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Proposal to the ISOLDE and Neutron Time-of-Flight Committee

Conversion Electron Study to Identify the Spherical 0_2^+ State in ^{32}Mg via its E0 Decay.

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1 Abstract

During an experimental campaign within the framework of the IS414 collaboration the (deformed) 0_2^+ state in ^{30}Mg at 1789 keV could be unambiguously identified during a conversion electron spectroscopy experiment. A very sensitive experimental technique has been developed that allows to measure even weak E0 decays. This way in ^{30}Mg the electric monopole strength could be determined as $\rho^2(\mathrm{E0}) = 5.7(12) \cdot 10^{-3}$, indicating a weak coupling between the different potential minima. This measurement proved for the first time shape coexistence in neutron-rich Mg isotopes at the borderline of the 'Island of Inversion'.
Based on this experimental result we want to now exploit the capabilities of this technique to aim for the first-time identification the excited (spherical) 0_2^+ state in ^{32}Mg. Unless in ^{30}Mg, where a candidate for the deformed 0_2^+ intruder state existed, in ^{32}Mg no spectroscopic candidate for the 0_2^+ state is available so far. Nevertheless, in case of a scenario with a low-lying 0_2^+ state (below 1.2 MeV) as discussed lateron, there is a fair chance even in view of the reduced beam intensity for ^{32}Mg studies to identify this important $0_2^+ \rightarrow 0_1^+$ transition inside the island of inversion.

2 Introduction

One of the most studied phenomena in the region of neutron-rich atomic nuclei around the $N = 20$ shell closure is the occurrence of strongly deformed ground states in Na, Mg and Ne isotopes. This so-called 'island of inversion' [1] (discovered already more than 30 years ago [2]) corresponds to the promotion of a pair of neutrons across the $N = 20$ shell gap, thus leading to the intrusion of deformed low energy (2p2h) states below the spherical (0p0h) states compared to nuclei closer to β stability. Despite considerable theoretical and experimental efforts the exact localization of the transition from normal to intruder-dominated configurations is not yet finally settled and even the origin of the large collectivity of the $0_{gs}^+ \rightarrow 2_1^+$ transition in ^{32}Mg is still under debate [3]. A coexistence of spherical and deformed 0^+ states is predicted to exist within and at the borderline of the 'island of inversion' in neutron-rich Mg isotopes around N=20 [4, 5], however, so far studies on spectroscopic properties focus on B(E2) values between the 0^+ ground state and the first excited 2^+ state [6, 7, 8, 9, 10, 11], while no first excited 0^+ state has been experimentally observed so far at the borderline or inside the island of inversion.
In Fig. 1 the 'inversion' between deformed and spherical 0^+ states occurring at ^{32}Mg in the chain of Mg isotopes is depicted by the energy difference between the two states as available from experiments and theoretical predictions [12, 13, 14, 15, 16, 17].
While the closed-shell nucleus ^{32}Mg exhibits a strongly deformed ground state as indicated by the large value of B(E2;$0_{gs}^+ \rightarrow 2_1^+$)=454(78)$e^2$fm^4 measured via (intermediate energy) Coulomb excitation [6] (confirmed by the 'safe' Coulex measurement at REX-ISOLDE resulting in B(E2;$0_{gs}^+ \rightarrow 2_1^+$)=434(52)$e^2$fm^4 [11]).

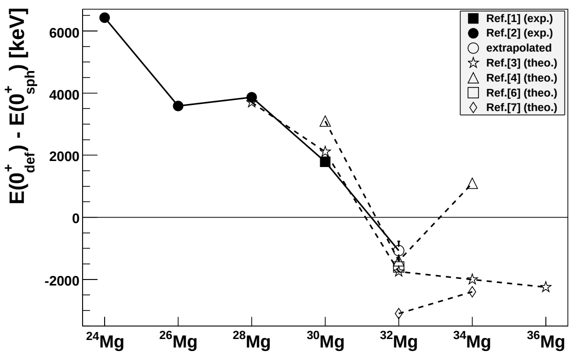

Figure 1: Measured and predicted energy difference between the 0^+ states of different deformation for various Mg nuclei.

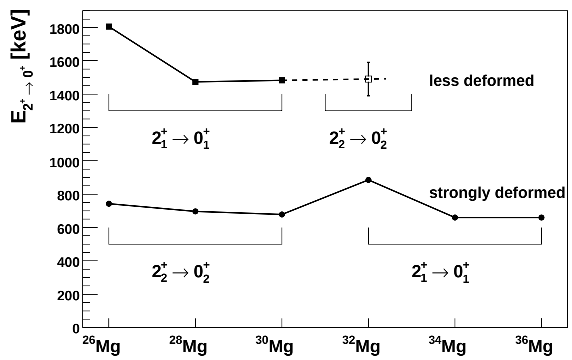

Figure 2: Systematics of strongly deformed and spherical (or much less deformed) $2^+ \rightarrow 0^+$ transitions in Mg isotopes (see text).

The ground state of ^{30}Mg was expected to be less deformed, whereas a (deformed) excited 0_2^+ state was theoretically predicted at an energy between 1.7-2 MeV (see Fig. 1) but has so far escaped observation. In Fig. 2 the systematics of $2^+ \rightarrow 0^+$ transitions in the Mg isotopic chain is shown first for the transitions between strongly deformed states ($2_1^+ \rightarrow 0_1^+$ inside the island of inversion, $2_2^+ \rightarrow 0_2^+$ for isotopes located outside) and second for the spherical (or much less deformed) transitions (^{24,26,28}Mg: [13]; ^{30}Mg: [12]; ^{32}Mg: [6], E($2_2^+ \rightarrow 0_2^+$) extrapolated from ^{30}Mg with 2_2^+ assignment of the 2551 keV level; ^{34}Mg: [7]; ^{36}Mg: [18]).
This picture already includes the underlying assumption used here to take the ground state transition energy from the (spherical) 2_1^+ state (1482 keV) as an indicator for the analogue (spherical) $2_2^+ \rightarrow 0_2^+$ transition in ^{32}Mg.

3 Results from previous experiment: Identification of the 0_2^+ state in ^{30}Mg via conversion electron spectroscopy

Studying the nuclear structure in the area of the 'Island of Inversion' in the vicinity of ^{32}Mg, one of the central results of experiment IS414 in 2007 was the identification of the 1789 keV level in ^{30}Mg as the deformed 0_2^+ state, resulting in a determination of the electric monopole strength $\rho^2(\mathrm{E0}) = 5.7(12) \cdot 10^{-3}$ indicating a weak coupling between the two potential minima in ^{30}Mg [25, 26]. A publication presenting these results is under preparation and close to being submitted to Physical Review Letters.
Fig. 3 shows the background-substracted electron spectrum gated on the β - E0 coincidence and the short lifetime of the ^{30}Na decay.

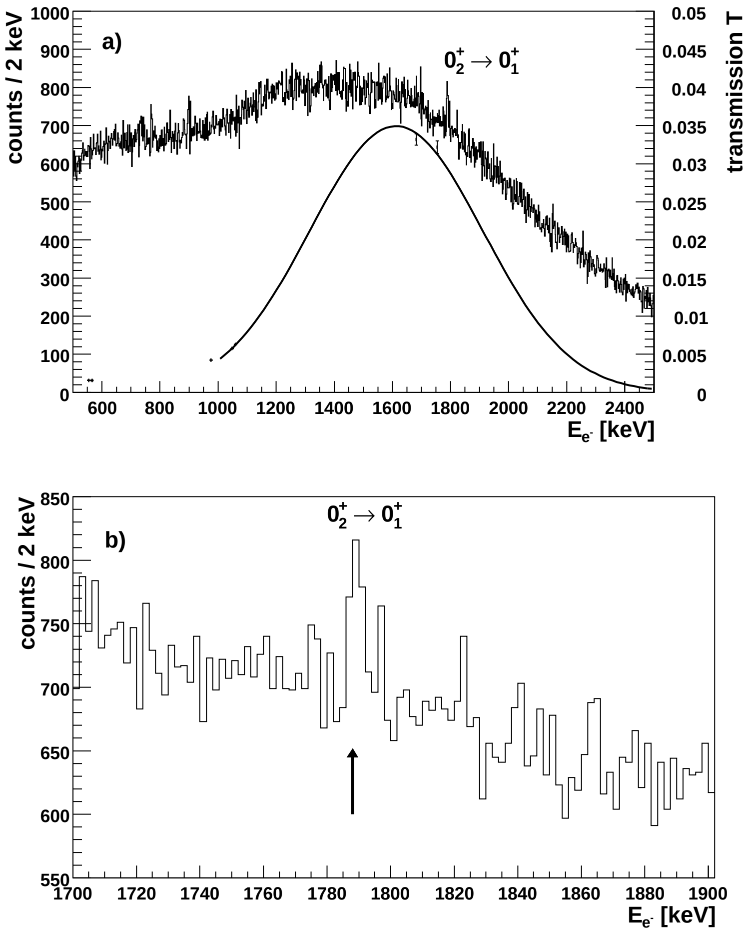

Figure 3: a) Background-subtracted electron spectrum measured in coincidence with signals in the plastic detector, gated on time differences $\leq$ 500 ms between the proton pulse and the registered β decay signal. Also shown is the transmission function of the Mini Orange spectrometer. The exponentially decreasing β decay energy spectrum (Q_β =17.3 MeV) gives rise to the rather high yield remaining below the transmission maximum. b) Expanded view to the electron spectrum in the region of the E0 transition in ^{30}Mg.

Figure 4: Magnetic Mini-Orange filter and transport system, consisting of eight wedge-shaped permanent magnets arranged around a central Pb absorber.

3.1 Experimental method

In the following section the experimental method used to obtain the result in ^{30}Mg descibed before will be outlined, since the same setup will be used for the planned experiment in ^{32}Mg.
It is forseen to use a Mini-Orange spectrometer for the detection of conversion electrons from the searched $0_2^+ \rightarrow 0_1^+$ E0 decay in coincidence with electrons from β decay registered in a plastic scintillator.

3.1.1 The Mini-Orange spectrometer

Mini-Orange spectrometers [21] combine the excellent energy and time resolution of a cooled Si(Li) detector with the high efficiency and energy selectivity of a magnetic Mini-Orange filter. The Mini-Orange is a focusing device for electrons and at the same time suppresses the high background from γ rays. In our setup the Mini-Orange consists of 8 wedge-shaped permanent magnets arranged around a central Pb absorber (a cylinder with a length of 30 mm and a diameter of 12 mm), thus resulting in a toroidal magnetic field of B=160 mT. Fig. 4 shows a photograph of the Mini Orange.
In the case of ^{30}Mg the transmission curve of the Mini-Orange was optimized for the expected E0 transition energy of 1788 keV (binding energy of K-electron = 1.3 keV in ^{30,32}Mg), resulting in a detection efficiency of 3.5% at this energy, as can be seen in Fig. 5.
Searching for a low-lying E0 transition in ^{32}Mg around 1 MeV the transmission curve can optimized in order to achieve an improved efficiency of 7.0% as can be seen from the red curve in Fig. 5.

3.1.2 Experimental setup

As it turned out during the experimental campaign on ^{30}Mg, we had to push our setup to the technically feasible limit in order to increase our sensitivity by suppressing electron background from β decay and Compton scattering, mainly induced from high-energy γ rays originating from the high Q_β value of 17.3 MeV for ^{30}Na.
When aiming for an E0 search in ^{32}Mg following β decay in ^{32}Na, we will face a similar situation, given the even higher Q_β = 19.75 MeV. Therefore all experimental experience gained in ^{30}Mg will have to be exploited for addressing ^{32}Mg.
We will use a thin-walled target chamber consisting entirely of aluminum in order to reduce the Compton scattering probability. The interior of the chamber will be coated with 15 mm Teflon plates which absorb backscattered Compton electrons.
Operated in coincidence with a (thin and fast) β plastic scintillator in close vicinity to the Al catcher foil, this setup is able to efficiently suppress background from β-decay electrons in the Si(Li) detector by a β – E0 coincidence measurement. With a diameter of ca. 50 mm and positioned in a distance of ca. 13 mm from the catcher foil, this β detector will have a solid angle coverage of $d\Omega/4\pi = 21\%$.

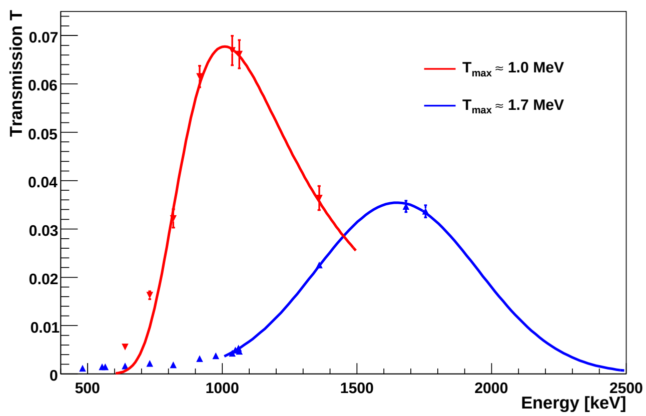

Figure 5: Transmission curve of the Mini-Orange filter and transport system, optimized for the measured E0 transition energy of 1788 keV from the 1789 keV 0_2^+ state in ^{30}Mg (blue curve). The red curve displays the transmission curve optimized for the search of a low-lying E0 transition energy around 1 MeV in ^{32}Mg.

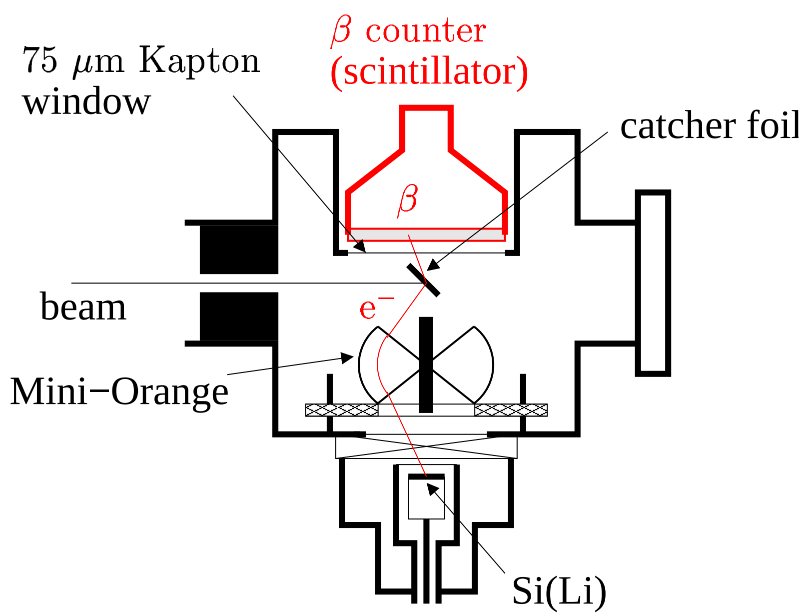

Figure 6: Sketch of the experimental setup operating a β-detector in coincidence with the Si(Li) of the Mini-Orange spectrometer.

The electrons from E0 decays will be detected in the Mini-Orange spectrometer with a transmission function optimized for a low-lying decay energy of the 0_2^+ state in ^{32}Mg around 1.1 MeV. The absolute efficiency of the Mini-Orange spectrometer at this energy is 7.0%, thus exhibiting a gain by a factor of 2 compared to the previous case in ^{30}Mg. A germanium detector placed outside the target chamber will be used for normalization purposes between γ and E0 decays and in order to identify the beam composition.

4 Discussion of the level scheme in ^{32}Mg

While in ^{30}Mg a clear candidate for the deformed 0_2^+ intruder state existed from fast timing studies, in ^{32}Mg no clear spectroscopic candidate for the 0_2^+ state is presently available.
So far only a broad range of theoretical predictions for the 0_2^+ state in ^{32}Mg have been published [15, 4, 14], placing this state in the energy region around 2 MeV (with the lowest prediction of $E(0_2^+) = 1.4$ MeV by the Strasbourg group [15]).
On the other hand Fig. 7 displays the most recent level scheme for ^{32}Mg obtained from β decay of ^{32}Na, as obtained in a still ongoing analysis [24] based on a data sample containing a statistics about a factor of 30 larger compared to the most recent published level scheme for ^{32}Mg from the work of Mattoon et al. [23]. In addition to the 2_1^+ state at 885 keV the 2321 keV level is the obvious candidate for the 4^+ state of the ground state band. A strong β feeding to the 4817 keV and 3036 keV levels with logft < 5 [19] indicates that these are negative parity states. They do not deexcite to the ground state, suggesting their spins to be 3^- and 2^- (or vice versa). The deexcitation pattern of the 3552 keV and 5245 keV states imply that these are medium spin states (above 2^+ and not 2^-), certainly excluding 0^+ or 2^+. The 2857 keV state is fed by this medium spin state, again excluding this level from being a 0^+ candidate. Also the 3121 keV state cannot be a 0^+ candidate since it is fed by a 2^- or 3^- state. However, either of these two states could be the 2^+ intruder. The 2550 keV level feeds the ground state rather strongly, while only a rather weak branch to the 885 keV 2_1^+ state was observed. Thus its spin is either 1^-, 1^+ or 2^+. This state is only fed by two γ rays from the negative-parity 2^- and 3^- states, which could either result from a strong feeding of these states or due to selection rules preferring the deexcitation to the same parity states. This would imply this level to be a 1^- state. However, it could as well be a 2^+ state. In this case it could be the 2^+ state from the γ band. However, this scenario is disfavoured by the strong feeding to the ground state. On the other hand, if the 2550 keV state would be the (spherical) 2_2^+ intruder state, the ground state decay would be in agreement with this assignment.

5 Proposed search for the E0-transition in ^{32}Mg

The identification of the spherical 0_2^+ state in ^{32}Mg would mark a milestone in the study of shape coexistence in the island of inversion. However, the success of an experimental search of this state strongly depends on its energetic position.
In the unfavourable case of a high-lying 0_2^+ (i.e. above $\sim$1.2 MeV) competition of the E2 transition to the 2_1^+ state together with the limited beam intensity for ^{32}Na as presently available would prevent the observation of the E0 transition. Nevertheless even in this case a lower limit could be established for the energy of the 0_2^+ state.
However, if the assignment of the 2550 keV level being the 2_2^+ intruder state were true, then our searched spherical 0_2^+ state would be located significantly below this state. Taking the $2_1^+ \rightarrow 0_1^+$ transition energy in the neighbouring ^{30}Mg of 1482 keV as a rough indication of the expected level spacing between the 0_2^+ and 2_2^+ states in ^{32}Mg, then our search for the spherical 0_2^+ state should focus on a rather low-lying candidate around 1070 keV. In such a scenario the competing E2 transition energy to the 2_1^+ state would amount to 185 keV, thus being significantly smaller compared to the 306 keV in ^{30}Mg for the analogue E2 transition. According to the E^5 scaling the E2 competition to the E0 decay would be reduced by more than an order of magnitude relative to the situation in ^{30}Mg. Moreover, in ^{32}Mg the 0_2^+ state is expected to be longer-lived compared to ^{30}Mg, thus reducing the contributions from prompt background if applying a delayed β-E0 coincidence gating condition. Also the shorter halflife of ^{32}Na (13.5 ms) compared to ^{30}Na (48 ms) would allow for a more strict gating condition, which besides improving the signal-to-background ratio would also be advantageous to discriminate against potential contributions

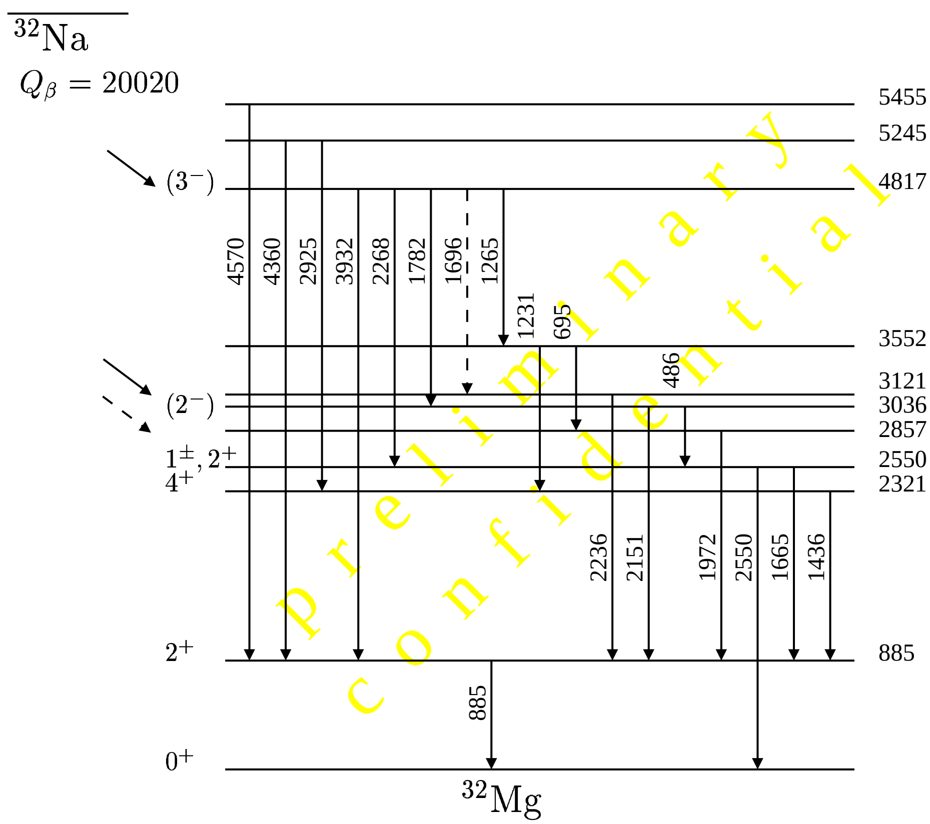

Figure 7: Decay scheme in ^{32}Mg as observed from β decay of ^{32}Na. Data are taken from an ongoing analysis [24].

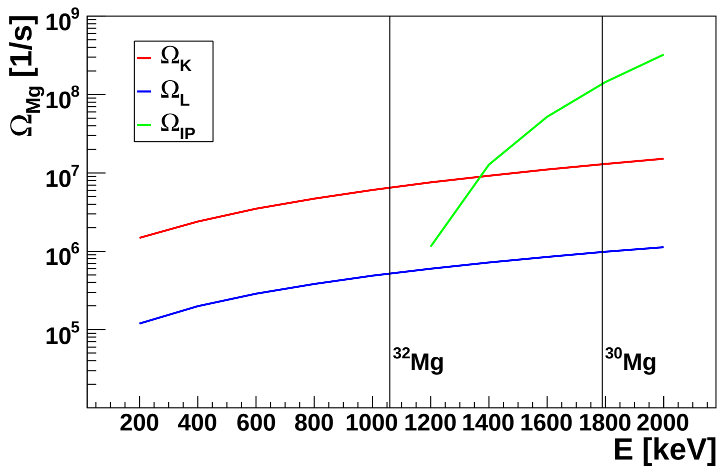

Figure 8: Electronic Ω factors for K and L conversion and internal pair creation ($\Omega_{\rm IP}$) in magnesium [22].

from multiply-charged ions. In addition competition by internal pair creation will completely vanish in the case of ^{32}Mg, as can be seen from Fig. 8, where the electronic Ω factors for K- and L conversion as well as for internal pair creation are plotted for Mg as a function of the 0_2^+ energy [22]. While for ^{30}Mg with E(0_2^+)= 1789 keV pair creation was dominating by an order of magnitude over conversion, in the scenario of a low-lying 0_2^+ state this contribution vanishes.
This proposed conversion electron experiment would represent a complementary experimental approach to the two-neutron transfer experiment to search for the 0_2^+ in ^{32}Mg already approved as IS470.

6 Rate estimates and beamtime request

In view of the unclear position of the 0_2^+ state we will focus our request to an exploratory measurement, testing the scenario of a low-lying 0_2^+ state at around 1 MeV with a limited request of beamtime that would be sufficient to find an indication of such an E0 transition.
Based on a beam intensity from ISOLDE of 100 particles/s for ^{32}Na (as provided by ISOLDE in previous studies with ^{32}Na β decay), this reduction of beam intensity by a factor of 40 relative to ^{30}Na will be partly compensated by the efficiency gain (factor 2) and the reduced E2 competition (factor 12.5). Moreover for a low-lying 0_2^+ state no competition by internal pair production will be present, which dominated over internal conversion by a factor of 10 in ^{30}Mg.. Thus scaling from our ^{30}Mg experiment we expect about 1.4 counts in the E0 peak per hour (for a $\sim$1 MeV E0 transition). Aiming at 100 counts in the E0 peak (which would be sufficient to confirm the underlying spectroscopic scenario while giving enough confidence in the success of a potential subsequent production experiment) results in a beamtime request of 11 shifts. This takes into account that in case of an indication for an E0 transition the time dependence of the line would have to be studied in order to prove the assignment to ^{32}Mg against potential contaminants.
Thus we are requesting 11 shifts for a ^{32}Na beam and 1 shift for stable beam tuning.

In total **12 shifts** are requested.

References

[1] E.K. Warburton et al., Phys. Rev. **C 41** (1990) 1147.

[2] C. Thibault et al., Phys. Rev. **C 12** (1975) 644.

[3] M. Yamagami et al., Phys. Rev. **C 69** (2004) 034301.

[4] K. Heyde and J.L. Wood, J. Phys. G: Nucl. Part. Phys. **17** (1991) 135.

[5] J.L. Wood et al., Phys. Rep. **215** (1992) 101.

[6] T. Motobayashi et al., Phys. Lett. **B346** (1995) 9.

[7] H. Iwasaki et al., Phys. Lett. **B 522** (2001) 227.

[8] B. Pritychenko et al., Phys. Lett. **B 461** (1999) 322.

[9] V. Chisté et al., Phys. Lett. **B 514** (2001) 233.

[10] O. Niedermaier et al., Phys. Rev. Lett. **94** (2005) 172501.

[11] O. Niedermaier, Ph.D. dissertation, Univ. Heidelberg (2005), http://deposit.ddb.de/cgi-bin/dokserv?idn=975806416

[12] H. Mach et al., Eur. Phys. J. **A25** (2005) s01 105.

[13] Evaluated Nuclear Structure Data File (ENSDF): http://www.nndc.bnl.gov/ensdf/

[14] R. Rodriguez-Guzman et al., Nucl. Phys. **A709** (2002) 201.

[15] E. Caurier et al., Nucl. Phys. **A693** (2001) 374.

[16] F. Novacki et al., private communication in: D. Guillemaud-Mueller et al., Eur. Phys. Journ. **A13** (2002) 63.

[17] T. Otsuka, Eur. Phys. Journ. **A20** (2004) 69.

[18] A. Gade et al., Phys. Rev. Lett. **99** (2007) 072502.

[19] G. Klotz et al., Phys. Rev. **C47** (1993) 2502.
(1956) 1035.

[20] J.L. Wood, E.F. Zganjar, C. de Coster and K. Heyde, Nucl. Phys. **A651** (1999) 323.

[21] J. van Klinken and K. Wisshak, Nucl. Instr. Meth. **98** (1972) 1; J.van Klinken, S.J. Feenstra, K. Wisshak and H. Faust, Nucl. Instr. Meth. **130** (1975) 427; J. van Klinken, S.J. Fenstra and G. Dumond, Nucl. Instr. Meth. **151** (1978) 433.

[22] J. Kantele, Handbook of Nuclear Spectroscopy, Academic Press 1995, ISBN 0-12-396440-7

[23] C.M. Mattoon et al., Phys. Rev. **C 75** (2007) 017302.

[24] H. Mach, private communication (2008).

[25] W. Schwerdtfeger et al., to be submitted to PRL (2008)

[26] W. Schwerdtfeger, Ph.D. dissertation, Univ. München (2008).