 \text{ mg/cm}^2\ Cu,$$

whereby the $^{132,134,136}Te$ and ^{138}Xe projectiles are excited at energies of 3.1 MeV/A in collisions with the layer of ^{48}Ti nuclei and experience precessions in the subsequent Gd

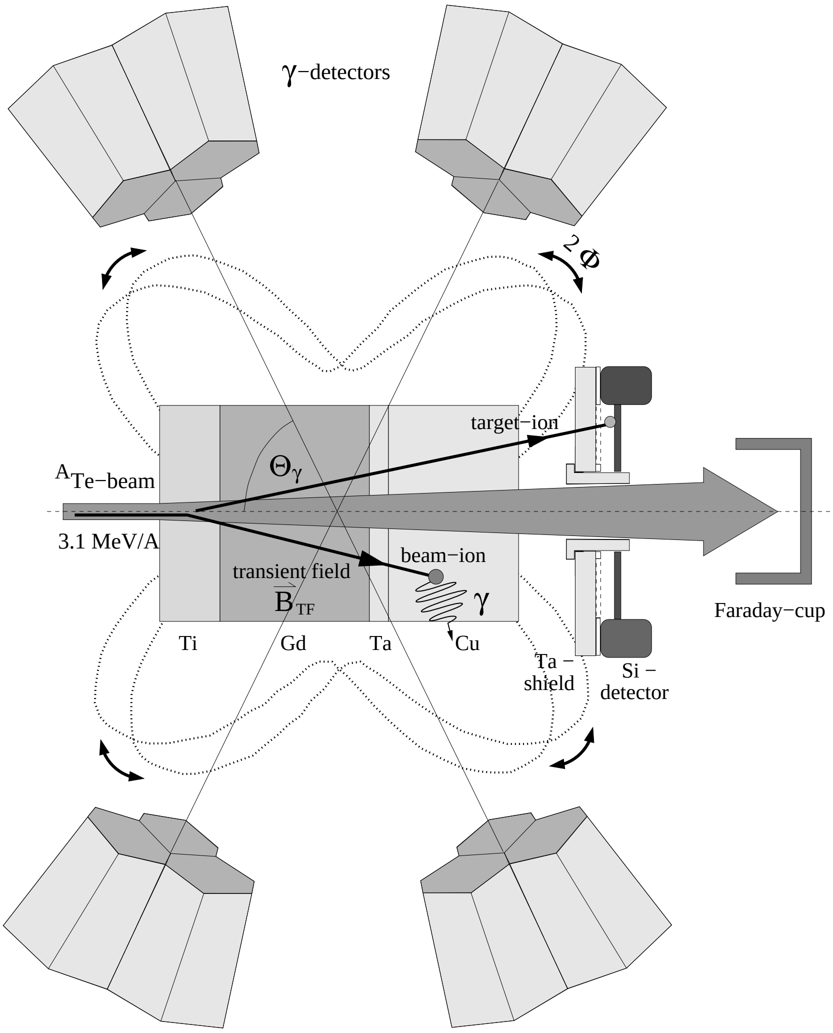

Figure 3: *Schematic view of target composition with the arrangement of particle detector and two pairs of MINIBALL γ detectors. Rotations of anisotropic γ-angular correlations for opposite directions of the TF are indicated. Trajectories of beam and target ions are displayed.*

layer which is magnetized by an external field of 0.05 Tesla. The copper backing serves as stopper for the excited nuclei providing a hyperfine interaction-free environment. De-excitation γ rays are measured with MINIBALL detectors in coincidence with forward scattered titanium ions which are detected in an annular Si detector at acceptance angles between 22° and 35° relative to the beam axis. The radioactive beam ions are steered through the centre hole of the detector and are stopped in a downstream Faraday cup. The particle detector is covered with a thin Ta foil to stop beam ions from large angle scattering in the target in order to avoid radioactive contamination of the detector. This target-detector arrangement (Fig. 3) has been tested in recent measurements using a stable

^{50}Ti beam [7]. It is noteworthy that the Doppler-shifted and broadened γ rays, emitted in flight from the also excited ^{48}Ti target nuclei, should not interfere with the γ lines from the excited projectiles of all three Te isotopes. Because of this relevant aspect isotopically pure ^{48}Ti is favoured over a natural Ta layer as target, although the other Ti isotopes may also not cause severe disturbances in the spectra in the energy region of interest. In fact, this situation has been verified by the measurements on neighbouring xenon isotopes [1].

The technique described ensures high detection efficiency of coincident γ rays due to kinematic focussing of the target ions in the beam direction and provides high spin alignment of the excited states followed by strongly anisotropic γ-angular correlations. The latter is a prerequisite to be sensitive to the spin precessions in the TF. Furthermore, the inverse kinematics implies high velocities of the Te ions with which large TF strengths are associated. This property has been shown in many previous experiments [3].

Four clusters of the MINIBALL detector array will be placed in pairs symmetric to the beam axis in the plane perpendicular to the applied magnetic field at angles Θ_γ, where the γ-angular correlations have their maximum slopes, $S(\Theta_\gamma) = 1/W(\Theta_\gamma)dW(\Theta_\gamma)/d\Theta_\gamma$ (Fig. 3). This experimental design has been used in many former measurements with the exception of the annular structure of the particle detector at forward angles: its effect on the anisotropy of the γ-angular correlation has been studied in detail in the above-mentioned test experiment [7].

For the $(2_1^+ \to 0_1^+)$ γ transitions slope values $|S(\Theta_\gamma = 65^\circ|$ of the angular correlations in the rest frame of the γ emitting nuclei are expected to be between 1.5 and 2.0. This spin alignment ensures large precession effects in counting rates for 'up' and 'down' directions of the external magnetic field. Precession angles, Φ^{est}, have been estimated for the present conditions of the different ^{A}Te beams and the specifics of the target using the computer program TRANSI (Table 1). In these calculations the precession angle Φ is given by [3]:

$$\Phi = g \cdot \frac{\mu_N}{\hbar} \int_{t_{in}}^{t_{out}} B_{TF}(v_{ion}(t)) \cdot e^{-\frac{t}{\tau}} dt \tag{1}$$

where g is the g factor of the state of interest and B_{TF} the transient field acting for the effective time $t_{eff} \simeq (t_{in} - t_{out})$ with entrance time t_{in} and exit time t_{out} of the ions in the Gd layer; the exponential accounts for the decay of the nuclear state with lifetime τ. The TF strength in the linear parametrization is given by [3]:

$$B_{TF} = B_{lin} \cdot G_{beam} \tag{2}$$

with

$$B_{lin} = a(Gd) \cdot Z \cdot \frac{v_{ion}}{v_0} \tag{3}$$

where G_{beam} is the attenuation factor of the TF induced by the beam ions and the strength parameter $a(Gd) \simeq 17$ Tesla.

For the present experimental conditions (Table 1) one obtains: $B_{lin} \simeq 4$ kTesla which gives rise to an effective TF of $B_{TF} \simeq 2.8$ kTesla where $G_{Te-beam} \simeq 0.7$ [3]. These data correspond for the three Te and the Xe isotopes to precession angles as quoted in Table 1.

Table 1: *Summary of the mean velocities of the Te and Xe ions traversing the Gd layer of the target, the effective interaction times with the TF and the estimated precessions calculated from Eqs.(1)-(3) based on the linear parametrization of the TF and g-factor predictions [5].*

Isotope	$g(2^+)^{theor}$	$< v_{ion}/v_0 >$	t_{eff} [ps]	Φ^{est} [mrad]
^{132}Te	+0.491	4.6	0.79	+50.
^{134}Te	+0.695	4.9	0.62	+58.
^{136}Te	–0.174	4.6	0.93	–21.
^{138}Xe	+0.291	4.0	1.07	+35.

4 Count rates and beam time request

In the following we give an estimate of the expected count rates and the beam time requested for the determination of the angular correlations and precessions aiming for a 10 % accuracy of the 2_1^+ g factors for $^{132,134}Te$, a 20 % accuracy for ^{136}Te and a 10 % accuracy for ^{138}Xe.

With intensities of the Te and Xe beams of $\sim 4 \cdot 10^6$ ions/s for $^{132,134}Te$, $\sim 4 \cdot 10^5$ ions/s for ^{136}Te and $\sim 2 \cdot 10^6$ for ^{138}Xe one obtains from Coulomb excitation cross-sections based on the known $B(E2)$ values (Fig. 2 and [5]) and the ^{48}Ti target including the particle detector acceptance, for each of the four detectors in the photopeaks coincident γ-count rates of:

$$^{132}Te(2_1^+ \to 0_1^+) : 2000 \text{ counts/h},$$
$$^{134}Te(2_1^+ \to 0_1^+) : 2400 \text{ counts/h},$$
$$^{136}Te(2_1^+ \to 0_1^+) : \;\; 160 \text{ counts/h and}$$
$$^{138}Xe(2_1^+ \to 0_1^+) : 1600 \text{ counts/h}.$$

With four γ detectors in the reaction plane and a 10 % or 20 % accuracy of the g factor one requires in each detector and field direction total peak intensities of $\sim$ 4.000 cts, 3.000 cts, 6.000 cts for ^{132}Te, ^{134}Te and ^{136}Te, respectively, and $\sim$ 15.000 cts for ^{138}Xe. These data imply a total beam time of 10 days composed of 2 days for both $^{132,134}Te$, 6 days for ^{136}Te and 2 days for ^{138}Xe.

In addition, we are planning a test experiment at the Cologne tandem accelerator with a stable ^{50}Ti beam and a carbon target (intead of ^{48}Ti) using the MINIBALL for

γ ray detection and an annular Si detector for detecting the forward scattered carbon ions, in almost identical geometry as for the planned REX-ISOLDE experiment. The main difference to the earlier test measurement [7] consists in the first use of MINIBALL for nuclear spin precessions in TF.

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