Probing a Variety of Nuclear Phenomena with DIAMANT and AFRODITE

S. M. Mullins[1], B. M. Nyakó[2], J. Timár[2], J. Gál[2], G. Kalinka[2], J. Molnár[2], R. A. Bark[1], G. Berek[1], E. A. Gueorguieva[1], K. Juhász[3], F. S. Komati[1], A. Krasznahorkay[2], T. T. Hlatshwayo[1,4], J. J. Lawrie[1], M. Lipoglavsek[5], S. M. Maliage[6], T. Malwela[6], S. H. T. Murray[1], S. S. Ntshangase[6], T. M. Ramashidza[6], J. N. Scheurer[7], J. F. Sharpey-Schafer[1], O. Shirinda[6], and P. Vymers[6]

[1] iThemba Laboratory for Accelerator Based Sciences, P.O.Box 722, Somerset West 7129, South Africa
[2] Institute of Nuclear Research, Bem tér 18/c, H–4026, Debrecen, Hungary
[3] Faculty of Informatics, University of Debrecen, Egyetem tér 1, H-4032, Debrecen, Hungary
[4] Department of Physics and Engineering, University of Zululand, Private Bag X 1001, KwaDlangezwa 3886, Kwa-Zulu Natal, South Africa
[5] Jožef Stefan Institute, 1000 Ljubljana, Slovenia
[6] Department of Physics, University of Western Cape, Private Bag X 17, Bellville 7535, South Africa
[7] CNRS-IN2P3-Université de Bordeaux I, 33175 Gradignan Cedex, France

Abstract. The DIAMANT light charged-particle detector has been coupled in two configurations with the AFRODITE γ-ray spectrometer at iThemba LABS in order to pursue a range of measurements. One configuration employed the "Chessboard" standalone front-wall of 24 CsI detectors, while the other consisted of the full-coverage DIAMANT array. In particular, the results of an investigation of incomplete fusions reactions via the ^{13}C + ^{170}Er entrance channel and the search for chirality in ^{109}Ag will be discussed.

1 Introduction

A bilateral agreement at governmental level exists between the Republic of South Africa and Hungary, the purpose of which is to facilitate scientific co-operation and collaboration over a wide range of fields. One of these ventures involves the iThemba Laboratory for Accelerator Based Sciences and the Institute for Nuclear Research ("ATOMKI") to enable the DIAMANT light-charged-particle detector [1] to be coupled with the AFRODITE γ-ray spectrometer [2]. This enabled charged-particle-γ-ray coincidence data to be obtained from a number of measurements that have been carried out during the first term of the collaboration, two of which will be discussed in some detail in this contribution.

2 Experimental set-up

2.1 The AFRODITE spectrometer

The AFRODITE γ-ray array consists of up to nine Compton-suppressed HPGe Eurogam-II-type clover detectors and eight unsuppressed Low Energy Photon Spectrometers (LEPSes). This combination gives AFRODITE a unique feature of high detection efficiency at both low and high γ-ray energies, with particularly high energy resolution for the LEPS detectors. The detector configuration for the measurements described below had four clovers each placed at 135° and 90°, respectively. Some LEPS detectors were employed in the measurements with the Chessboard, since it was possible for them to have an unobstructed view of the target. This was not possible when the full DIAMANT array was used, and due to the severe absorption below E_γ ~200keV, the LEPSes were largely redundant. The event trigger required a prompt clover-clover coincidence timed relative to the RF pulsing of the Separated Sector Cyclotron (SSC).

2.2 The DIAMANT array

The DIAMANT array for the detection of light charged-particles consists of up to 84 CsI crystals coupled to p-i-n diodes. The performance and characteristics of the array are described in Ref: [1]. A stand-alone front wall of 24 CsI detectors constructed in ATOMKI, known as the "Chessboard", was used in one of the two measurements described below. The γ-γ AFRODITE trigger provided the "master" condition needed to gate the VXI electronics [3] of the CsI array in "slave" mode . Hence, this enabled both γ-γ and charged-particle-γ-γ coincidence data to be collected. Thus, this provided the opportunity to quantify the detection efficiency of the Chessboard and the full DIAMANT.

3 Experimental measurements

3.1 Incomplete fusion in the ^{13}C + ^{170}Er reaction

The ^{13}C + ^{170}Er reaction was studied at two beam energies, namely 80 and 70 MeV, with one weekend's worth of data accumulated at each energy. Offline three E_γ-E_γ coincidence matrices were generated, one with no condition on the Chessboard, one required that at least one α-particle had been detected and the third that two α-particles had been detected in prompt coincidence with two of the AFRODITE clover detectors. The matrices were inspected with the aid of ESCL8R from the RADWARE [4] suite of analysis programmes in order to keep track of and record the spectroscopic information contained therein. This information was used to extract the energies and intensities of all coincident γ-ray transitions emitted by the various residual nuclei from which yields and feeding patterns were derived. Since

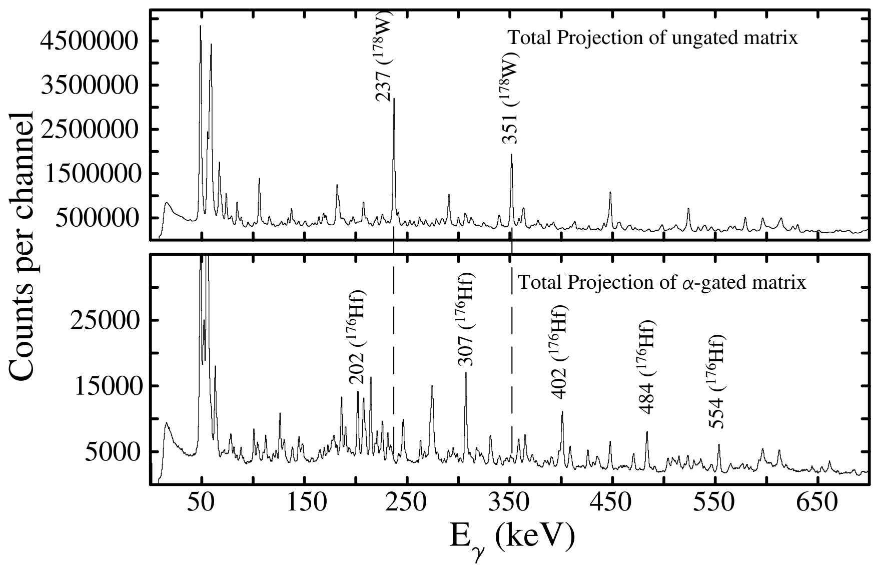

Figure 1. Total projection spectra of ungated and single-α-gated E_γ-E_γ matrices from the ^{13}C + ^{170}Er reaction at 80 MeV.

the pure xn channels are expected to be overwhelmly due to complete-fusion evaporation processes of "classical" fully-equilibrated compound-nucleus character, they provided a normalization against which to compare the yields of the single-αxn and two-αxn products. The results of the analysis and interpretation as it stands at present will be discussed below.

3.2 Search for chiral behaviour and band termination in ^{109}Ag

The existence of nuclear chirality, when the three angular momentum vectors of the rotating triaxial core, the particle-type quasiparticle(s), and the hole-type quasiparticle(s) in a nucleus are perpendicular to each other, is one of the most intriguing questions of contemporary high-spin nuclear structure studies. Rotational doublet-band candidates for chiral structures have been observed mostly in two regions of the nuclear chart centred around ^{134}Pr [5] and around ^{104}Rh (for example, see Ref: [6]). In this second region the Rh isotopes are rather well studied, but besides these nuclides, experimental evidence for chiral doubling has been proposed only in ^{100}Tc. Thus, it is of considerable interest to search for these doublet bands in the nearby Ag nuclei. In the Rh/Ag/Tc region, chiral rotation is expected for the $\pi g_{9/2}\nu h_{11/2}$ configuration in odd-odd nuclei and for the $\pi g_{9/2}\nu(h_{11/2})^2$ configuration in odd-mass nuclei.

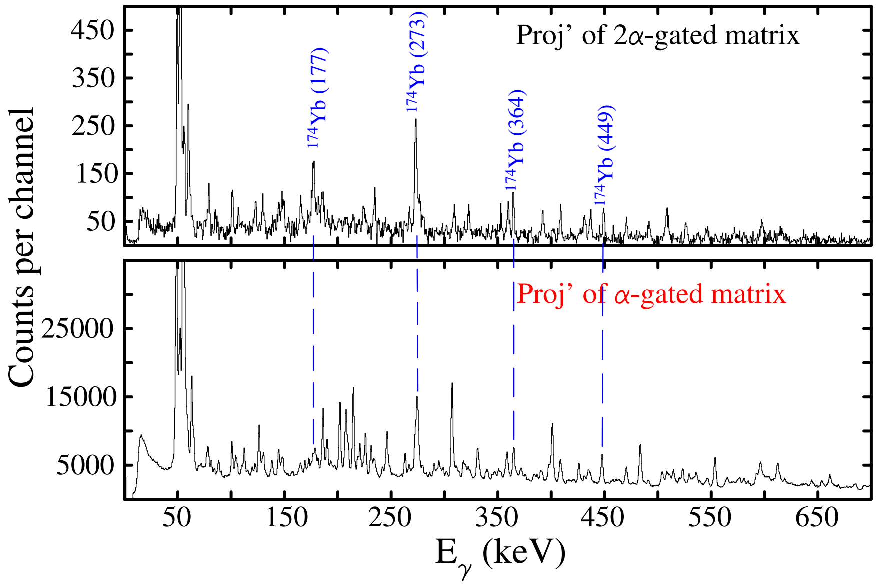

Figure 2. Total projection spectra of two-α-gated and single-α-gated E_γ-E_γ matrices from the ^{13}C + ^{170}Er reaction at 80 MeV.

High-spin states of ^{109}Ag have been studied by Pohl *et al.* [7] using the ^{96}Zr(^{18}O,p4n) reaction, where they have observed a ΔI=1 positive-parity band linked to the $\pi g_{9/2}$ band, and assigned the $\pi g_{9/2}\nu(h_{11/2})^2$ configuration to it. The band has been observed up to spin 35/2$\hbar$, by identifying only the strong cascade of M1 transitions. Since only a relatively small amount of data was collected, there were insufficient statistics to allow the observation of the weak E2 cross-over transitions. The aim of the present experiment was to extend the structure to higher spins, to observe the cross-over transitions, and, primarily, to search for the expected chiral partner of this band utilising the same reaction at a beam energy of ~80 MeV, but collecting about an order of magnitude larger statistics.

Data were collected during four weekends when a ^{18}O beam was directed at an energy of 82 MeV onto a stack of two ^{96}Zr foils, enriched to 85%. Eight clover detectors of the AFRODITE spectrometer and the full DIAMANT charged-particle array detected the γ rays and the charged particles, respectively. Altogether ~140 million $\gamma\gamma$-coincidence events were recorded. Approximately 30 million events of them corresponded to pxn channels of which ~10 million came from the ^{109}Ag channel.

4 Results

4.1 Incomplete fusion in the $^{13}C + ^{170}Er$ reaction

The strongest single-α exit channel in the 80 MeV data was $\alpha 3n$ corresponding to the ^{176}Hf residual nucleus. In the "raw" ungated E_γ-E_γ matrix, the yield of ^{176}Hf was $\sim$8% relative to the strongest exit channel, namely ^{178}W which was populated via $5n$ evaporation. This is considerably higher than the yields of $\sim$1% predicted by standard evaporation codes in which only complete fusion is treated. Moreover, absolutely no yield whatsoever is predicted for two-αxn exit channels leading to the ytterbium (Z = 70) nuclei which are clearly seen in figure 2. Level schemes for these ytterbium nuclei are shown in figure 3. The most strongly fed of these was ^{174}Yb ($2\alpha n$, or perhaps ^{9}Be, exit channel) which was observed to $18\hbar$, populated with a maximum intensity of $\sim$40% compared to ^{176}Hf in the single-α-gated matrix. This raised the possibility whether in fact it was the complementary ^{9}Be fragment which had been detected in the Chessboard. This was investigated by generating an E_γ-E_γ matrix under the condition that two-α particles were detected, the total projection of which is shown in the upper panel of figure 2. The ^{174}Yb transitions are still present, albeit with an intensity of $\sim$1.7% when compared to the single-α-gated spectrum. The efficiency for the detection of a single α-particle was determined to be $\sim$15%

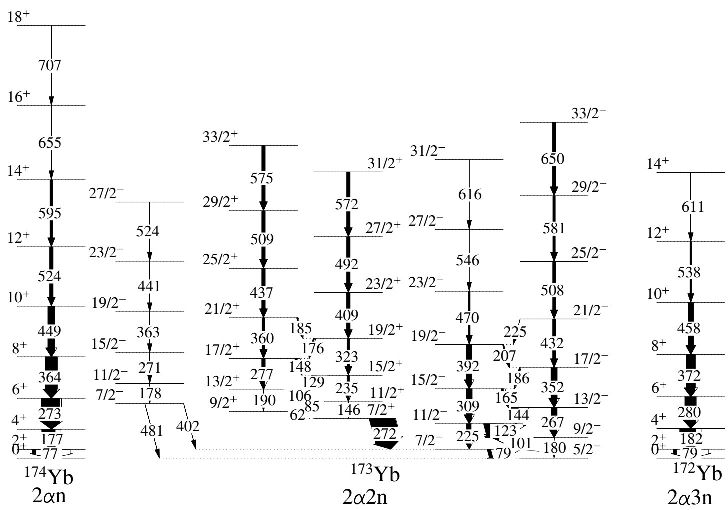

Figure 3. Level schemes which show states populated in stable ytterbium nuclei via two-αxn channels from the $^{13}C + ^{170}Er$ reaction at 80 MeV.

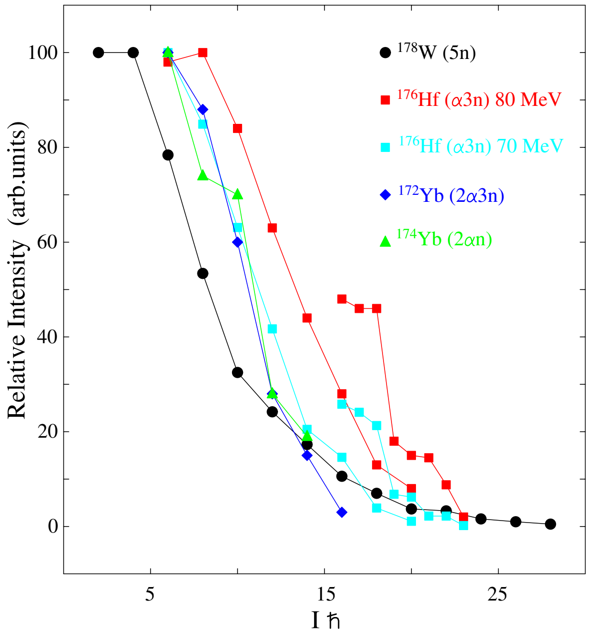

Figure 4. Plots of normalized (at maximum to 100%) γ-ray transition intensities versus spin of the emitting state for various bands in ^{178}W, ^{176}Hf, ^{172}Yb and ^{174}Yb, populated in the ^{13}C + ^{170}Er reaction at 80 (and 70 MeV for ^{176}Hf).

from comparing the intensities of the ^{176}Hf ground-state band in the un-gated and single-α gated projections of the corresponding E_γ-E_γ matrices. Hence, the efficiency for detecting two α particles can be estimated to be $(0.15)^2 \times (23/24) \simeq 2\%$. Thus, the (two-$\alpha$-gated)/(single-$\alpha$-gated) intensity ratio of the ^{174}Yb ground-state band is consistent with complete break-up of the ^{13}C beam into three α particles and the neutron. The details of the break-up process remain to be understood, since there is a possibility that there is massive transfer of an α particle in the entrance channel, with subsequent disassociation of the complementary ^{9}Be fragment into α + α + n.

The incomplete fusion process is localized around grazing impact parameters [8]. Since the grazing angle depends strongly on the energy of the incident beam, the angular distribution of the un-fused fragment shows a similarly strong dependence. Unfortunately it was not possible to investigate this is in sufficient detail due to the limited angular coverage of the Chessboard. Further measurements are planned with the full version of DIAMANT, which will most likely take place sometime during 2008.

The localization around grazing collisions in incomplete fusion reactions is expected to result in a narrow region of spin over which structures in the corresponding residual nuclei are populated. Consequently rotational bands in these nuclei should show a rapid increase in intensity at spin values localized near to a value corresponding to the grazing angular momentum, less that carried off by the unfused fragment and subsequent evaporated particles. That is, the narrow spin range corresponds to fusion of the complementary fragment at near-grazing impact parameters. Since the break-up energy needs to be included in the energy of incident beam, the effective energy-per-nucleon of the fusing fragment is higher than the optimum value if it itself had been used as the projectile.

The aforementioned localization near to grazing collisions for incompete fusion reactions has been investigated in the present case by the extraction of normalized transition intensities for the ground-state bands in ^{176}Hf ($\alpha 3n$), ^{172}Yb ($2\alpha 3n$), ^{174}Yb ($2\alpha n$) and, for comparison, ^{178}W ($5n$) at a beam energy of 80 MeV, together with ^{176}Hf at 70 MeV. The results are presented in figure 4, along with those for the K^{π} = 16^{+} four-quasiparticle band in ^{176}Hf. What is immediately apparent is the smooth, gradual increase of intensity with decreasing spin for ^{178}W, as would be expected for feeding following the complete fusion process in which a wide range of impact parameters contributed. The bands in ^{176}Hf, ^{174}Yb and ^{172}Yb exhibit a more rapid increase of intensity with decreasing spin, consistent with a major contribution from incomplete fusion reactions localized to near-grazing collisions.

4.2 Search for chiral behaviour and band termination in ^{109}Ag

The analysis of several $E_{\gamma}E_{\gamma}$-coincidence matrices that were constructed from the event-by-event data is in progress. A symmetrized matrix was generated from the proton-gated events from which a proton-detection efficiency of $\sim$50% was determined. The matrix too was analysed with ESCL8R from the RADWARE package [4]. Two examples of coincidence spectra are shown in figure 5. Comparing the observed γ-ray spectrum in coincidence with the 299 keV transition with that of published by Pohl *et al.* [7] an order of magnitude increase in counts was obtained.

The observed coincidence relationships were used to build an extended level scheme of the ^{109}Ag nucleus which is shown in figure 6. Bands B, C, and D were extended to higher spins, the crossover E2 transitions in band B could be observed, and two crossover E2 transitions in band C could be observed, too. A few new γ rays were found, such as the E_{γ}=356 keV transition shown in figure 6, which were observed in coincidence with the transitions in bands B and C. These new transitions may originate from the chiral partner band, but lack of statistics prevented their firm placement in the level scheme.

Matrices for Directional Correlations from Oriented states (DCO) analysis and the determination of linear polarizations were also created and are currently under analysis. It should be possible to obtain DCO and linear-polarization results for the strongest transitions in ^{109}Ag. Though angular distribution measurements have already been performed by Pohl *et al.* [7] for these transitions, linear polarizations have not been measured yet. These results are important to enable firm parity assignments to be made to bands B, C, and D.

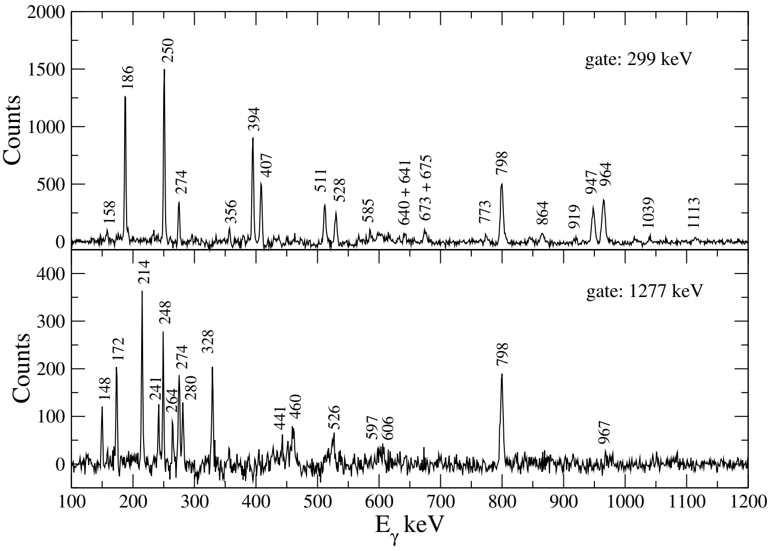

Figure 5. Examples of gated coincidence spectra for ^{109}Ag showing γ rays in band B (upper panel) as well as in bands C and D (lower panel). The energies are given in keV.

At present, it is possible to observe the level scheme up to spin $\sim$20 $\hbar$ which is considerably lower than the value of which termination is expected, namely $\sim$30 $\hbar$. Thus, the additional aim of the experiment, to study band termination, unfortunately could not be fulfilled.

5 Conclusions

The DIAMANT light-charged-particle array, in both full and standalone front-wall "Chessboard" modes has been successfully coupled with the AFRODITE γ-ray spectrometer. A number of measurements have been carried out during the first term of the collaboration. One of these concentrated on the investigation of incomplete fusion reactions instigated by the bombardment of a ^{170}Er target with ^{13}C ions at incident energies of 80 and 70 MeV. Comparison of the intensities of the single-αxn exit channels to hafnium nuclei (predominantly ^{176}Hf at E_C = 80 MeV) and two-αxn exit channels to stable ytterbium nuclei (^{172}Yb, ^{173}Yb and ^{174}Yb) suggests that the latter are populated when there is complete break-up of the ^{13}C beam into its α-α-α-n "cluster" constituents. This process is expected to be localized around grazing collisions. The steeper increase in γ-ray transition intensities in the single-

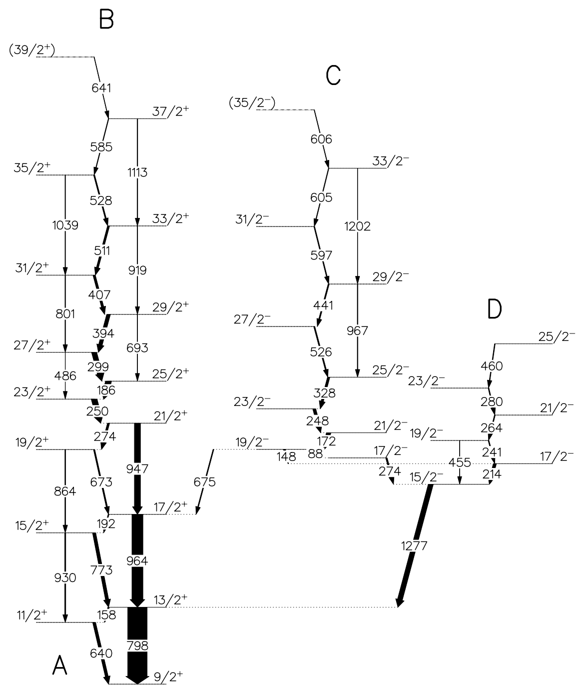

Figure 6. Level scheme of ^{109}Ag obtained in the present experiment. The energies are given in keV, while the width of the transitions are proportional to their relative intensities.

or two-αxn channels with spin when compared to the ground-state band of ^{178}W which was populated via the $5n$ complete-fusion-evaporation channel is consistent with this suggestion. It would be of interest to compare the relative yields of the single-αxn, two-αxn and pure xn exit channels with the predictions of the sum-rule model of Wilczynski *et al.* [9] for both the 70 and 80 MeV data.

An investigation of chirality and band termination in the stable nucleus ^{109}Ag via the ^{96}Zr(^{18}O,$p4n$) reaction at 82 MeV has thus far not yielded firm evidence for either effect. This is partly due to contamination from competing reaction channels which arose from the lighter Zr isotopes in the 85%-enriched ^{96}Zr target. Since the chiral partner to the $\pi g_{9/2}\nu(h_{11/2})^2$ configuration, and the putative terminating states that may compete with the latter above spin $30\hbar$, are likely to be weakly populated, experimental selectivity is crucial. To that end, further measurements are planned with a more efficient detector set-up which will allow charged-particle-γ-γ-γ coincidence data to be obtained.

Future developments of the AFRODITE-DIAMANT combination will make use of the newly funded data-acquisition system which will utilize state-of-the-art Digital Signal Processing technology. The system will have sufficient channels to process all outputs from the full complement of detectors in both arrays. In addition, the 5-year research plan for iThemba LABS contains a request for a suite of large volume, highly segmented clover detectors which will take the sensitivity of AFRODITE, in conjunction with DIAMANT and other complementary detectors, to new heights. This will enable researchers to capitalize on the opportunities that will arise from the installation of two additional 18GHz ECR ion sources at iThemba LABS in 2008, which bodes well for the future of accelerator based sciences and training in South Africa, hand-in-hand with co-operative projects such as the present one with Hungary.

Acknowledgments

This work is supported by the National Research Foundation (NRF) of South Africa under grants GUN 2067469 and GUN 61851, and by the National Office for Research and Technology (NKTH) and the Agency for Research Fund Management and Research Exploitation (KPI) of Hungary under grants TéT DAK–5/03 and ZA–7/2006.

References

1. J. N. Scheurer, M. Aiche, M. M. Aleonard, G. Barreau, F. Bourgine, D. Boivin, D. Cabaussel, J. F. Chemin, T. P. Doan, J. P. Goudour, M. Harston, A. Brondi, G. La Rana, R. Moro, E. Vardaci and D. Curien, *Nucl. Instr. Meth. A* **385**, 501 (1997).
2. R. T. Newman, J. J. Lawrie, B. R. S. Babu, M. S. Fetea, S. V. Förstch, S. Naguleswaran, J. V. Pilcher, D. A. Raave, C. Rigollet, J. F. Sharpey-Schafer, C. J. Stevens, F. D. Smit, G. F. Steyn, C. V. Wikner, D. G. Aschman, R. Beetge, R. W. Fearick, G. K. Mabala, S. Murray, D. G. Roux, W. Whittaker and N. J. Ncapayi, *Balkan Phys. Lett.*, Special Issue, p. 182 (1998).
3. J. Gál, G. Hegyesi, J. Molnár, B. M. Nyakó, G. Kalinka, J. N. Scheurer, M. M. Aléonard, J. F. Chemin, J. L. Pedroza, K. Juhász and V. F. E. Pucknell, *Nucl. Instr. Meth. A* **516**, 502 (2004).
4. D. C. Radford, *Nucl. Instr. Meth. A* **361**, 296 (1995).
5. C. M. Petrache, D. Bazzacco, S. Lunardi, C. Rossi Alvarez, G. de Angelis, M. De Poli, D. Bucurescu, C. A. Ur, P. B. Semmes and R. Wyss, *Nucl. Phys. A* **597**, 106 (1996).
6. J. Timár, C. Vaman, K. Starosta, D. B. Fossan, T. Koike, D. Sohler, I. Y. Lee and A. O. Macchiavelli, *Phys. Rev. C* **73**, 011301(R) (2006).
7. K. Pohl. P. H. Regan, J. E. Bush, P. E. Raines, D. P. Balamuth, D. Ward, A. Galindo-Uribarri, V. P. Janzen, S. M. Mullins and S. Pilotte, *Phys. Rev. C* **53**, 2682 (1996).
8. G. D. Dracoulis, A. P. Byrne, T. Kibédi, T. R. McGoram and S. M.Mullins, *J. Phys. G: Nucl. Part. Phys.* **23**, 1191 (1997).
9. J. Wilczynski, K. Siwek-Wilczynska, J. Van Driel, S. Gonggrijp, D. C. J. M. Hageman, R. V. F. Janssens, J. Lukasiak, R. H. Siemssen and S. Y. Van Der Werf, *Nucl. Phys. A* **373**, 109 (1982).