# RESEARCH ON NEUTRON CLUSTERS

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A new approach to the production and detection of multineutrons, based on breakup reactions of beams of very neutron-rich nuclei, is presented. The first application of this technique to the breakup of $^{14}$Be into $^{10}$Be and $4n$ revealed 6 events consistent with the formation of a bound tetraneutron. The description of these data by means of an unbound tetraneutron resonance is also discussed. The experiments that have been undertaken at GANIL in order to confirm this observation with $^{12,14}$Be and $^{8}$He beams are presented. Special attention is paid to the angular correlations of some candidate events observed in the channel ($^{8}$He,$^{4}$He).

## 1. Neutral nuclei

Stable systems formed by few nucleons, such as $^{3}$H and $^{3,4}$He, have long played a fundamental role in testing nuclear models and the underlying N-N interaction. Their ground states, however, do not appear to be particularly sensitive to the form of the interaction. New perspectives should be provided by light nuclei exhibiting very asymmetric $N/Z$ ratios. For example, among the $N = 4$ isotones one finds the two-neutron halo structure around the $\alpha$ particle in $^{6}$He, or the ground state of $^{5}$H observed as a relatively narrow, low-lying resonance. Concerning the lightest isotone, $^{4}$n, nothing is known.

The existence of neutral nuclei has been a long standing question in nuclear physics. Over the last forty years very different techniques have been employed in various laboratories for the search of multineutrons, mainly $^{3,4}$n, without success[1]. All the techniques consisted of two stages, the formation and the detection of the multineutron, and the negative results were always interpreted as due to the extremely low cross-section of the reaction

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used to form the multineutron. Theoretically, *ab initio* calculations[2] suggest that neutral nuclei are unbound. However, the uncertainties in many-body forces, the already relatively poor knowledge of the two-body $n$-$n$ interaction, and in general the lack of predictive power of these calculations, do not exclude the possible existence of a very weakly bound $^4$n.

## 2. Neutron stars

One could argue that multineutrons, bound systems of neutrons, already exist: neutron stars. They are, however, at a very different size scale and held together by gravity. Is there any straightforward link between the possible existence of multineutrons at the nuclear scale and the characteristics of neutron stars?

The possible existence of multineutrons would not have any implication in the core composition, not even in the whole interior as at densities beyond $\rho_0$ nuclei dissolve —also neutral nuclei would. They could only appear in the inner crust, in which $^{56}$Fe coexists with very neutron-rich nuclei and free neutrons, but this is a very small part of the star and any effect would be far beyond the present experimental capabilities.

On the other hand, attempts are being made in order to link the properties of neutron stars with those of the most neutron-rich stable nucleus, $^{208}$Pb. Theoretical models explore in this way the $N$-$N$ interaction for $N > Z$. In that sense, multineutrons could provide a very important input, as their possible existence would constraint strongly the $N$-$N$ interaction in an almost proton-free environement like the one found in neutron stars.

## 3. A new approach

We have recently proposed a new approach to the production and detection of multineutron clusters[1]. The technique is based on the breakup of energetic beams of very neutron-rich nuclei and the subsequent detection of the liberated multineutron cluster in liquid scintillator modules. The detection in the scintillator is accomplished via the measurement of the energy of the recoiling proton ($E_p$). This is then compared with the energy derived from the flight time ($E_n$), possible multineutron events being associated with values of $E_p > E_n$.

In light neutron-rich nuclei, components of the wave function in which the neutrons present a cluster-like configuration may be expected to appear. Owing to pairing and the confining effects of any underlying $\alpha$-clustering on the protons, the most promising candidates may be the

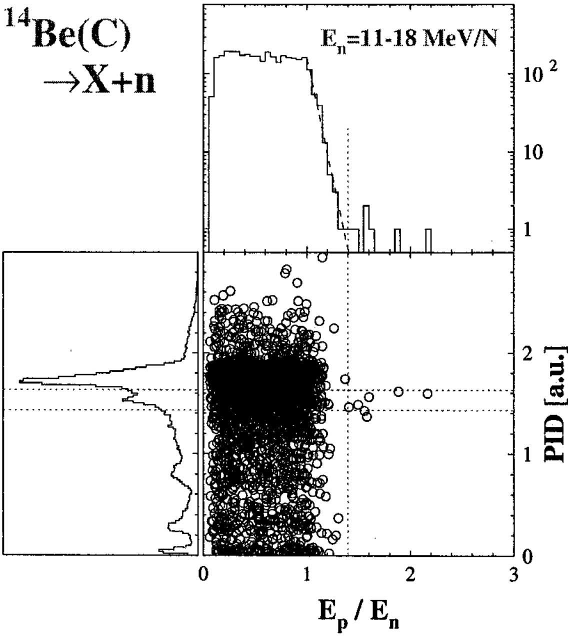

Figure 1. Scatter plot, and the projections onto both axes, of the particle identification parameter versus $E_p/E_n$ for the data from the reaction C($^{14}$Be,X+$n$). The PID has been projected for all neutron energies. The dotted lines correspond to $E_p/E_n$ = 1.4 and to the region centred on the $^{10}$Be peak[1].

drip-line isotopes of Helium and Beryllium, $^8$He ($S_{4n}$ = 3.1 MeV) and $^{14}$Be ($S_{4n}$ = 5.0 MeV). As breakup reactions present relatively high cross-sections (typically ~ 100 mb), even only a small component of the wave function corresponding to a multineutron cluster could result in a measurable yield with a moderate secondary beam intensity. Furthermore, the different backgrounds encountered in previous experiments are obviated in direct breakup.

The method has been applied to data from the breakup of $^{11}$Li, $^{14}$Be and $^{15}$B beams. In the case of $^{14}$Be, some 6 events have been observed with characteristics consistent with the production and detection of a multineutron cluster, most probably in the channel $^{10}$Be+$^4$n (Fig. 1). Special care was taken to estimate the effects of pileup; that is the detection for a breakup event of more than one neutron in the same module. Three independent approaches were applied and it was concluded that at most pileup may account for some 10% of the observed signal. The most probable scenario was concluded to be the formation of a bound tetraneutron in coincidence with $^{10}$Be[1].

## 4. Bound or resonant state?

Following the publication of our paper[1], many theoretical papers have investigated the conditions needed for the binding of a four neutron system[2]. The overall conclusion is that the present knowledge on the $n$-$n$ interaction and the physics of few-body systems do not predict a bound $^4$n. Interestingly, however, the calculations of Pieper suggested that it may be possible for the tetraneutron to exist as a relatively low-energy, broad resonance.

Two scenarios were confronted[1] in order to explain the events observed: the scattering of a bound $^4$n on a proton, and the detection of several neutrons in the same module (pileup). The hypothesis of a bound $^4$n was found to be consistent with the experimental observations, while the estimates of pileup obtained, mainly through Monte-Carlo simulations, were one order of magnitude too low.

If the four neutrons, however, form a resonance at low energy, the decay in flight will lead to four neutrons with very low relative momentum, and one could expect that the probability of some of them to enter the same module may increase. The simulations presented[1] have therefore been modified in order to include the decay of a $^4$n resonance[3].

The results of the simulations show the expected increase of the pileup probability towards low resonance energies. For a given resonance energy, the results do not depend much on the width. A significant increase of the pileup probability appears below $E = 2$ MeV, the resonance energy suggested by Pieper[2]. A resonance bellow 2 MeV may, therefore, be consistent with the events observed[1]. We note that preliminary results of an experiment measuring the $\alpha$ transfer in the reaction $^8\mathrm{He}(d, {}^6\mathrm{Li})4n$ suggest a resonant structure about 2 MeV above threshold[4].

## 5. New experiments and results

The confirmation of the multineutron candidate events observed with a higher intensity $^{14}$Be beam and an improved charged particle identification system, and the search for similar events in the breakup of $^8$He, were proposed at GANIL. Even if the intensity and quality of the $^8$He beam, delivered by SPIRAL, should be much higher, structural effects may well lead to a stronger $^4$n component in $^{14}$Be g.s. than, say, in $^8$He. For example, the configuration of the neutrons in a $^4$n system, $(1s)^2(1p)^2$, is closer to that of the valence neutrons in $^{14}$Be than to those in $^{8}$He. Therefore, if no events were observed during the $^{8}$He run the question whether the tetraneutron exists would remain open.

Unfortunately, several problems concerning the cyclotron lead to null results after two different attempts with $^{14}$Be beams, in 2001 and 2002. An analysis of the channel ($^{14}$Be,$^{8}$Be), planned in order to search in parallel for the existence of the hexaneutron, could not be performed either. The reanalysis of data from a previous experiment on the breakup of $^{12}$Be, specially the ($^{12}$Be,$^{8}$Be) channel, was also undertaken[6]. No clear evidence of such events appeared.

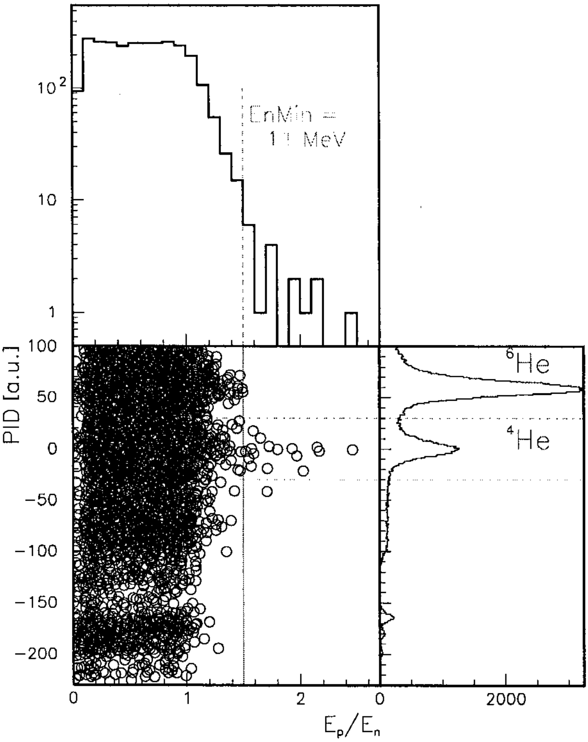

Figure 2. Same as in figure 1 for the data from the reaction C($^{8}$He,X+$n$). The PID has been projected for all neutron energies. The dotted lines correspond to $E_p/E_n$ = 1.4 and to the region centred on the $^{4}$He peak[5].

On the other hand, some data were acquired with a high intensity $^{8}$He beam from SPIRAL. Preliminary results[5] exhibit the same kind of signal observed previously[1], an abnormal number of high-energy proton recoils in the $-4n$ channel with respect to all other channels (Fig. 2).

## 6. Angular correlations and $^4$n resonances

Due to the (relatively) higher statistics and to the lower beam energy (13 MeV/N compared to the 35 MeV/N of the $^{14}$Be beam), the analysis of the relative angle between the $^4$He fragment and the neutron in the proyectile frame becomes feasible. This analysis was already introduced in the $^{14}$Be data[1], but was not developed in detail due to the energy constraints.

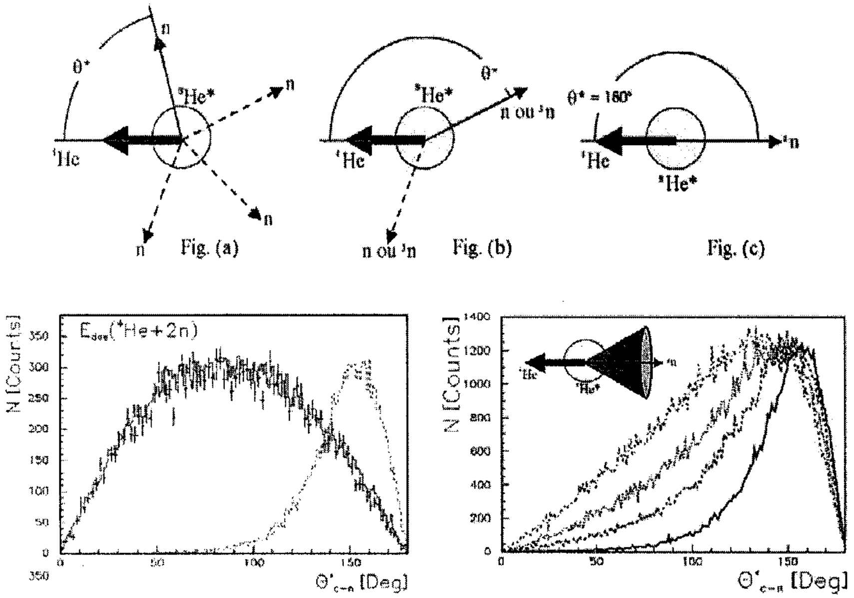

Figure 3. Angular correlations between the $\alpha$ particle and the neutron in the $^8$He reference frame $(\theta^*_{cn})^5$. On the upper row, the 5, 3 and 2 body phase-space scenarios. On the lower-left panel, all the data (points), the 5 body phase-space simulation (solid line) and the $^4$n bound state scenario (dotted line). On the lower-right panel, the $^4$n resonant state simulations from 0.1 MeV to 2 MeV (from right to left).

The results of the simulations are presented in Fig. 3. The 5 body phase-space simulation describes very accurately the whole data. But most importantly, the bound and resonant states lead to significantly different correlation patterns, being in the resonant case different for each of the resonance energies.

This parameter is therefore sensitive to the nature of the tetraneutron state, and, in the case of the resonance hypothesis, to its energy. The 14 events observed on Fig. 2 lie in the region between 60 and 160 degrees[5], and seem in principle closer to the low-energy resonant state hypothesis, but the analysis is still in progress.

## 7. Conclusion

After four decades of experimental search for multineutrons, or neutral nuclei, the new approach described here has lead to the first observation of events that can, at present, be only explained through the existence of a $4n$ state. This state could be a very weakly bound (neutral) nuclei[1], or a broad low-energy resonance[3]. Following the most complete calculations to date[2], the most likely scenario should be the latter.

Among the different attempts at confirmation, only the one using an intense $^8$He beam from SPIRAL was successful. The preliminary results, and the analyses in progress, seem to confirm the existence of the $^4$n state[5]. A new experiment aiming to study the ($^{14}$Be$^*$,$^{10}$Be+$^4$n) channel using one proton knock-out from a more intense $^{15}$B beam will be undertaken at GANIL in 2005.

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# NEUTRON TRANSFER STUDIED WITH A RADIOACTIVE BEAM OF $^{24}$NE, USING TIARA AT SPIRAL

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A general experimental technique for high resolution studies of nucleon transfer reactions using radioactive beams is briefly described, together with the first new physics results that have been obtained with the new TIARA array. These first results from TIARA are for the reaction $^{24}$Ne(d,p)$^{25}$Ne, studied in inverse kinematics with a pure radioactive beam of $10^5$ pps from the SPIRAL facility at GANIL. The reaction probes the energies of neutron orbitals relevant to very neutron rich nuclei in this mass region and the results highlight the emergence of the N=16 magic number for neutrons and the associated disappearance of the N=20 neutron magic number for the very neutron rich neon isotopes.

## 1. Introduction

A great hope for the future in radioactive beam experiments is to be able to map out the changing shell structure for very exotic nuclei, away from stability, where this arises from effects such as the monopole migration of orbital energies and the changes brought about by alterations in the surface environment and spin-orbit splitting[1]. Nucleon transfer reactions such as (d,p), (p,d) etc. are an established means of populating and studying nuclear levels that have a substantial single-particle structure. The development of techniques to use such reactions with radioactive beams, across a wide range of beam energies and masses and with high energy resolution, will open the way to exploit transfer across new regions of the nuclear chart and hence to study the new nuclear structure effects that evolve.

The technique that is described here, and implemented via the new TIARA array used in association with the VAMOS spectrometer and the EXOGAM gamma-ray array, is designed to achieve excitation energy resolution of better than 20-40 keV in the final nucleus. This is an order of magnitude better than can be achieved in a reasonable experimental setup that uses charged-particle observations only[2]. The complete kinematical detection of the binary transfer reaction products specifies the reaction channel cleanly, where the identification of the heavy (beam-like) particle at least in Z is required, and the light (target-like)-particle detection allows angular distributions to be measured for any mass of projectile.

The present paper updates and extends results of the analysis in progress, reported elsewhere[3,4].

## 2. The TIARA Array

The requirement to use inverse kinematics in order to study nucleon transfer reactions, induced on radioactive species by protons and deuterons, imposes certain rather general requirements on the detection system to be used. The kinematics turns out to lead to particular reactions always appearing in the same characteristic range of laboratory angles and with similar energies, regardless of the mass or velocity of the incident beam[5,4]. This allows a general purpose transfer apparatus to be designed.

The design philosophy and detailed description of TIARA has been discussed elsewhere[3,6] but, briefly, the aim was to surround the target with a charged particle array that approached $4\pi$ coverage, with reasonable energy measurement and an angular resolution of 1 or 2 degrees. This array needed to be very compact so that a high gamma-ray efficiency of >15% (at 1.3 MeV) could be achieved, whilst avoiding the exposure of gamma-ray detectors to decay radiation from beam particles scattered in the forward 40°. In the present setup, the TIARA array covers 82% of $4\pi$ with active silicon and the gamma-ray detectors are in a close cube geometry and thus subtend 67% of $4\pi$. The setup is mounted in front of a magnetic spectrometer which is used to separate physically the direct beam and the transfer reaction products, after the target. The region around the target is shown in Fig. 1.

## 3. Experimental Details

The TIARA system was set up in front of the VAMOS spectrometer at GANIL[7], which was operated in dispersive mode at zero degrees. Direct beam was intercepted just in front of the focal plane detectors. The support frame and four detectors of EXOGAM[8] surrounded the TIARA chamber. All events in which a particle was detected in TIARA were recorded. The gamma ray parameters were recorded via the VAMOS acquisition system and events were correlated with TIARA in real time via an event stamping method developed at GANIL.

Figure 1. The four EXOGAM detectors, in a compact cube geometry, are shown mounted around the TIARA vacuum vessel, which is symmetric (both cylindrically and forward-backward around the target) and narrows down to just 98mm in diameter near the target. The TIARA array is inside, and the beam enters through a target selection mechanism, also located inside the vessel at the lower right.

An isotopically pure beam of $^{24}$Ne was supplied at 10 MeV/nucleon after reacceleration in the CIME cyclotron connected to the SPIRAL facility at GANIL. The beam intensity of $10^5$ pps was a factor of two lower than the maximum due to a limitation placed on the emittance, which limited the beam spot on target to a diameter of approximately 2mm base width. The target was 1 mg/cm$^2$ of $CD_2$ self supporting on a thin 25mm diameter frame.

A test experiment was performed with a stable beam of $^{14}$N at similar intensity and beam quality, in order to verify that normal kinematics (d,p) results from the literature could be reproduced with the TIARA setup. Good agreement was found[9].

## 4. Results

The isotopic identification for beam-like particles recorded at the focal plane of VAMOS is shown in Fig.2. This is derived from measured $\Delta E$, $E$ and time-of-flight parameters plus a ray tracing calculation that used the horizontal and vertical angles and positions measured at the focal plane. The ray tracing algorithm employed a neural network that was trained using a set of theoretically calculated rays obtained by numerical integration of their trajectories through VAMOS[10] and this gives results identical to an algebraic algorithm developed at GANIL.

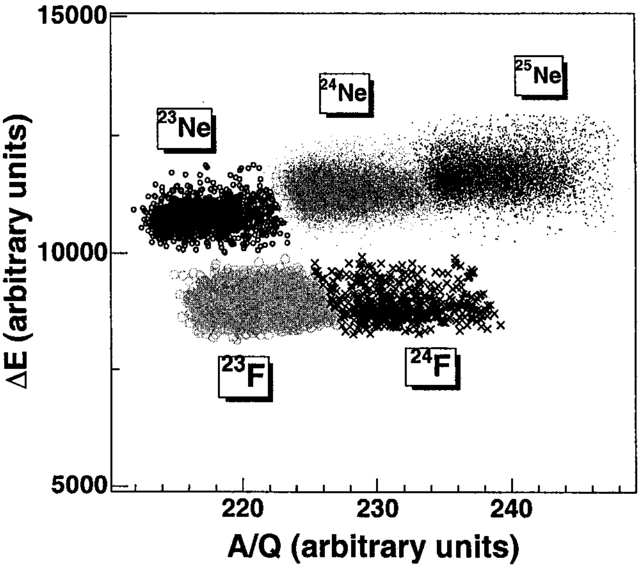

Figure 2. Particle identification for particles recorded behind the beam stop at the focal plane of VAMOS.

By selecting the $^{24}$Ne ions in Fig.2, the scattered deuterons recorded in TIARA could be analysed. The $^{24}$Ne momentum changes sufficiently quickly with scattering angle that very forward scattered elastics can still avoid the beam stop. The energy of the deuterons changes rapidly with their angle[5] and, by using energy cuts, the elastic angular distribution could be extracted (see Fig.3). A good fit was obtained using the optical potential measured for d+$^{26}$Mg at a similar energy[11]. The normalization obtained using these elastic data allowed absolute transfer cross sections to be extracted with confidence. From the measured energy and angle recorded for

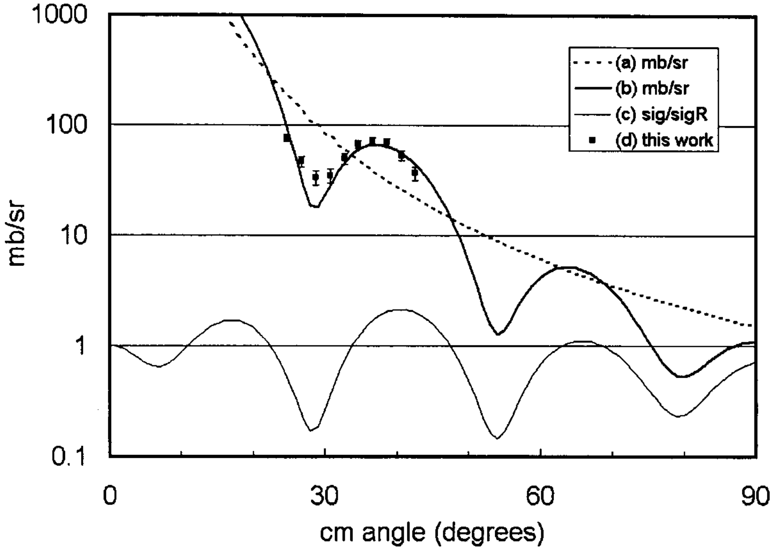

Figure 3. Angular distribution for d + $^{24}$Ne elastic scattering: (a) Rutherford formula, (b) optical model calculation (see text), (c) ratio of (b) to (a), and (d) present measurements.

protons from the (d,p) reaction to make $^{25}$Ne (cf. Ref.3) the excitation energy spectrum for states in $^{25}$Ne could be deduced. Different peaks in this spectrum could be used to gate the spectrum of associated gamma rays. Example data are included in Fig.4. An important result of this analysis was that the excitation energies of the populated states could be fixed with an accuracy of order 30 keV. The limiting factor in this accuracy was the poor statistics of the gamma ray spectrum. This was in fact severely compromised in the present experiment by an intermittent fault in an electronic discriminator unit, and the eventual aim in this type of experiment will be to use individual gamma ray peaks to apply gates in the analysis. In the present case, however, it was still of vital importance that the gamma ray data could fix the energies and the number of peaks to be fitted to the (poorer resolution) excitation energy spectra derived from the particle energies. These fits are shown in the inset of Fig.4. The data are just sufficient to allow limited gamma-gamma coincidence analysis. In the case of the state near 4 MeV it can be seen that the 1.7 MeV and 2.4 MeV gamma rays seen in its decay [Fig.4(b)] appear to be in coincidence [Figs.4 (c) and (d)]. The excitation energy spectrum (derived from the proton energy and angle) was fitted with 5 peaks. The widths of these peaks depended on the experimental resolution of the system, and this was in turn dependent on the detection angle of the proton. Thus, the data were binned for angular

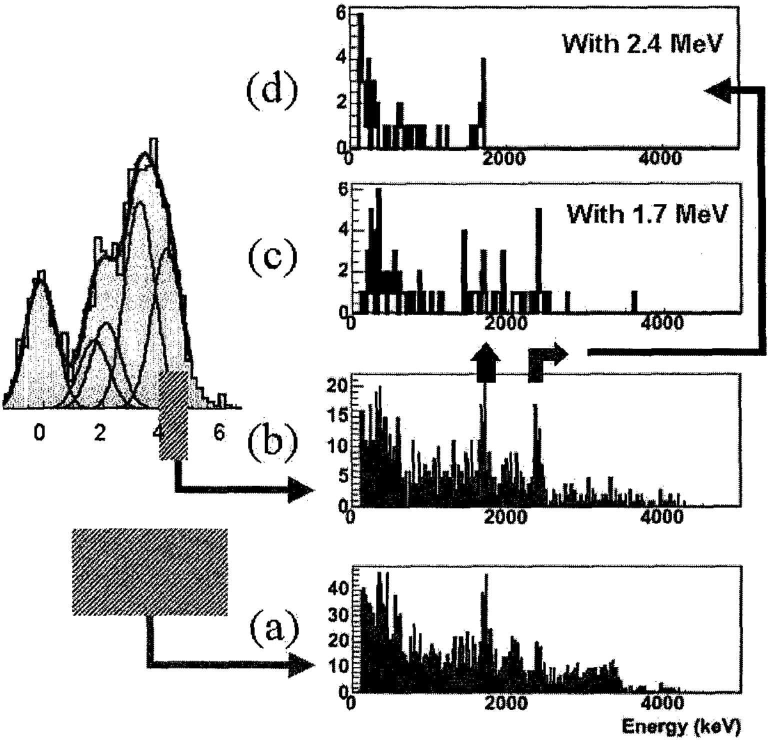

Figure 4. Gamma ray energy spectra from $d(^{24}Ne,p\gamma)^{25}Ne$ gated according to the excitation energy spectrum derived from the proton energy and angle (shown in inset): (a) all excited states, (b) peak near 4 MeV, (c) as for (b) but also requiring a coincident 1.7 MeV gamma ray, (d) as for (b) but requiring a 2.4 MeV gamma ray.

regions chosen to be 8° wide in order to give sufficient statistics for fitting. In order to fit the angular distributions, different optical model potentials were investigated, taken from (d,p) reactions on neighbouring nuclei $^{26}$Mg[11] and $^{22}$Ne[12]. A systematic comparison with adiabatic calculations according to the prescription of Johnson and Soper[13] was also performed. The adiabatic analysis was adopted for the extraction of spectroscopic factors, which were determined by normalising the theoretical curve to the data for each state, with particular emphasis placed on the data for the smallest center of mass angles (closest to 180° in the laboratory)[14].

The results of the analysis are included in Table 1. The identifications of the spins are discussed below. In general, spectroscopic factors extracted in this fashion have an uncertainty of order 20% arising from the assumptions in the reaction theory, and this is the dominant source of uncertainty in the quoted results.

Table 1. Results for states in $^{25}$Ne identified as being populated in neutron transfer on $^{24}$Ne. Previous E$_x$ is from Reed *et al.* and USD refers to a 1*s*0*d* shell model calculation.

| E$_x$ (MeV) present | E$_x$ (MeV) previous | $\ell$ ( $\hbar$ ) transfer | $J^\pi$ | $S$ present | $S$ USD | E$_x$ (MeV) USD |
|---|---|---|---|---|---|---|
| 0 | 0 | 0 | $1/2^+$ | 0.80 | 0.63 | 0 |
| 1.680 | 1.703 | 2 | $5/2^+$ | 0.15 | 0.10 | 1.779 |
| 2.030 | - | 2 | $3/2^+$ | 0.44 | 0.49 | 1.687 |
| 3.330 | - | 1 | $3/2^-$ | 0.75 | - | - |
| 4.030 | - | (3) | $7/2^-$ | 0.73 | - | - |

## 5. Discussion

The key feature emerging from Table 1 is that the state identified as the first $3/2^+$ state in $^{25}$Ne, which reflects most directly the single particle energy of the $0d_{3/2}$ shell model orbital, is substantially higher than predicted. The identification rests on both the relative strength of this "particle" state compared to the $0d_{5/2}$ "hole" state and the observed gamma decay pathways. The shift of order 350 keV is presumably due to matrix elements in the USD effective interaction that are not well determined from data on less neutron rich nuclei. The shift can be understood very naturally in the monopole shift picture[15,1], in which the emptying of the $d_{5/2}$ proton orbital in the more neutron rich N=15 isotones removes an attractive interaction that lowers the neutron $0d_{3/2}$ energy for nuclei closer to stability. This tends to make N=16 a magic number for neutron rich nuclei. Simultaneously, the gap to the negative parity orbitals $0f_{7/2}$ and $1p_{3/2}$ is reduced and N=20 loses its magicity[16].

The state identified as the $5/2^+$ is almost certainly the state seen in beta decay[17] at 1.703 MeV and has also been seen recently in neutron knockout from $^{26}$Ne[18]. This latter observation also supports the identification of the 1.703 MeV level as the hole state and the newly observed level at 2.03 MeV as the $3/2^+$ state. The further implications of these results are still under investigation.

## Acknowledgments

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# RARE ISOTOPES INVESTIGATIONS AT GSI (RISING) USING RELATIVISTIC ION BEAMS

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The first experiments performed using fast fragmentation beams and the RISING gamma-ray spectrometer are reviewed and their results are discussed. Plans for future campaigns using ions which are slowed down and stopped in a catcher will also be presented, including details of experiments which measure magnetic moments (g-factor) and β decays using an active stopper.

## 1. Introduction

The study of atomic nuclei and their dynamics at low excitation energies has been performed over several decades using more and more sophisticated experimental techniques. The themes of modern day nuclear structure research are changing. On one hand, they are refocusing towards the study of low-spin properties and the associated complete spectroscopy. On the other hand, nuclear structure research is now able to manipulate an extremely important degree of freedom, namely the neutron-to-proton ratio, with the advent of the new radioactive beam facilities. Thus, predictions of present-day nuclear models can be tested and the effects due to the underlying neutron-proton degree of freedom can be thoroughly studied. Moreover, new properties can be revealed, such as the coupling of bound states with the continuum, dilute nuclear matter, clustering and new decay modes. With the availability of Radioactive Ion Beams (RIBs), all essential degrees of freedom become available for experimental manipulation. However, such work requires infrastructure that can only be afforded on an international scale. That said, the discovery potential is very large and new facilities, such as RIA and the GSI extension FAIR, will be built in the coming decade.

Essential for RIB and stable-beam research is the use of high-performance detector arrays to study properties of stable and exotic nuclei. Large γ-ray spectrometers, such as EUROBALL and Gammasphere, were developed for the study of high-spin physics where they have been very successful. Nowadays they are being partly converted towards lower-spin applications. The most advanced project in this direction concerns the EUROBALL spectrometer, which was dismantled in 2003 for that specific goal. The 15 EUROBALL Cluster detectors are now installed at the Fragment Separator (FRS) at GSI as part of the RISING project [1]. It is also worth noting that the other major components of the Euroball spectrometer have been successfully installed at the RITU spectrometer in Jyvaskyla and within the CLARA array at INFN-Legnaro for use in experiments with stable beams.

## 2. The RISING fast beam campaign

The first RISING campaign (spokesman P. Reiter) ran from summer 2003 until spring 2005 and was aimed at γ–ray spectroscopy of exotic nuclei moving at relativistic energies. The set-up was conceived in such a way that the gamma-ray detection efficiency was maximized with the restriction on the energy resolution of one percent for each individual Euroball Cluster detector at recoil velocities of v/c = 0.43. Due to the Lorentz boost, it implied a strongly asymmetric set-up whereby all detectors were mounted behind the target in three rings around the 16 cm wide beam tube. With this set-up, a photopeak efficiency of 2.81% (at 1.33 MeV) and an energy resolution of 1.56% were attained [1]. For some of the fast beam experiments, two additional rings holding seven MINIBALL triple detectors were added, increasing the photopeak efficiency to 7.3%. In the backward direction, eight $BaF_2$ detectors from the HECTOR array were mounted. These detectors were used to measure very high-energy γ rays and also provide a very good timing reference. Behind the target the Calormetric Telescope (CATE) [2] array was used to identify the scattered particles and break-up products. It consists of position sensitive thin Si and thick CsI(Tl) ΔE-E telescope detectors. For data analysis, each event was tracked and reconstructed. Figure 1 shows a photograph of the complete 'Fast Beam RISING setup'.

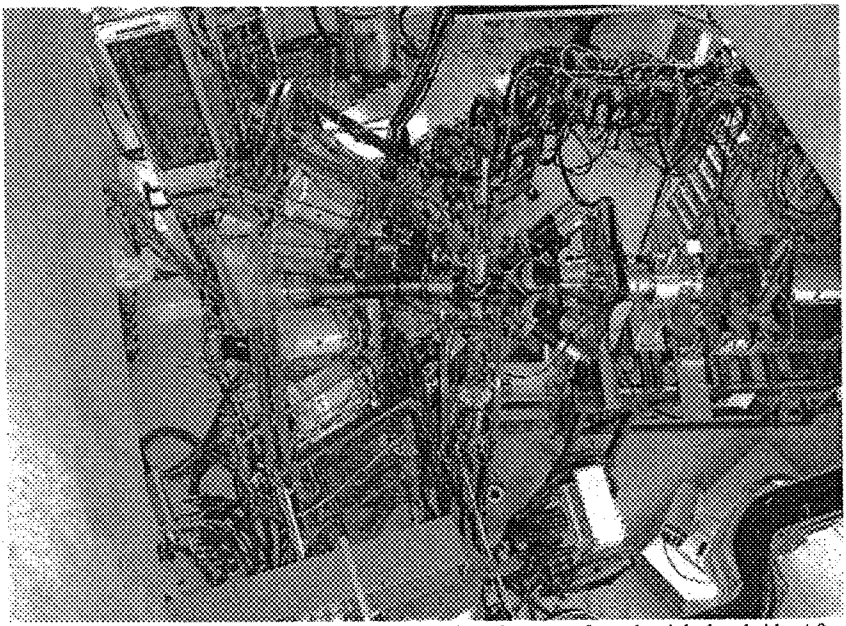

Figure 1. RISING fast beam setup. The beam enters into the set-up from the right-hand side. After hitting the target, the ions are detected in the CATE detector array. The γ rays are detected using the HECTOR array (right), the MINIBALL detectors (middle) and the EUROBALL Cluster detectors (left).

The first results of the fast campaign are now available. Relativistic Coulomb excitation was used in several experiments in order to extract the B(E2) value of the first excited state in a number of unstable nuclei, providing an independent test of the collectivity of this fundamental excitation. For $^{56}$Cr and $^{58}$Cr, the results confirm the presence of a subshell closure at N=32, which was already indicated by the anomalous excitation energy of the first excited $2^+$ state in $^{56}$Cr [3]. The result represents a challenge for large scale shell-model calculations which overestimate the $B(E2;2^+ \rightarrow 0^+)$ value for this nucleus. In the $^{108}$Sn isotope the obtained $B(E2;2^+ \rightarrow 0^+)$ value is in agreement with the theoretical calculations [4].

In order to study proton-rich unstable nuclei, two-step fragmentation reactions were used in several experiments. Preliminary results on the T=3/2 mirror nuclei in the A~50 region show the potential of this method [5]. In addition to the first results discussed above, a significant number of other new results are expected following the completion of the complex data analysis associated with these experiments, including those performed with the addition of the MINIBALL detectors to the RISING array.

## 3. The g-factor campaign

Static nuclear moments (specifically magnetic dipole and electric quadrupole moments) represent critical tests for the nuclear wave functions obtained within theoretical models, since only one state is involved in the calculation of the expectation values of these observables. The magnetic moment $\mu$, being the product of the nuclear g-factor and the spin I, is a very sensitive probe of the single-particle structure of nuclear states. High-spin isomers in the region of doubly-magic nuclei often have a rather pure single-particle configuration, for which the g-factor is a very good observable to determine the valence nucleon configuration. Measurements of nuclear g-factors can also serve as stringent tests of spin and parity assignments [6]. This is particularly true in far-from-stability regions where such assignments are often based on systematics and theoretical predictions.

Starting in the autumn of 2005, the RISING collaboration will be performing a dedicated campaign of g-factor measurements (spokeswoman G. Neyens) using the Time Differential Perturbed Angular Distribution (TDPAD) method. The method of g-factor or a spectroscopic quadrupole moment determination for an isomeric state is based on measuring the perturbation of the $\gamma$–ray anisotropy due to externally applied magnetic (or electric) interactions, following the implantation of the spin-oriented isomeric beam into a suitable stopper (i.e., a crystal or foil). This method has been used extensively over the last couple of decades for measurements of static moments of isomeric states which were produced (and spin-aligned) following in-beam fusion-evaporation reactions [6]. However, in order to investigate isomers with lifetimes in the range of $10^{-7} - 10^{-4}$ s in neutron-rich nuclei, the projectile fragmentation and projectile fission reactions are the most suitable (and often the *only* available) methods for producing spin-orienting and selecting the isomers in a fast and efficient way.

To date, only a few TDPAD measurements have been made on isomers produced in fragmentation reactions at intermediate energies of the primary beam [7,8,9]. The major difference between these and former in-beam experiments is that the isomers are first mass separated in-flight using dipole magnets. During the separation process, the reaction-induced spin orientation needs to be maintained until the moment of implantation. The hyperfine interaction between the nuclear and random-oriented electron spin can cause a loss of orientation during the flight through vacuum. To avoid it, there are two possibilities: either (i) the isomer is produced without electrons (fully stripped fragments) or (ii) the isomeric beam is selected in a noble-gas-like charge state. The primary beam high energies used in fragmentation reactions mean that most fragments can be produced fully stripped, and therefore such beams have been used so far. In a pioneering experiment, Schmidt-Ott and collaborators demonstrated that considerable alignment (~ 30%) is observed in the $^{43m}$Sc isomeric ensemble selected with the FRS at GSI and produced in the fragmentation of a relativistic $^{46}$Ti beam (500 MeV/u) [7].

For the planned experiments at the FRS a dedicated magnet system allowing magnetic fields up to about 1.5 T (with a gap of 5 cm between the poles) and up to 1.1 T (with a gap of 10 cm) will be used. The γ decays will be detected using 8 EUROBALL Cluster detectors mounted in a close geometry in the horizontal plane (see Fig.2).

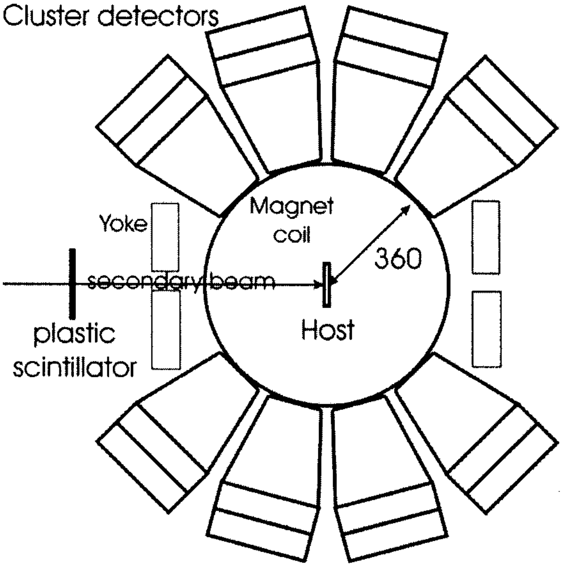

Figure 2. Schematic layout of the TDPAD set-up for measuring isomeric g-factors viewed from above. Detectors are at 36 cm from the stopper and at relative angles of 60° to each other. The total γ-ray detection efficiency is estimated of 4%.

Experiments with fully stripped fragments were limited so far to nuclei up to mass number $A_{max} \approx 80$ using intermediate energies as provided at e.g. GANIL, RIKEN and MSU. This is because the probability of picking up electrons increases with Z for a fixed beam energy, while it decreases with the beam energy for a given Z. RISING will address mass $A \approx 100 \rightarrow 200$ nuclei. The proposed experiments can be performed at present only at GSI, because the energy and charge of the primary beam at other facilities are not high enough. Furthermore, the fragmentation of a relativistic $^{238}$U beam (available only at GSI) offers the unique possibility of studying isomers in neutron-rich nuclei approaching $^{132}$Sn. The presence of spin-alignment in fragments produced by a relativistic $^{238}$U fission reaction will be demonstrated for the first time as part of the g-RISING campaign.

The proposed g-factor studies focus on nuclei in regions along shell closures (Z=50 and Z=82) and near doubly magic nuclei. Near the Z=50 shell closure, the structure of isomeric states which consist of rather pure particle and/or hole configurations with respect to the doubly-magic proton-rich $^{100}$Sn and the doubly-magic neutron rich $^{132}$Sn cores will be investigated. Study of the g-factors of isomers in these regions will help to pin down the suggested configurations and spin assignments, as well allowing investigation of the properties of the M1 operator and its suggested quenching at the extremes of isospin between $^{100}$Sn and $^{132}$Sn.

Nuclei along the Z=82 proton shell closure exhibit a variety of nuclear structures at low excitation energy. In the neutron mid-shell region, a transition from a typical shell model type structure towards more collective states seems to set in. The g-factors in this region are investigated to probe the onset of collectivity in the isomeric wave functions.

## 4. The stopped beam campaign

Following the g-factor measurements the RISING Stopped Beam Campaign (spokesman P. Regan) will start. Here the 15 EUROBALL Cluster detectors will be used to build a compact array around a passive or active stopper. They will be used to measure $\gamma$-rays following $\beta$ decay to excited states and to measure the direct decay of long lived isomers. For the study of the former process, a position sensitive silicon detector will be used as an active stopper so that the incoming heavy ion can be correlated to its subsequent $\beta$ decay.

The compact set-up is expected to reach a photopeak efficiency of 11% at 1.33 MeV and 20% at 0.662 keV (see Fig.3). It can be extended with 8 $BaF_2$ fast scintillators for fast-timing experiments. The FRS will be used in monochromatic mode which allows the stopping of selected isotopes in a 1mm thick Si stopper at the focal plane. This allows a spreading of specific species across a wide area of the focal plane, both increasing the sensitivity of the experiments and allowing longer decay times for subsequent heavy-ion-implantation $\beta$–decay correlation measurements to take place.

The physics aims of the Stopped RISING project are focused on obtaining spectroscopic information on nuclei with highly exotic proton-to-neutron ratios. These include specific studies of : (i) isospin and seniority isomers along the N=Z line (specifically $^{54}$Ni and N=Z=41→43); (ii) the use of 'cold fragmentation reactions' to populate rather neutron-rich nuclei and in particular isomeric states arising from the maximal spin coupling of two-particle (or hole) states in near doubly magic systems 'south' of $^{132}$Sn ($^{130}$Cd) and $^{208}$Pb ($^{206}$Hg, $^{204}$Pt); (iii) the investigation of very neutron-rich Zr nuclei approaching the $^{110}$Zr harmonic oscillator double shell closure following projectile fission reactions; (iv) and the utilization of K-isomeric states to map out collectivity and axial symmetry around the valence proton-neutron-product (Np,Nn) maximum nucleus $^{170}$Dy.

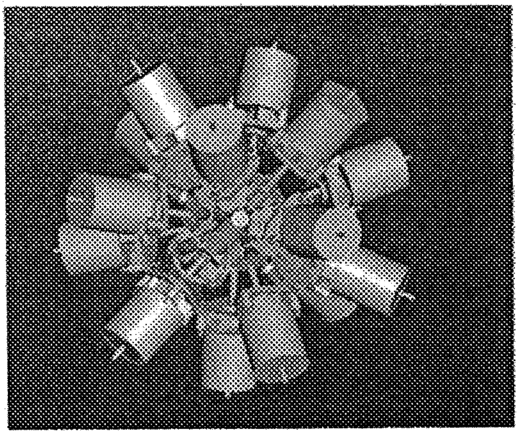

Figure 3. CAD drawing of the Stopped Beam RISING array.

## 5. Conclusions

The RISING project is aimed at frontier research in nuclear structure physics using relativistic RIBs. It therefore has to combine the complicated FRS infrastructure with state-of-the-art γ-ray detectors. Although as expected several technical problems can arise (e.g., atomic background, operation of the FRS in new settings) the project is moving forward and the first experiments are providing new and interesting results and, more importantly perhaps, paving new experimental pathways into the unknown regions of the Ségre chart. These experiments will be of vital importance for the future FAIR and RIA facilities. The first results of the fast beam campaign are now available and a new series of experiments using stopped beams will be performed in 2006–2007. RISING is a major effort of the European nuclear physics community and has already demonstrated that the traditional low- and high-spin communities can merge and pursue common scientific goals in the future.

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