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Evolution of single particle and collective properties in the neutron-rich Mg isotopes

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for the MINIBALL and REX-ISOLDE collaborations

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Abstract

We propose to study the single particle and collective properties of the neutron-rich Mg isotopes in transfer reactions and Coulomb excitation using REX-ISOLDE and MINIBALL. From the Coulomb excitation measurement precise and largely model independent $B(E2; 0^+_{g.s.} \to 2^+_1)$ will be determined for the even-even isotopes. For the odd isotopes the distribution of the E2 strength over a few low-lying states will be measured. The sign of the M1/E2 mixing ratio, extracted from angular distributions, is characteristic of the sign of the deformation, as is the resulting level scheme. The neutron-pickup channel in the transfer reactions will allow for a determination of the single particle properties (spin, parity, spectroscopic factors) of these nuclei. This information will give new insights in changes of nuclear structure in the vicinity of the island of deformation around ^{32}Mg. A total of **24 shifts** of REX beam time is requested.

1 Introduction

Presently one of the most interesting regions in the chart of nuclides in nuclear structure research far from stability is around $Z = 12$ and $N = 20$ (^{32}Mg). Even though much information on the nuclei in this region was obtained in the last 27 years (mainly from beta-decay and ground state property measurements) a detailed and systematic understanding is still missing. Even today the extend (in Z and N) of the region of large collectivity around ^{32}Mg is unclear and information on excited states is largely missing. No systematic study of the single-particle and collective properties of very neutron rich nuclei is available, which would play a major role in the understanding of nuclear structure under the extreme conditions of large N-Z-asymmetry and weak binding, and which would therefore provide stringent tests of nuclear models.

It was found already in 1975 by Thibault *et al.* [1] in their mass measurements that the isotopes ^{31,32}Na are more tightly bound than expected. This behavior was explained [2] as the filling of the $f_{7/2}$ intruder orbits, i.e. an inversion of the standard shell ordering and hence the breakdown of the $N = 20$ shell closure.

The vanishing of the $N = 20$ shell closure is exemplified in Fig. 1, where the energies of the first 2^+ states for the Mg and Si isotopes are shown as a function of neutron number. The high energy for the $N = 20$ nucleus ^{34}Si shows a strong shell effect at $Z = 14$, while for ^{32}Mg the energy even drops below that of ^{30}Mg indicating a complete vanishing of the shell closure at $Z = 12$. The $B(E2; 0^+_{g.s.} \to 2^+_1)$ values for the Mg isotopes are shown in Fig. 2. Also here no indication of a shell closure is visible at $N = 20$ for $Z = 12$. There is, however, a rather large uncertainty on the measured values and for ^{30,32}Mg different groups obtained different results even if employing the same experimental method (intermediate-energy[1] Coulomb excitation). This might indicate that systematic uncertainties e.g. due to nuclear effects (Coulomb-nuclear interference) are not fully understood. A precise model-independent measurement is therefore very important.

Also shown in Fig. 2 (and Tab. 1) are theoretical predictions by several groups [3, 4, 5] showing, besides a strong theoretical interest, that a firm measurement is urgently needed to distinguish between them. In addition the experimental information can serve as an input to nuclear structure models for heavier isotopes, which could be improved significantly.

Information on the first 3 excited states in the neutron-rich Mg isotopes is summarized in Tab. 1. One can see that already for ^{29}Mg (3 neutrons from stability) the spin of the first excited state is unknown and for ^{31}Mg also the ground state spin is uncertain. For instance the most likely value for the ground state spin of ^{31}Mg is 3/2 [6], but a very recent and preliminary β-NMR (TDPAD) measurement [7] is only consistent with a spin of 7/2. Here it is not fully certain, however, that the ground state spin was measured.

Notable very recent results include the identification of excited states in ^{33}Mg [8] and ^{34}Mg [9], and the determination of the $B(E2; 0^+_{g.s.} \to 2^+_1)$ value of ^{34}Mg [10]. In the year 2000 an excited state was observed in ^{31}Na [11], however due to poor resolution, low statistics, and a high background below 200 keV a model independent analysis was

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[1] $E_{\rm beam} \sim 50$ MeV/u

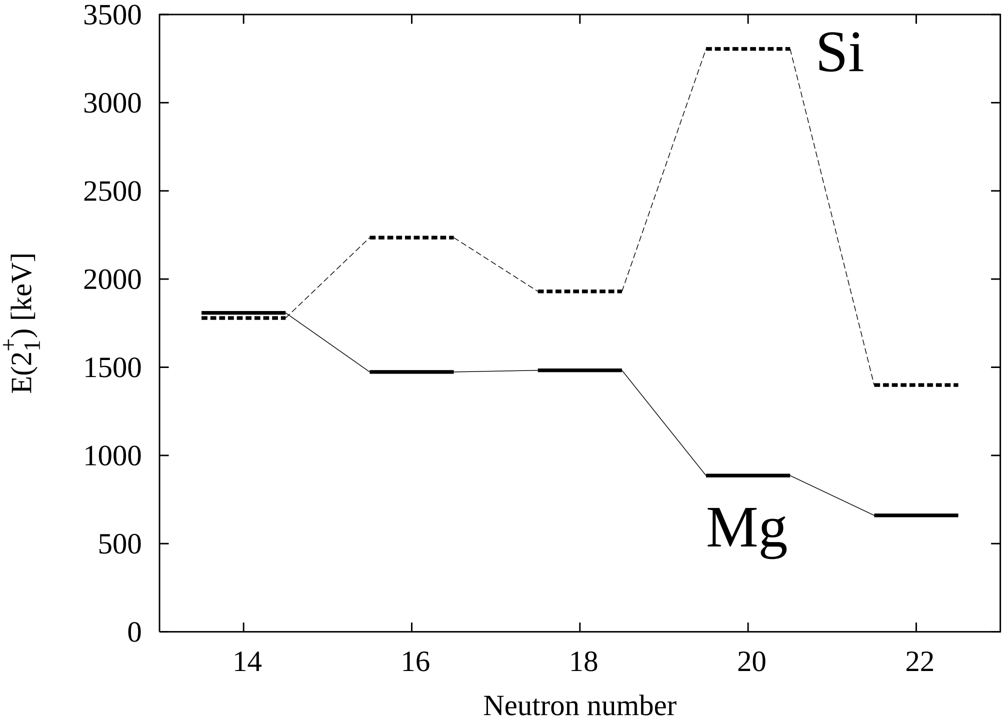

Figure 1: Shown are the excitation energies of the first 2^+ states as a function of neutron number for the Mg and Si isotopes. One can clearly see the pronounced $N = 20$ closed shell structure in the Si ($Z = 14$) isotopes and the absence of it in Mg ($Z = 12$).

not possible. An extremely large deformation of $\beta_2 = 0.6$ was deduced for ^{34}Mg [10] and ^{31}Na [11].

Until now most of the spectroscopic information on the neutron-rich Mg nuclei has been obtained in β decay studies of Na isotopes (e.g. [8]) and in experiments using intermediate energy[2] beams (Coulomb excitation and secondary fragmentation). The large atomic background and large Doppler shifts in these reactions both due to the high beam energy restrict these measurements to even-even nuclei and only in special cases can these methods be applied to odd-even or odd-odd nuclei. At REX-ISOLDE this limitation does not exist.

We therefore propose a systematic study of collective and single particle properties of the neutron-rich Mg isotopes using transfer reactions and Coulomb excitation. The emitted photons will be registered by the MINIBALL Ge array. Due to the high efficiency of the array (~10% at 1.3 MeV) and the use of thick targets high-resolution spectroscopy can be performed even with modest beam intensities.

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[2] $E_{\text{beam}} \sim 50$ MeV/u

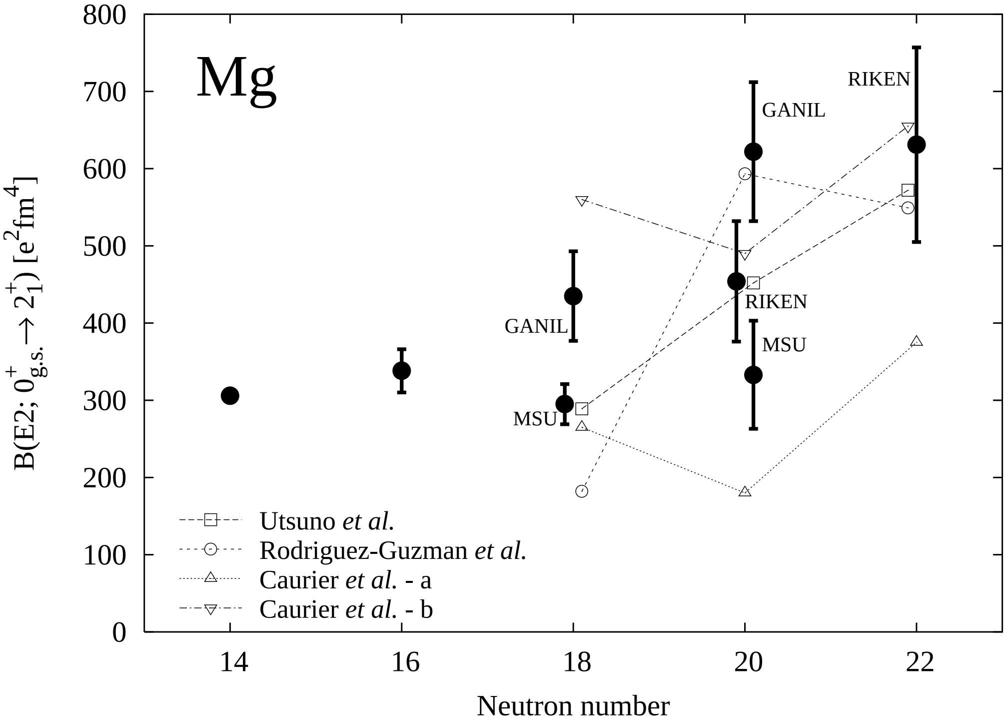

Figure 2: $B(E2; 0^+_{g.s.} \rightarrow 2^+_1)$ values of Mg isotopes as a function of neutron number. The $N = 20$ nucleus ^{32}Mg shows a large $B(E2; 0^+_{g.s.} \rightarrow 2^+_1)$, contrary to expectation for a closed shell nucleus. Theoretical values are plotted with open symbols, experimental values with filled circles. In Ref. [5] (Caurier *et al.*) calculations were performed without (a) and with (b) intruder configurations.

Isotope	^{26}Mg	^{27}Mg	^{28}Mg	^{29}Mg	^{30}Mg	^{31}Mg	^{32}Mg	^{34}Mg
$J^{\pi}_{g.s.}$	0^+	$1/2^+$	0^+	$3/2^+$	0^+	$(3/2)^+$	0^+	0^+
E_1 [keV]	1808.73	984.92	1473.4	54.6	1482.2	50.5	885.5	660^5
J^{π}_1	2^+	$3/2^+$	2^+	1/2 to 5/2	2^+		2^+	2^+
E_2 [keV]	2938.34	1698.63	3862.7	590	1788.8	221	2117	2120^5
J^{π}_2	2^+	$5/2^+$	0^+		1 to 4^+			4^+
E_3 [keV]	3588.56	1940.35	4020.2	1094.5	1820.2	461	2321	
J^{π}_3	0^+	$5/2^+$	4^+		1 to 3			
$B(E2; 0^+_{g.s.} \rightarrow 2^+_1)$ [e^{2}fm^4] *experiment*	306(4)		338(28)		$295(26)^2$ $435(58)^3$		$454(78)^1$ $333(70)^2$ $622(90)^3$	$631(126)^4$
$B(E2; 0^+_{g.s.} \rightarrow 2^+_1)$ [e^{2}fm^4] *theory*	Ref. [3] Ref. [4] Ref. [5] - normal Ref. [5] - intruder				289 182 265 560		452 593 180 490	572 549 375 655

Table 1: Some properties of the lowest states of the neutron-rich Mg isotopes. The values have been taken from the following references: ^{1} - [12](RIKEN), ^{2} - [13](MSU), ^{3} - [14](GANIL), ^{4} - [10](RIKEN), ^{5} - [9](RIKEN). The remaining values were taken from [15].

2 Physics Goals

The goals of this experiment are:

- the determination of the $B(E2; 0^+_{g.s.} \rightarrow 2^+_1)$ with high precision for $^{26,28,30(,32)}$Mg. The current values for the radioactive isotopes have a 10-20% error and the results of some measurements are inconsistent.[3] The isotope ^{26}Mg is stable and its properties are well known serving as a test case for the proposed experiment.

- the identification of the 4^+ state and the measurement of the corresponding $B(E2; 2^+ \rightarrow 4^+)$ for the even-even isotopes.

- the measurement of the (low-lying) E2 strength for odd-even isotopes ^{27,29,31}Mg which will be distributed over several (low-lying) levels. The resulting level scheme is characteristic of the sign of the deformation [16]. In addition, from the sign of the E2-M1 mixing ratio, extracted from the angular distributions, the sign of the deformation can be extracted [17].

- the measurement of the single particle properties of $^{27\text{-}32}$Mg using neutron-pickup reactions on the ^{9}Be and ^{2}H targets resulting in spin and parity assignments and spectroscopic factors.

The systematic information gained will help to further delineate the boundary of the island of deformation around ^{31}Na. In addition other reaction channels will possibly provide new information on other isotopes as well. The main channels observed in the test experiments are proton-pickup on ^{2}H and fusion evaporation on the ^{9}Be target.

3 Experimental Method

3.1 Coulomb Excitation

Assuming first order perturbation theory to be valid the Coulomb excitation cross sections have been calculated using the prescription given in [18]. The cross sections for Coulomb excitation of the first excited 2^+ states in ^{30,32}Mg are shown in Fig. 3 (thick lines) as a function of the charge number of the target nucleus; the current maximum beam energy of REX of 2.2 MeV/u was used. The cross sections are in the range between 100 mb and 1 b and an optimum target material seems to be Ni ($Z = 28$). The *safe distance* condition[4] is fulfilled for all scattering angles if the distance of closest approach in a head-on collision, $2a_0$, is larger than $R_1 + R_2 + S$.[5] For a Ni ($Z = 28$) target S will be 2 fm (dotted line in Fig. 3), which is not considered completely safe. However, by limiting (in the analysis) the

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[3] Whether the ^{32}Mg measurement is possible depends on the available beam intensity in the experiment.

[4] *Safe* means safe from nuclear interaction in the excitation process to allow a model independent analysis.

[5] $R_{1,2}$ are the nuclear radii of projectile and target.

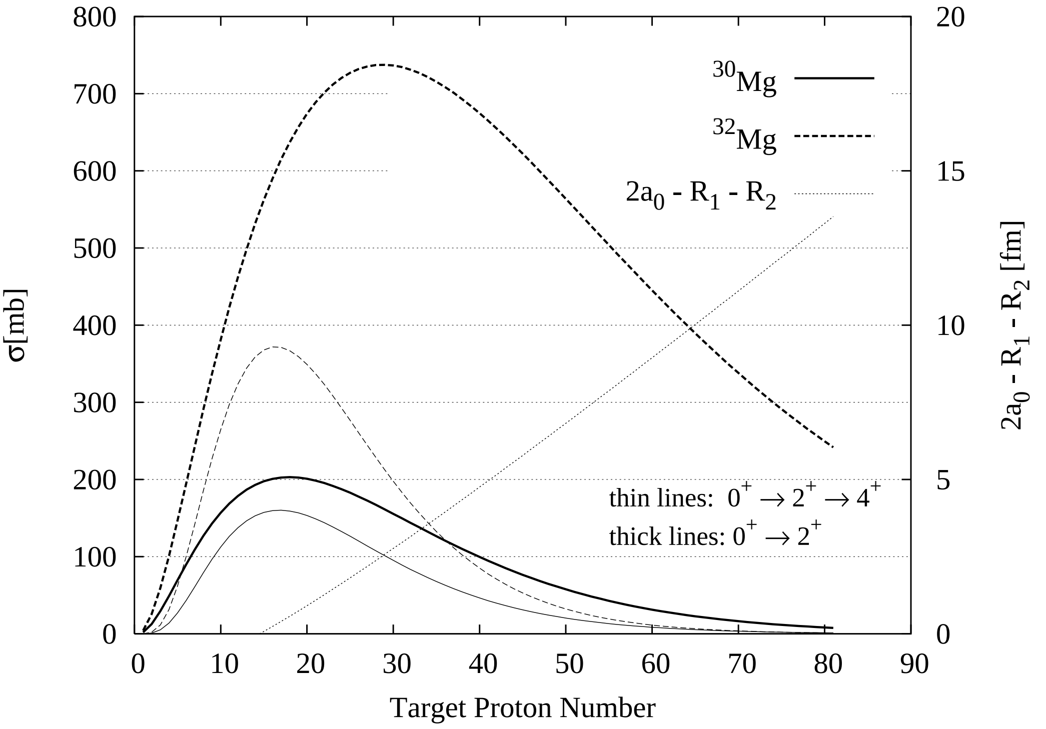

Figure 3: Coulomb excitation cross section as a function of target charge. The thick lines assume an excitation from the ground state to the first excited 2^+ state and the thin lines a double excitation to the 4^+ state. The dotted line shows the closest distance the nuclear *surfaces* can reach, where a_0 is the half-distance of closest approach in a head-on collision.

accepted angular range of the scattered particles a more stringent safe distance condition between the nuclear surfaces can be fulfilled (e.g. $S = 5$ fm) that would result in a more model independent analysis. Alternatively all the scattering angles and therefore a higher cross section can be utilized if a larger uncertainty on the extracted $B(E2; 0^+_{g.s.} \rightarrow 2^+_1)$ (due to the influence of the strong interaction) can be accepted.

The double Coulomb excitation cross section $0^+ \rightarrow 2^+ \rightarrow 4^+$ has also been estimated according to [19] (thin lines in Fig. 3) using the energies in row E_2 in Tab. 1 as the 4^+ energies and the same $B(E2)$ as for the $0^+ \rightarrow 2^+$ excitation. For the higher intensity beams (^{28,30}Mg) this excitation should be observed in this experiment. The identification of the 4^+ states would give important information on the character of the excitation (rotation or vibration).

3.2 Transfer Reactions

In anticipation of experiments at REX-ISOLDE Lenske and Schrieder [20] theoretically investigated the possibilities of one nucleon transfer reactions with deuterium targets for the study of nuclei far from stability. They showed that single nucleon transfer cross sections can reach large values of up to 150 mb at beam energies typical for REX-ISOLDE (i.e. 2.2 A MeV). This behavior is mainly due to the (kinematic) Q-value matching and the extended wave functions for neutron-rich isotopes. In addition to calculations with a deuterium target also ^{9}Be was discussed as a target nucleus. The calculated cross sections for neutron pickup from ^{9}Be are on the same order as the corresponding cross sections for a deuterium target. The main advantage of using also a ^{9}Be target, in addition to the deuterium target, is that the proton pickup reaction, which is a strong transfer channel for a deuterium target, is strongly suppressed for ^{9}Be as the proton separation energy is much larger than the neutron separation energy ($S_{\mathrm{n}} = 1.7$ MeV, $S_{\mathrm{p}} = 16.9$ MeV). Therefore, a comparative measurement with the ^{9}Be target will help to assign the γ transitions observed with the deuterium target to the corresponding final transfer product. It should be mentioned in this context that, at REX-ISOLDE beam energies, all theoretical tools necessary to analyze the experimental data are well developed (see e.g. [21, 22, 23]).

In preparation for experiments at REX-ISOLDE using the MINIBALL spectrometer a test experiment was performed at the MPI-K in Heidelberg. The main result was that it is indeed possible to perform also with low intensity beams one neutron/proton pickup studies on ^{2}H and ^{9}Be targets in inverse kinematics by purely γ spectroscopic means. A detailed report is given in [24].

Since the energy and the scattering angle of the light transfer products (protons and ^{8}Be particles for neutron-pickup on ^{2}H and ^{9}Be, respectively) are measured the excitation energy of the heavy transfer product can be obtained. Even though the resolution is fairly poor (only about 500keV - 1MeV) complementary information is obtained, which helps assigning the observed γ transitions.

It should be pointed out that in *neutron pickup* reactions on *neutron-rich* nuclei the nucleus to be studied has picked up one extra neutron, which corresponds to a gain of about a factor of 10 in beam intensity, since a less exotic beam (by one neutron) can be used.

3.3 Results of the Commissioning Experiment in November 2001

In order to study the operation of the MINIBALL cluster detectors in close proximity to the REX accelerator and with a *radioactive* beam a test experiment with only one MINIBALL triple cluster detector and the MINIBALL data acquisition system was performed in November 2001[6]. In addition to the MINIBALL detector a position sensitive Si telescope detector was employed.

Fig. 4 shows a first γ spectrum obtained in the test experiment with a stable ^{23}Na beam with an energy of 2.0 MeV/u.[7] A Doppler broadened γ transition of 440 keV can be observed, corresponding to the deexcitation of Coulomb excited ^{23}Na beam on a Ni target. Also seen is a strong background at energies below 250 keV. This background was

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[6] The first radioactive beam was accelerated by REX in October 2001.

[7] The maximum REX-ISOLDE energy of 2.2 MeV/u was not available during the test experiment.

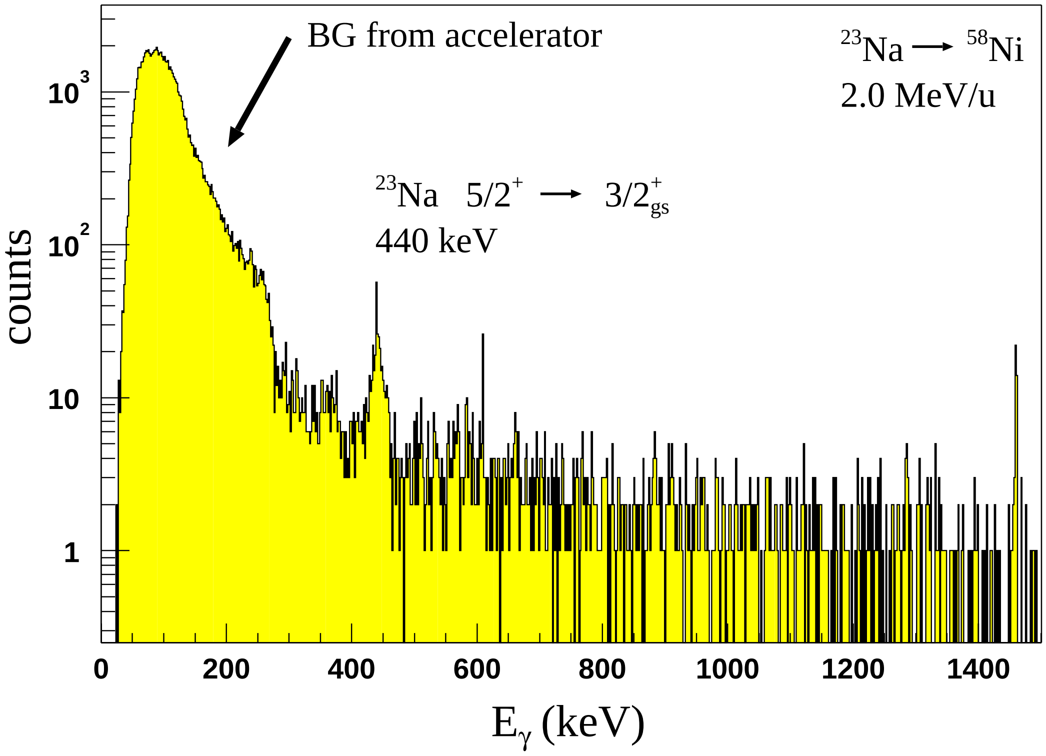

Figure 4: Coulomb excitation of a stable ^{23}Na beam, the first beam accelerated by REX-ISOLDE to a beam energy of 2.0 MeV/u in this test experiment, on a Ni target. The background caused by the accelerator could be completely removed in later runs by a proper shielding of the resonators.

subsequently suppressed by the installation of a shielding wall between the accelerator and the experimental setup.

Fig. 5 shows two γ spectra obtained with an unstable ^{24}Na beam impinging on a ^{9}Be target. The top panel shows the spectrum in coincidence with any signal in the Si detector above threshold, whereas for the bottom panel the detection of *two* particles in the Si detector was required, which selects the neutron-pickup channel, since the light transfer product ^{8}Be decays immediately into two α particles. Several Doppler broadened lines can be seen in the top panel, whereas a known transition in ^{25}Na stands out when neutron pickup is required. In addition a low lying transition at 89 keV was also observed (not shown) demonstrating the advantage of this method in comparison to high energy reactions, where a strong background at low energies impedes any measurement. Another finding of the test experiment was that the β decay background is sufficiently suppressed by the coincidence requirement.

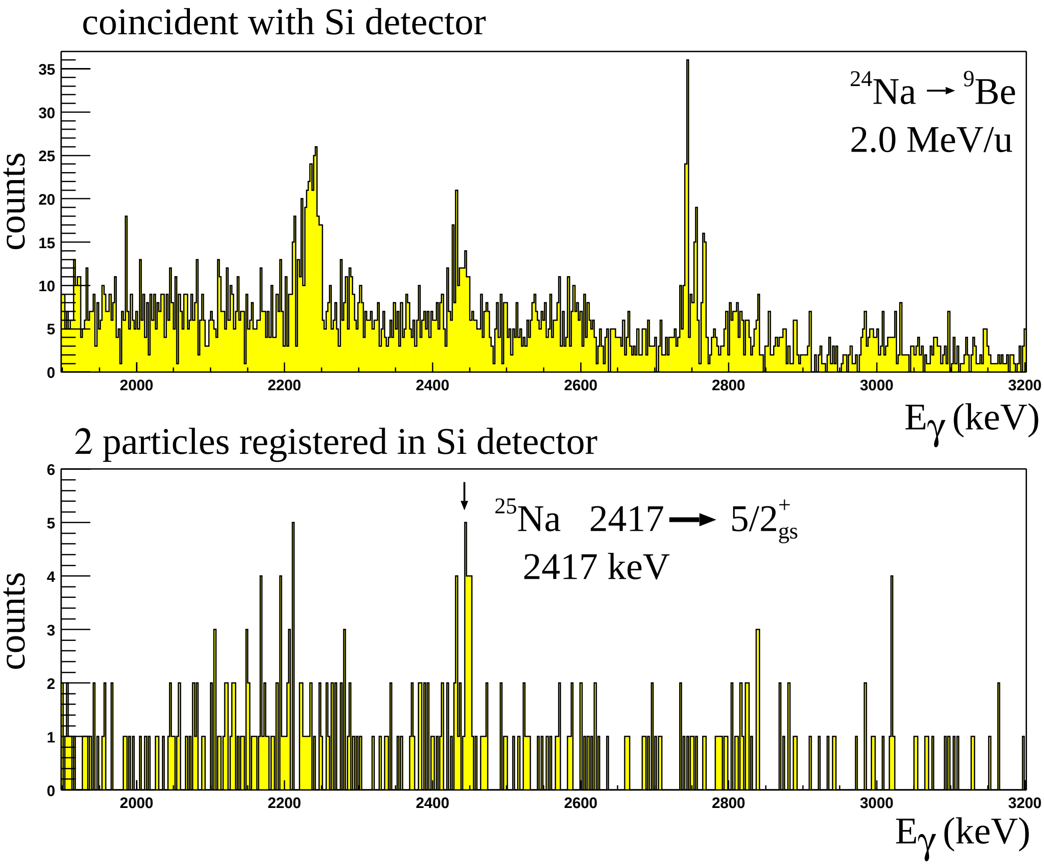

Figure 5: First neutron pickup measurement from ^{9}Be performed with a radioactive ^{24}Na beam accelerated by REX-ISOLDE to 2.0 MeV/u. Requiring the detection of 2 particles selects the neutron-pickup channel and results in the observation of excited states in ^{25}Na (lower panel).

3.4 Experimental Setup

We propose to use a resonance ionization laser ion source (RILIS) with a UC ISOLDE target to produce low-energy beams of neutron-rich radioactive Mg isotopes, which will be accelerated by REX-ISOLDE to an energy of 2.2 MeV/u and will be incident on Be, CD_2, and Ni targets,[8] where neutron-pickup (Be, CD_2) and Coulomb excitation (Ni) will take place. The emitted γ rays will be detected by the MINIBALL array with a typical efficiency of around 10% at 1 MeV photon energy. Scattered reaction products will be detected in coincidence with γ rays by a double-sided silicon strip telescope covering forward angles from about 20° to 80°, which will allow particle identification and the determination of the particle direction and its energy. This information will be used to select the reaction

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[8] the use of heavier targets will be investigated

channel and to determine the excitation energy of the heavy reaction product after transfer. The measured direction of the particle will be used (especially for the Coulomb excitation measurement, where large scattering angles occur) together with the position information from MINIBALL to correct for the Doppler shift of the detected photons. A thin PPAC [25] placed in the beam line after the target will be used for beam particle counting. Absolute cross sections can then be obtained by comparison to known reaction channels (e.g. Coulomb excitation of the target) and directly via beam particle counting at low beam intensities.

The setup for both types of experiments (pick-up and Coulomb excitation) is identical and only the target has to be changed. All targets necessary for the experiment will be mounted on a target wheel inside the chamber and can be changed in a very short time without breaking the vacuum.

4 Beam Time Request

Typical cross sections (100 mb – 1 b) and typical target thicknesses (1 mg/cm^2) result in reaction probabilities of about 10^{-5}. To collect 1000 events in the full-energy peak 10^9 beam particles are required (assuming a γ efficiency of 10%) We therefore request a total of **24 shifts**, which are distributed as shown in the following table. **One day** of beam time will be required to adjust the setup and for beam tuning.

beam	isolde rate (s^{-1})	rex rate (s^{-1})	shifts
^{26}Mg			1
^{27}Mg	$4 \cdot 10^7$	$8 \cdot 10^5$	1
^{28}Mg			2
^{29}Mg	$1.6 \cdot 10^6$	$3 \cdot 10^4$	2
^{30}Mg	$7 \cdot 10^5$	$1.5 \cdot 10^4$	4
^{31}Mg			11
^{32}Mg	$> 10^3$	> 20	
		total:	**21**

For the REX rates an efficiency of 2% was assumed, which might be improved significantly. For some isotopes no recent rate measurement [26] was available and a smooth behavior was assumed. The 11 shifts for ^{31,32}Mg will be distributed depending on the actual production rates of these isotopes. For each isotope the beamtime will be used in equal parts for each of the three targets (CD$_2$, ^{9}Be, Ni). The properties of the isotope ^{26}Mg (stable) are well known and serve as a test case for the experiment.

5 Final Remark

The proposed experiment would yield a systematic understanding of the collective and single particle properties of the neutron-rich Mg isotopes especially in the vicinity of the island of deformation around ^{32}Mg. The results will be complementary to the ones obtained from the experiment IS379 [27] to be performed in April 2002. The experiment is part of the thesis work of O. Niedermaier.

If approved the experiment can efficiently be combined with the proposal [28] on sub-barrier fusion.

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