

## The K600 with CAKE and BaGeL

R. Neveling<sup>1</sup>, F.D. Smit<sup>1</sup>, P. Adsley<sup>1,2</sup>, J.W. Brummer<sup>2</sup>, J. Carter<sup>3</sup>,  
C. Aa. Diget<sup>4</sup>, H.O.U. Fynbo<sup>5</sup>, M. Freer<sup>6</sup>, N.J.H. Hubbarb<sup>4</sup>, D.G.  
Jenkins<sup>4</sup>, M. Kamil<sup>7</sup>, M. Khumalo<sup>7</sup>, M. Kohne<sup>2</sup>, K.C.W. Li<sup>2</sup>, P.Z.  
Mabika<sup>7</sup>, D.J. Marin-Lambarri<sup>1,7</sup>, N.J. Mukwevho<sup>7</sup>, F. Nemulodi<sup>1</sup>, P.  
von Neumann-Cosel<sup>8</sup>, P. Papka<sup>2</sup>, L. Pellegrini<sup>1,3</sup>, V. Pesudo<sup>1,7</sup>, B.  
Rebeiro<sup>7</sup>, E. Sideras-Haddad<sup>3</sup>, G.F. Steyn<sup>1</sup>, J.A. Swartz<sup>5</sup>, S.  
Triambak<sup>7</sup>, I.T. Usman<sup>3</sup>, C. Wheldon<sup>6</sup>, Tz. Wheldon<sup>6</sup>, J.J. van Zyl<sup>2</sup>

<sup>1</sup> iThemba Laboratory for Accelerator Based Sciences, Somerset West, South Africa

<sup>2</sup> Stellenbosch University, Department of Physics, Stellenbosch, South Africa

<sup>3</sup> University of the Witwatersrand, School of Physics, Johannesburg, South Africa

<sup>4</sup> University of York, Department of Physics, York, United Kingdom

<sup>5</sup> Aarhus University, Department of Physics and Astronomy, Aarhus, Denmark

<sup>6</sup> University of Birmingham, School of Physics and Astronomy, Birmingham, United Kingdom

<sup>7</sup> University of the Western Cape, Department of Physics, Bellville, South Africa

<sup>8</sup> Institute für Kernphysik, Technische Universität Darmstadt, Darmstadt, Germany

E-mail: [neveling@tlabs.ac.za](mailto:neveling@tlabs.ac.za)

**Abstract.** Medium energy hadronic scattering and reactions at very small scattering angles, including zero degrees, can be studied with low background and high energy resolution with the K600 magnetic spectrometer at iThemba LABS. Such measurements are notoriously difficult to perform, but highly sought after due to the advantage of being very selective to excitations with low angular momentum transfer. This simplifies the analysis of the many possible contributions to the spectra due to the complex nature of the nuclear interaction. The recent addition of coincident particle and gamma detection to the zero degree capability enhances the selectivity of such a facility, which opens up a host of new opportunities to be explored. The details of the new facility and capabilities thereof are described.

### 1. Introduction

The K600 magnetic spectrometer at the iThemba Laboratory for Accelerator Based Sciences (iThemba LABS), South Africa, is a kinematically corrected quadrupole dipole dipole (QDD) magnetic spectrometer for light ions. In recent years the capability to measure inelastically scattered particles and reactions at extreme forward angles that includes zero degrees was successfully developed [1], making it one of only two facilities worldwide (the other being at RCNP, Japan [2]) where high energy resolution is combined with zero degree measurements at medium beam energies.

The advantage of such measurements is the selectivity it provides to excitations with low angular momentum transfer. For this reason it represents a valuable experimental tool for research into a wide range of topics such as studies of the fine structure of giant resonances such as the giant dipole resonance (GDR) [3] and the giant monopole resonance (GMR) [4], pygmy dipole resonance (PDR) studies [5], finding and identifying cluster states [6], as well as

astrophysical investigations related to the Hot-CNO breakout process and type I X-ray bursts [7].

The selectivity of zero degree measurements can be improved through coincident decay measurements. For example, coincident gamma detection during inelastic alpha-particle scattering measurements at zero degrees is known to enable detailed spectroscopy of electric-dipole excitations below the particle threshold, allowing the PDR to be completely isolated from other multi-polarities [8].

While such measurements can in principle be performed with the existing infrastructure, various modifications and improvements were made to improve detection efficiencies. For example, the geometry of the 524 mm diameter sliding seal scattering chamber [1] is not optimized to accommodate ancillary detector systems, either Si detectors inside or high-purity germanium (HPGe) detectors outside. A new, smaller, 280 mm diameter scattering chamber was therefore designed and installed in 2014. This new scattering chamber presents substantially less material for gammas and charged particles to scatter from before reaching the ancillary detectors. Especially for detectors mounted outside the sliding seal scattering chamber the 50 mm thick Al walls 32 mm above and below the scattering plane presented a problem. The new scattering chamber has detachable shells, greatly improving operator access when working on internal detector setups. These detachable shells consists of only 3 mm thick Al for most of the azimuthal angle range. They can be replaced with flat sheets which will allow for a minimum separation of 50 mm between the target and any external detectors mounted on the scattering plane.

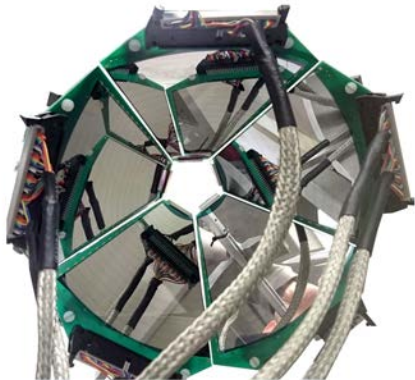
Coincident detection techniques are nothing new, nor is it the first time that such measurements are performed with the K600. However, the efficiency, granularity and also the fact that these measurements are made at zero degrees, all combine to make the facility unique. The new dedicated coincident charged particle decay detector system which can be mounted inside the new scattering chamber will be described in Section 2. A description of the coincident gamma decay detection system will be provided in Section 3. A summary and future outlook is presented in the last section.

## 2. Coincident charged particle decay detection

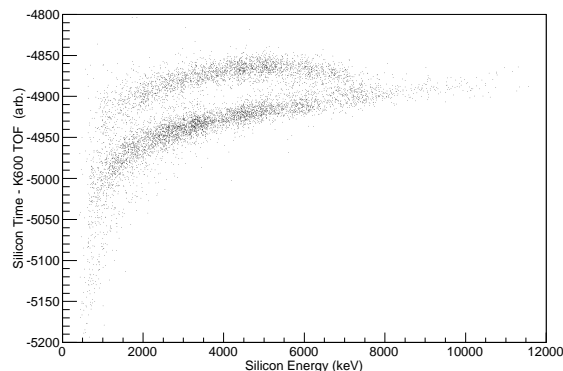
Charged particle decay products can be observed with the Coincidence Array for K600 Experiments (CAKE), which consist of five TIARA HYBALL MMM-400 double sided silicon strip detectors (DSSSDs) in a lampshade configuration, as shown in Fig. 1. Each of the 400  $\mu\text{m}$  thick wedge-shaped DSSSDs consists of 16 rings and 8 sectors, and can be positioned at either forward or backward angles with the rings covering the polar angle range  $114^\circ \leq \theta_{lab} \leq 166^\circ$ . This results in coverage of  $\sim 26\%$  of the decay particle solid angle for the case of inelastic  $\alpha$ -scattering, where the recoil nucleus is practically stationary. The DSSSD's allows for the detection of protons up to 7 MeV and  $\alpha$ -particles up to 28 MeV. The target-detector separation is  $\sim 100$  mm which is sufficient for identification of protons and  $\alpha$ 's through TOF measurements, as shown in Fig. 2.

For each focal-plane event all signals from CAKE within a time window of six  $\mu\text{s}$  are digitized in four 12-bit peak sensing VME Analog-to-Digital Converters (ADC). These are the 32-channel CAEN V785 models. Acquiring data in this manner yields both K600 singles as well as K600 + CAKE coincidence events. A beam pulse selector at the entrance of the cyclotron can be employed to ensure a sufficient time window for coincidence measurements. DSSSD rates of less than 5kHz per detector are routinely experienced. This rate is shared by the 24 active elements per detector, resulting in rates of only a few hundred Hz per active element. The typical energy resolution for the DSSSD's of  $\sim 60$  keV (FWHM), determined with a  $^{228}\text{Th}$  source, does not take into account target thickness effects during the coincidence measurement.

As an example where a better understanding of nuclear structure can be achieved through



**Figure 1.** A picture of the Coincidence Array for K600 Experiments (CAKE).



**Figure 2.** A particle identification (PID) plot of the time-of-flight (TOF) versus the energy of decay particles detected with CAKE. The top locus represent protons, and the bottom locus represents  $\alpha$ -particles.

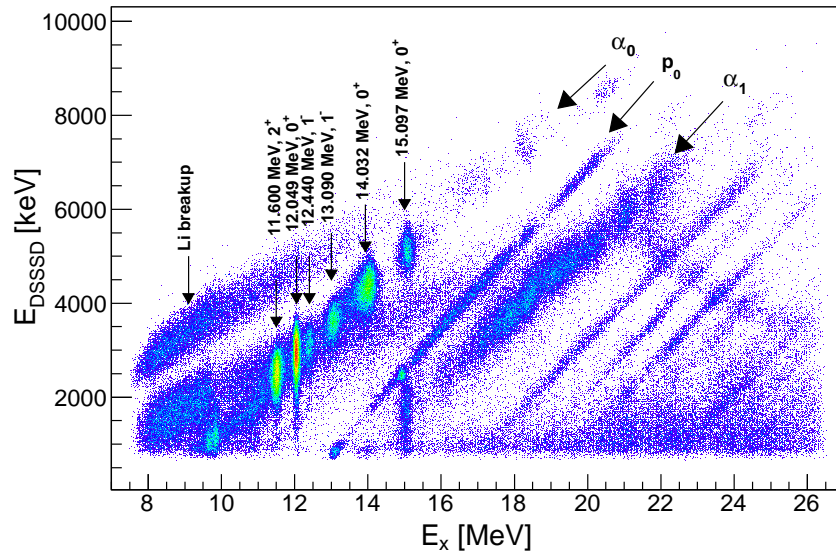
coincident decay measurements of charged particles at zero degrees, we consider clustering phenomena in light nuclei, in particular  $\alpha$ -clustering. Light nuclei are expected to exhibit cluster-like properties in excited states with a low density structure. The Hoyle state, the  $0_2^+$  state at 7.654 MeV in  $^{12}\text{C}$ , may be considered the prototype of a state that exhibits  $\alpha$ -particle condensation [9], i.e. it is considered to have a  $3\alpha$  gas-like structure similar to a Bose-Einstein condensate consisting of three  $\alpha$  particles all occupying the lowest  $0S$  state. It is expected that equivalent Hoyle-like states should also exist in heavier  $N\alpha$  nuclei such as  $^{16}\text{O}$ . The measurement of particle decay widths of the  $0_6^+$  state in  $^{16}\text{O}$ , presently considered to be a candidate for a Hoyle-like state, is required for a characterization of its cluster structure.

Inelastic  $\alpha$ -particle scattering at zero degrees has the advantage that it only excites natural parity states, and particularly the  $0^+$  states. Such a measurement, coupled with coincident observations of the  $^{16}\text{O}$  decay products, is therefore an ideal tool to measure the particle decay width of the  $0_6^+$  state in  $^{16}\text{O}$ . An experiment was performed at iThemba LABS where the  $^{16}\text{O}(\alpha, \alpha')$  reaction at 200 MeV was investigated [10]. A  $^{nat}\text{Li}_2\text{CO}_3$  target was employed as the best non-gaseous compromise for an  $^{16}\text{O}$  target. Coincidence data were extracted by gating on the prompt peak in the coincidence time spectrum, which yielded a random-to-real coincidence ratio of  $\frac{1}{50}$ . The coincidence matrix for all events with the target excitation energy as measured by the K600 on the horizontal axis and the energy of the charged particle decay as measured in CAKE on the vertical axis is shown in Fig. 3.

The facility was also successfully used to, amongst others, measure the proton decay branching ratios in unstable nuclei by means of the (p,t) reaction on a stable target [11]. Such measurements have astrophysical relevance due to the influence of the branching ratios on the calculation of breakout reactions in type 1 X-ray bursts.

### 3. Coincident gamma decay detection

The array referred to as the Ball of Germaniums and LaBr<sub>3</sub> detectors (BaGeL) was conceived to take advantage of the capability to perform high energy-resolution inelastic  $\alpha$  scattering measurements at  $0^\circ$ . This makes it possible to pursue high-resolution spectroscopy of the low-

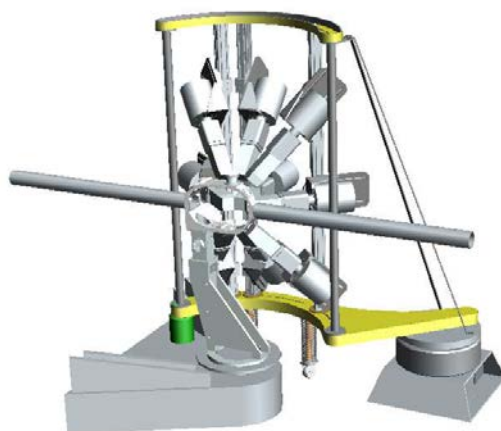


**Figure 3.** Two-dimensional coincidence matrix for inelastically scattered  $\alpha$ -particles from a  $^{nat}\text{Li}_2\text{CO}_3$  target summed over all CAKE channels. Three  $^{16}\text{O}$  decay channels ( $\alpha_0$ ,  $\alpha_1$ ,  $p_0$ ) are indicated, as well as prominent low spin states in  $^{16}\text{O}$ . The indicated Li breakup locus appears prominently in the lower excitation energy region, and extends weakly into the  $\alpha_0$  decay channel. At higher excitation energies numerous proton decay channels from  $^{12}\text{C}$  and  $^{16}\text{O}$  are visible. A display threshold of  $>3$  was used in plotting the data.

lying E1 strength through the  $(\alpha, \alpha'\gamma)$  reaction.

BaGeL refers not only to the array of HPGe's that will be used in coincidence with the K600, but to the whole infrastructure designed to make coincident  $\gamma$  detection possible. This includes, amongst others, the necessary LN2 cooling and monitoring systems, which is designed to be independent of the existing systems of the AFRican Omnipurpose Detector for Innovative Techniques and Experiments (AFRODITE) array [12]. Furthermore, the design of BaGeL was made in such a way that it is highly flexible and configurable, making it easy to install a range of different detector systems for a wide range of geometries. This allows one to tailor detection capabilities to the experimental requirements, e.g. the high energy resolution capabilities of HPGe detectors or the high detection efficiencies of LaBr<sub>3</sub> detectors. The basic BaGeL support structure has a clamshell design as shown in Fig.4. The center of rotation for the two arms are 828 mm from the beam center, and during beam tuning the detectors in the 90° position can be removed to a perpendicular distance of 2045 mm away from the beam-line. This will ensure minimum neutron damage to sensitive HPGe detectors during beam tuning.

For the BaGeL commissioning run scheduled for October 2016 [13] it is envisaged that the eight HPGe Clovers (each with four crystals approximately 40 x 40 x 70 mm<sup>3</sup> in size) available at iThemba LABS will be used. The expected  $\gamma$ -ray energy resolution is  $\sim 15$  keV for the energy range of interest to PDR studies, which is 5-8 MeV. The absolute photo-peak efficiency for the array was calculated to be 0.6% for a target-detector separation of 170 mm for  $\gamma$ -rays of 6 MeV (assuming add-back). The currently available 12-bit CAEN ADCs are not optimum to exploit the high energy resolution capabilities of HPGe detectors. For this reason the collaboration acquired two 8-channel 16-bit Struck SiS3302 ADCs. Once these are fully commissioned more will be acquired to enable the full instrumentation of eight HPGe's with 16-bit ADCs.



**Figure 4.** An illustration of the one arm of BaGeL on the beam-right side, instrumented with nine HPGe's. The particle beam enters the central scattering chamber from the right. The K600 is located on the left. Note however that for the near future the HPGe detectors will only be placed at backward angles.

#### 4. Summary and outlook

During the past decade the constant developments of K600 magnetic spectrometer at iThemba LABS has helped to create a powerful facility that can be used to perform unique measurements in nuclear structure research. The developments to enable coincident decay particle measurement were already used to good effect in multiple experiments, and we are optimistic about the future of the BAGEL development.

At the same time we are looking ahead to further development of the facility. For particles below  $\sim 80$  MeV in the focal plane the K600 is at present operated in a single scintillator trigger mode, due to the fact that the particles stop in the first scintillator in the focal plane. The resultant high trigger rate, mostly due to zero degree background (very low energy particles that do not penetrate beyond a mm into the scintillator), ultimately limits data acquisition rates and therefore potentially limits the scope of studies that could be performed. A new trigger scintillator that will consist of scintillating fibers was therefore designed. These scintillating fibers ( $1.5 \times 1.5 \times 1800 \text{ mm}^3$ ) are much thinner than existing scintillators (thickness = 3.175 mm, 6.35 mm or 12.7 mm), which means that a trigger made by a coincidence signal of two scintillators will again be possible for particles of 80 MeV and below, in this way getting rid of the unwanted low energy background. The much improved light transport capabilities compared to existing scintillator trigger geometry (thickness  $\times 100 \times 1000 \text{ mm}^3$ ) means that the scintillating fiber detector will be much more efficient than using a standard scintillator with dimensions  $1.5 \times 100 \times 1000 \text{ mm}^3$ .

Finally, in order to detect heavy ions in the focal plane a new position sensitive detector is required. This could also benefit the detection of low energy light ions (as well as 200 MeV  $\alpha$ 's) since the thick Kapton vacuum exit window in front of the existing focal plane detectors limits the position resolution. Potential candidates include different geometries of cathode strip MWPC (Multi Wire Proportional Counter) detectors. Such a development, envisaged to start in the near future, is however dependent on manpower and financial restrictions.

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