Measurement of one-neutron removal momentum distribution and interaction cross section in the island of inversion around N=20

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Motivation :

The island of inversion around N=20 in the neutron-rich region of the nuclear chart has been subject of many studies over the last few years. The interesting observation of the breakdown of N=20 shell closure [1] brought in new challenges to understand the nuclear structure in this region. The deformation of ^{32}Mg was observed in various studies [2-4]. The deformation is attributed to an inversion of the order of the *pf*-shell orbitals and $d_{3/2}$ orbitals of the neutrons. The neutron-rich Mg isotopes, ^{33}Mg and ^{35}Mg, are thus interesting to investigate in order to understand their structures and cause of the N=20 magic number disappearance in this region. This proposal is motivated by our aim to investigate the single particle orbitals and their occupancies which constitute the ground state of ^{33}Mg. The matter density distribution of ^{34,35}Mg will be derived. This will also reflect on the single particle orbitals occupied by the neutrons.

A naïve shell model ordering of orbitals would suggest a ground state spin of $7/2^-$ for ^{33}Mg. However the allowed beta decay branch of ^{33}Na to the ground state of ^{33}Mg suggested the most plausible spin of the ground state of ^{33}Mg to be $3/2^+$ indicating the inversion of the $f_{7/2}$ and $d_{3/2}$ orbitals [5]. It is suggested that the ground state of ^{33}Mg has a two-particle one-hole nature. The decay branches to other bound as well as unbound states were also observed, providing a tentative level scheme for ^{33}Mg [5]. The intermediate energy Coulex measurement suggested that ^{33}Mg has a deformation similar to other nuclei in the island of inversion [6]. Till today this tentative spin assignment has not been confirmed directly by any reaction study or magnetic moment measurement. The proposed experiment will determine the spin and parity assignment to the ground state of ^{33}Mg.

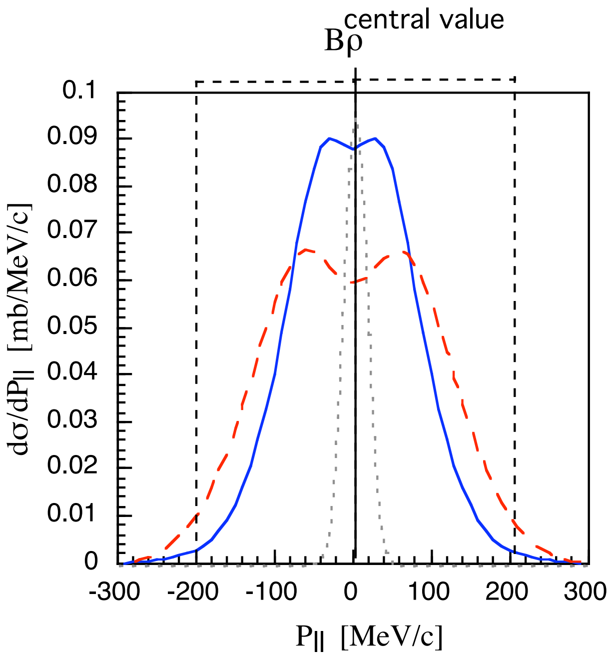

Fig.1 Longitudinal momentum distribution calculated by the ^{32}Mg core + n eikonal model with 'core' ^{32}Mg in its ground state. The two possibilities of valence neutron is shown $d_{3/2}$(blue solid line) $f_{7/2}$(red dashed line). The dotted vertical lines show the ±1% momentum acceptance which can be covered in one magnetic rigidity setting of the FRS. The grey dotted line shows the momentum resolution of the system.

The study of the longitudinal momentum distribution ($P_{\|}$) from one-neutron removal from a nucleus is known to provide clear evidence for intruder orbitals in neutron-rich nuclei. The shape of this momentum distribution in the rest frame of the nucleus reflects the wavefunction of the single particle orbitals occupied by the knocked-out neutron [7,8]. Fig.1 shows the momentum distributions calculated in core+n eikonal model reaction theory for the neutron in ^{33}Mg occupying either the $d_{3/2}$ or the $f_{7/2}$ orbital. The shapes as well as the amplitudes of the distributions differ sizably. Thus, a $P_{\|}$ measurement of ^{33}Mg will provide us with a clear signature of its ground state spin and configuration.

Moving to the more neutron-rich region no information exists presently on the ground state of ^{35}Mg. The only experimental information existing on this nucleus now is its measured mass. The nucleus ^{35}Mg shows a sudden drop in its separation energy. The value however has a large uncertainty. The recent mass measurement at GANIL [9] yields a value of $S_n = 0.709^{+0.875}_{-0.709}$ MeV. The lower direction of the separation energy might even allow some interesting exotic structure formation in this nucleus which might involve reordering of orbitals. Thus a measurement of density distribution and root mean square radius of this nucleus is interesting. The beam intensity for ^{35}Mg being fairly low, an investigation of its momentum distribution is postponed for the future.

Experiment :

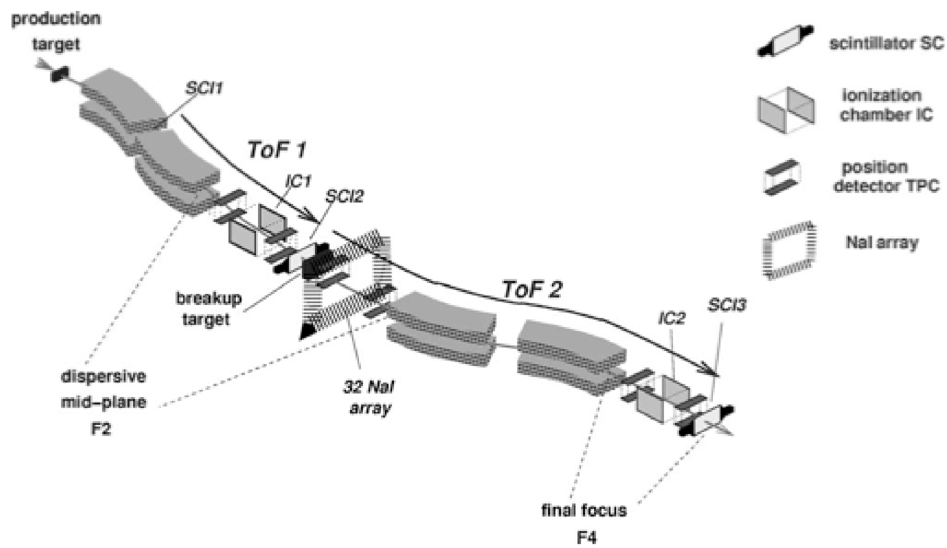

Fig.2 Schematic Layout of the experimental setup adopted from Ref.[12].

The experiment will be performed using the fragment separator FRS at GSI operated in the energy loss (i.e. dispersion-matched mode). Such ion optics have been very successfully used for measuring momentum distributions of neutron rich Carbon [10], oxygen, fluorine[11], and proton-rich ^{8}B [12].

A primary beam of ^{48}Ca with an intensity of 10^9/spill at 1*A* GeV, will be used to produce the neutron-rich ^{33}Mg by projectile fragmentation. The primary production target will be Be. The carbon reaction target will be located at the second dispersive focal plane, S2. The optimum yield condition for ^{33}Mg at the reaction target have been ascertained by a Monte Carlo simulation using the code MOCADI [13]. A schematic sketch of the experimental arrangement is shown in Fig.2.

The incident beam will be identified event by event using time of flight (TOF) measured between plastic scintillators placed at S1 (SCI1) and S2 (SCI2), the magnetic rigidity, and energy loss measured using an ionization chamber (IC1) placed at F2 upstream of the C reaction target.

The optimum Be target thickness is found to be 6 g/cm^2. The size of the scintillator at S1 which acts as an active collimator will be ±5cm. The total rate of fragments at S1 under this condition is estimated to be 5.5×10^3 /sec for the FRS tuned for ^{33}Mg, while the rate drops for the ^{35}Mg setting. Thus under both setting conditions the detector at S1 can be operated without any problem. The above conditions lead to production of ^{33}Mg with an intensity of ~ 28/sec and decreases as we move to the more neutron-rich species to 0.5/sec for ^{35}Mg, on the reaction target. These production rates are based on cross sections calculated by the EPAX 2.1 code. It maybe mentioned here that ^{33}Mg can also be produced using ^{40}Ar primary beam but the production cross section is 50 times lower than with ^{48}Ca. The resultant intensity on reaction target for such a choice of primary beam with an intensity of 10^{10}/spill is ~ 21/sec. Since the production cross section using EPAX may have some uncertainty we choose the beam with higher production cross section. At the beginning of the experiment the first half of FRS will be tuned to have ^{33}Mg as the fragment with central rigidity incident on the target.

For measuring the momentum distribution after one-neutron removal from ^{33}Mg, second half of FRS will be tuned to collect the fragments ^{32}Mg at the final focus S4. These fragments will be identified using TOF between scintillators (SCI2) at F2 to (SCI3) at F4, the energy loss using an ionization chamber (IC2). The position of the fragments will be measured using the TPC tracking detectors. The position at F4, after dispersion matching, is proportional to the internal momentum distribution of the fragment which we are aiming to measure. The use of a 4g/cm^2 thick C reaction target at the dispersive focus S2 will require the normal dispersion from S2-S4 to be reduced by ~3.6% for achieving the dispersion-matched condition. The momentum resolution ($\sigma P_{\|}$), including ion optical effects, position resolution of 500μm(σ), as well as multiple scattering in the reaction target, detectors and vacuum windows, is expected to be $\sigma P_{\|}$~ 17 MeV/c. The dotted line in Fig.1 shows the resolution, in comparison to the distributions that are expected from breakup of ^{33}Mg. The momentum acceptance of FRS is ±1%. Thus we can see from figure 1 (vertical dotted lines), that a fairly good part of the momentum distribution can be measured in a single rigidity setting of FRS.

In addition to this basic setup an array of Ge or NaI detectors will be placed forward of the target for detecting the gamma rays in coincidence with the one-neutron-removal fragments. Besides determining the composite shape of the momentum distribution, the detection of gamma rays will allow the possibility of obtaining partial momentum distributions for different configurations constituting the ground state of ^{33}Mg. We consider a gamma ray detection efficiency of ~ 5% in the count rate estimate.

In order to derive the density distribution and root mean square radius, we aim to measure the interaction cross section of $^{33-35}$Mg. It maybe mentioned here that this will extend radii measurements existing upto ^{32}Mg, across N=20 [14]. A measurement of this observable using three different targets will allow us to derive a model independent shape of the density distribution. For ^{33}Mg we will restrict the momentum acceptance at S1 further to ensure 99% transmission after the reaction target. For ^{34,35}Mg the ±5cm S1 acceptance of the plastic scintillator at S1 allow for 99% transmission. It should also be mentioned here that the high energy beams available only at GSI make this facility an ideal site for measuring the interaction cross section. At lower energies, theoretical interpretation of the data to derive an unambiguous density distribution is difficult.

Beamtime request :

The cross section for one-neutron removal calculated in an eikonal model is ~ 20-30 mb. Assuming the primary beam cycle time to be 3 sec and a C reaction target of $4 g/cm^2$, the count rates for detecting the one-neutron-removal fragment from ^{33}Mg (i.e. ^{32}Mg) are shown in Fig.3. Three different conditions where the core fragment ^{32}Mg is in its ground state (circles) or in its first excited state(squares and triangles) for a spectroscopic factor of 1.0 have been considered. Thus it is seen that the minimum measuring time for obtaining the partial momentum distribution to the excited state of ^{32}Mg is 2.5 days. For estimation of non-target background 0.5 day of measurement is needed.

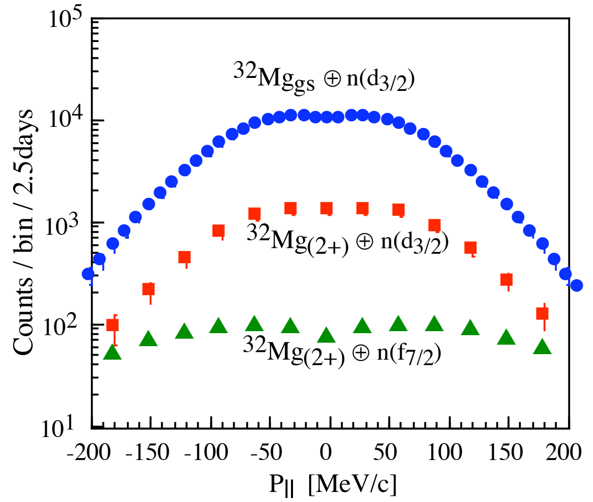

Fig.3 Expected count rates for the one-neutron-removal fragment ^{32}Mg from ^{33}Mg. The circles (blue) correspond to the condition where ^{32}Mg is in its ground state and the neutron in the $d_{3/2}$ orbital with spectroscopic factor =1.0 and bin size=10MeV/c. The squares (red) and triangles (green) correspond to the case where ^{32}Mg is in its first excited 2^+ state and the neutron is the $d_{3/2}$ and $f_{7/2}$ orbital, respectively. In this case the spectroscopic factor =1.0 and bin size = 30MeV/c

The momentum resolution needs to be measured by tuning the second half of the FRS to the incident beam, i.e. ^{33}Mg and ^{35}Mg. In addition to determining the momentum resolution this tune of the FRS will also allow us to measure the interaction cross section of ^{33}Mg and ^{35}Mg.

The interaction cross section is based on the method of transmission, thus a 99% transmission after the reaction target is necessary. This is achieved by restricting the momentum acceptance at S1, before the target. Besides relying on the calculated transmission by MOCADI simulation, the stability of the acceptance condition will be checked in offline analysis by ensuring that the derived interaction cross section remains unchanged by making narrower position selections before the reaction target. The position sensitive detectors placed before the target are necessary for this purpose. This will thus require collection of sufficient amount of statistics. The time for the interaction cross section measurements has been estimated to achieve an accuracy ~ 1% for $^{33,34}Mg$, and ±3% for ^{35}Mg, with count rate expected through the simulated collimations necessary at S1 for 99% transmission. If smaller collimation is found to be necessary through the position information, the accuracy will be affected. Keeping this in mind the beamtime requested should allow successful measurement within ±7% accuracy.

Table 1 summarizes the total beamtime request. We request 7 days measuring time for all the studies mentioned above and 3 days of beam tuning for the various FRS settings and electronics setup.

Table 1 Summary of beamtime request

Secondary Beam	FRS 2nd half (S2-S4) tuned to	Reaction Target	Hours
^{33}Mg	^{32}Mg	C	60
^{33}Mg	^{32}Mg	none	12
^{33}Mg	^{33}Mg	C	6
^{33}Mg	^{33}Mg	none	3
^{33}Mg	^{33}Mg	Be	6
^{33}Mg	^{33}Mg	none	3
^{33}Mg	^{33}Mg	Al	6
^{33}Mg	^{33}Mg	none	3
^{35}Mg	^{35}Mg	C	12
^{35}Mg	^{35}Mg	none	6
^{35}Mg	^{35}Mg	Be	12
^{35}Mg	^{35}Mg	none	6
^{35}Mg	^{35}Mg	Al	12
^{35}Mg	^{35}Mg	none	6
^{34}Mg	^{34}Mg	C	6
^{34}Mg	^{34}Mg	none	3
^{34}Mg	^{34}Mg	Be	6
^{34}Mg	^{34}Mg	none	3
^{34}Mg	^{34}Mg	Al	6
^{34}Mg	^{34}Mg	none	3
Secondary beam tunings	^{33,34,35}Mg	C + none	45
Electronics Setup			24
Total beamtime	**Main user**		**240**
			=10 days

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