Towards Super Heavy Nuclei Spectroscopy with a Gamma Ray Tracking Detector

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In this contribution the emphasis will be on the capabilities of the new generation of Ge arrays based on a new concept of detection using Gamma Ray Tracking and recent advances in crystal segmentation technology which will enable in-beam spectroscopy towards super heavy elements.

1. Physics Motivations

The existence of **super heavy** nuclei is a striking manifestation of shell effects. Since the heaviest nuclei are weakly bound in their ground state, it is important to determine the limiting spin and excitation energy that they can sustain. Their rotational properties constitute an excellent laboratory to test HFB mean-field theory at extreme masses, far away from the ones where the effective forces have been adjusted. Their observation at high spin gives additional information on the fission barrier which governs their survival probability. Another important question to address concerns the influence of the pairing correlations on the rotational properties (pairing is crucial in reproducing the dynamical moment of inertia $\Im^{(2)}$).

A beautiful example of γ-ray spectroscopy performed on **heavy elements**, came out from an experiment[1,2] in which the excited states (up to spin $18\hbar$) of ^{254}**No** have been investigated (the heaviest nucleus studied in γ-ray spectroscopy so far). The observed rotational band, as shown by M. Leino in this conference, firmly established that the nucleus is deformed and constitutes an important confirmation of the predictions. Furthermore, recent calculations[3] using a pairing force adjusted on SD bands in the mass $\sim$150 region surprisingly reproduce the $\Im^{(2)}$ of the observed ground-state rotational band in ^{254}No. In addition, in order to gain some understanding about the single-particle shell structure, the emphasis will be on the investigation of the properties of odd-*A* heavy elements. However, to extend the study of these nuclei towards odd-mass nuclei and/or heavier masses is experimentally difficult because they are created with extremely low cross sections (few nanobarn) and with a very high fission background. These problems can be overcome by combining a very efficient γ-ray detection and an appropriate residual nucleus identification. On the other hand, because of the very high e^- conversion probability at low energies and large Z, it will be crucial to measure conversion e^- in coincidence with γ rays from these states.

All these important features have been discussed in several sessions of this conference by different speakers as can be seen in the final proceedings.

2. Why Do We Need a New Generation of γ Arrays?

2.1. Current Arrays and their Limitations.

During the last two decades the development and improvement of very efficient 4π Ge detectors have provided an enormous amount of information on the structure of the atomic nucleus. The state of the art with respect to $4\pi\gamma$ arrays is represented by EUROBALL[4] in Europe and GAMMASPHERE[5] in the USA. Figure 1 illustrates the view of EUROBALL built from 239 Ge crystals. It consists of 15 Clusters detectors (each composed of 7 encapsulated Ge detectors), 26 Clovers (4 Ge detectors in one cryostat) and 30 standard Ge detectors. Each type of the EUROBALL detectors

is surrounded by BGO shields, which suppress the Compton-escaped γ rays and therefore provide a significant improvement in the spectrum quality.

Even though these large arrays still enable new interesting studies of physics at the extreme and will allow experiments at very low cross sections as expected for super heavy nuclei or with the radioactive beam facilities in the next few years, their performance is close to the ultimate limit that can be obtained with escape-suppressed devices.

A totally new concept is required in order to further increase the efficiency and granularity. To make the next major advance, one would replace the BGO shields by active Ge to build a highly segmented Ge shell.

2.2. Design and Performances of the Future Array: AGATA.

The aim of the TMR (Training and Mobility for Researchers, launched in 1997 and coordinated by R. Lieder) program is to design a 4π Ge array based on a new concept of detection using Gamma Ray Tracking and recent advances in crystal segmentation technology. This concept is based on the ability to locate, within few mm, each interaction point in the Ge detector and consequently track the scattering sequence of an incident γ ray. The tracking method will consist of the reconstruction of the full γ-ray energy by combining the appropriate interaction points. As a result, this will provide a significant gain in the efficiency because the Compton shields (which limit the Ge solid angle) will not be necessary and will be replaced by active Ge detectors to give for the first time a real 4π Ge ball. GEANT simulations have already shown the capabilities of the tracking concept for a new generation of $4\pi\gamma$ Ge array. However a high
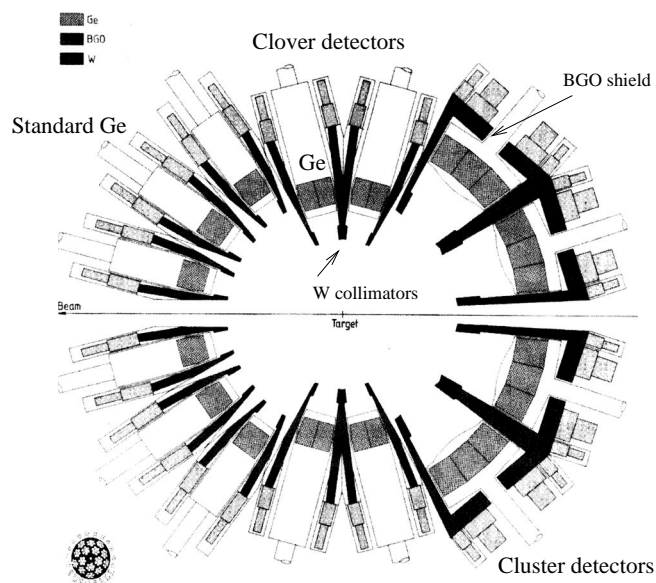

Figure 1. Section view of EUROBALL built from 239 Ge crystals. It consists of 15 Clusters detectors at backward angles, 26 Clovers at 90°, and 30 standard Ge detectors at forward angles. Each detector is surrounded by BGO shield.

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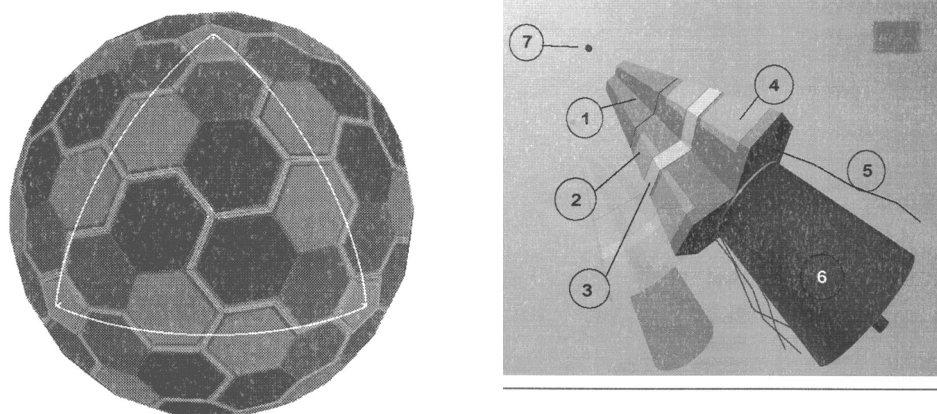
Figure 2. The final AGATA configuration with encapsulated crystals grouped triple-clusters detectors is shown in the left side of the panel. The right panel shows the detector module for AGATA. The 36-fold segmented Ge is marked by (1), preamplifier (2), frame-support (3), digital pulse processing electronics (4), fiber-optics read-out (5), LN2-dewar (6), and target position marked by (7).

TABLE 1: **The tracking array performances illustrated in terms of comparison between EUROBALL and AGATA. The efficiencies and peak-to-total quantities are given for low and high γ-ray multiplicities.**

	Ge weight / kg	Detectors [Crystals]	$\epsilon\omega$ [P/T] / % $M_\gamma = 1$	$\epsilon\omega$ [P/T] / % $M_\gamma = 30$
Ideal sphere	233	—	65 [85]	36 [60]
AGATA	225	70 [190]	40 [65]	25 [50]
EUROBALL	210	239	9.4 [50]	6.5 [37]

TABLE 2: **Comparison between GAMMASPHERE and AGATA in terms of expected counts for a 200 keV line in double coincidence and for two different reactions which populate the indicated nuclei. The fusion cross sections are also indicated and taken from Reference 9.**

Reaction		Cross section	GAMASPHERE	AGATA
^{208}Pb(^{48}Ca, $2n$)^{254}No	$Z = 102$	3 μb	25	1000
^{208}Pb(^{50}Ti, $2n$)^{256}Rf	$Z = 104$	$\approx$10 nb	0.2	10

degree of confidence in the reconstruction of the γ-ray path can only be obtained with highly segmented detectors which results in a better localisation of the γ-ray position. It has been demonstrated that a position resolution of ≤5 mm, which is needed for γ-ray tracking, can be achieved by pulse shape analysis of the segment signals using digital electronics.

This new type of spectrometer requires the optimisation of several parameters:
• the full-energy or photopeak efficiency must be maximised,
• a very good peak-to-toal ratio (P/T),
• an excellent angular resolution in order to reduce the Doppler broadening,
• a high counting rate capabilities,
• a suitable free inner space available for additional detectors inside the Ge ball.
These features can be obtained with the new generation of spectrometers such as AGATA (Advance GAmma Tracking Array).[6]

Indeed, this new generation of γ-ray calorimeters, such as **AGATA** in Europe or **GRETA**[7] in the USA, will provide a dramatic gain in efficiency above any presently existing array such as **EUROBALL** or **GAMMASPHERE**. An important gain in the resolving power will also be achieved since the angle at which the γ ray is emitted will be much better defined allowing the Doppler broadening to be greatly reduced, especially for nuclei with large v/c. Indeed, to quantify the performance of a 4π array, the concept of resolving power is usually introduced; this corresponds to the ability to isolate a given sequence of γ rays from a complex spectrum.

This future detector will be a powerful tool to be used with high intensity **stable beams** as well as for the next generation of radioactive beam accelerators such as **SPIRAL2 or EURISOL** in Europe or the **RI Beam Factory** in RIKEN. It will clearly open up new possibilities concerning rare phenomena at high spin (or high multiplicity) and high excitation energy as well as very far from stability.

In view of its modularity and symmetry, the selected configu-

ration for AGATA corresponds to a Ge ball with 70 cryostats composed of triple 36-segmented clusters. The final geometry will consist of 180 irregular hexagons and 10 pentagons as shown in Figure 2. The total number of segments in the array is therefore 6780.

2.3. Performances of AGATA. The tracking performances are illustrated in terms of a comparison between EUROBALL and AGATA arrays. The simulations are performed using the GEANT package for different γ multiplicities as can been seen in Table 1. The obtained results (efficiency, Peak/Total) are taken from Reference 8 and references therein.

Table 1 clearly illustrates the capabilities of the new generation of Ge arrays which enable the in-beam spectroscopy of heavy elements. However, for the study of heavier element ($Z = 104$ and beyond) would not be possible with existing arrays as the production cross section drops dramatically.

For example, the production yield of ^{256}Rf in the ^{50}Ti + ^{208}Pb reaction is only about few nanobarn! and one would expect 10 counts in the peak at 200 keV γ ray with AGATA instead of less than 1 count with EUROBALL in 10 days run. Table 2 shows a comparison between GAMMASPHERE (9% efficiency) and AGATA in terms of expected counts for γ-ray spectroscopy.

Again, γ-ray spectroscopy studies become possible with a combination of high granularity and ultra-high counting rate capabilities. Only a Gamma Ray Tracking spectrometer is able to satisfy these different and sometimes conflicting needs. With such new devices a gain of 50 to 100 for the sensitivity is expected compared to EUROBALL.

References

(1) P. Reiter, T. L. Khoo, C. J. Lister, D. Seweryniak, I. Ahmad, M. Alcorta, M. P. Carpenter, J. A. Cizewski, C. N. Davids, G. Gervais, J. P. Greene, W. F. Henning, R. V. F. Janssens, T. Lauritsen, S. Siem, A. A. Sonzogni, D. Sullivan, J. Uusitalo, I. Wiedenhöver, N. Amzal, P. A. Butler, A. J.

Chewter, K. Y. Ding, N. Fotiades, J. D. Fox, P. T. Greenlees, R.-D. Herzberg, G. D. Jones, W. Korten, M. Leino, and K. Vetter, Phys. Rev. Lett. **82**, 509 (1999).

(2) M. Leino, H. Kankaanpää, R.-D. Herzberg, A. J. Chewter, F. P. Heßberger, Y. Le Coz, F. Becker, P. A. Butler, J. F. C. Cocks, O. Dorvaux, K. Eskola, J. Gerl, P. T. Greenlees, K. Helariutta, M. Houry, G. D. Jones, P. Jones, R. Julin, S. Juutinen, H. Kettunen, T. L. Khoo, A. Kleinböhl, W. Korten, P. Kuusiniemi, R. Lucas, M. Muikku, P. Nieminen, R. D. Page, P. Rahkila, P. Reiter, A. Savelius, Ch. Schlegel, Ch. Theisen, W. H. Trzaska, and H.-J. Wollersheim, Eur. Phys. J. A **6**, 63 (1999).

(3) T. Duguet, P. Bonche, and P.-H. Heenen, Nucl. Phys. A **679**, 427 (2001).

(4) J. Simpson, Nucl. Phys. A **654**, 178c (1999).

(5) I. Y. Lee, Nucl. Phys. A **520**, 641c (1990).

(6) R. M. Lieder, W. Gast, H. M. Jäger, L. Mihailescu, M. Rossewij, J. Eberth, G. Pascovici, H. G. Thomas, D. Weisshaar, F. Beck, D. Curien, G. Duchêne, E. Pachoud, I. Piqueras, C. Rossi Alvarez, D. Bazzacco, M. Bellato, Th. Kroell, Ch. Manea, B. Quintana, R. Venturelli, D. R. Napoli, D. Rosso, P. Spolaore, A. Geraci, A. Pullia, G. Ripamonti, F. Camera, B. Million, O. Wieland, J. Lisle, A. G. Smith, R. Well, P. Nolan, A. Boston, D. Cullen, M. Descovich, T. Enqvist, B. Cederwall, E. Ideguchi, J. van der Marel, J. Nyberg, B. Herskind, G. Sletten, J. Wilson, R. Henck, D. Gutknecht, and K. Jääskeläinen, Nucl. Phys. A **682**, 279c (2001).

(7) M. A. Deleplanque, I. Y. Lee, K. Vetter, G. J. Schmid, F. S. Stephens, R. M. Clark, R. M. Diamond, P. Fallon, and A. O. Macchiavelli, Nucl. Instrum. Methods A **430**, 292 (1999).

(8) A. Korichi, *Workshop on Future of Nuclear Structure Gamma Spectroscopy with Stable Beams, Strasbourg, France, 2001*.

(9) F. P. Heßberger, S. Hofmann, V. Ninov, P. Armbruster, H. Folger, G. Münzenberg, H. J. Schött, A. G. Popeko, A. V. Yeremin, A. N. Andreyev, and S. Saro, Z. Phys. A **359**, 415 (1997); S. Hofmann, *Experimental Nuclear Physics in Europe, Sevilla, Spain, 1999*, AIP Conf. Proc. **495** (AIP, New York, 1999), p. 137.