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Studies of Nuclei Far From Stability in the A=80 Mass Region

By

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Abstract

A three-stage thin film detector for the identification of heavy ion fragments was investigated in beam at HHIRF. An experiment on Eu-152 for the purposes of calibrating a four-crystal Germanium polarimeter was performed. The instrument was then used in an experiment to establish polarities for the low lying transitions in ^{82}Sr . The spectral fitting code, ROBFIT, was applied to the data analysis and shown to perform well on the extraction of weak peaks in high background situations.

1. Introduction

During the final year of this grant four activities were carried out. The first was a continuation of work on the three-stage thin film particle detector; the objective being the development of a relatively simple and inexpensive method for determining the charge and mass of individual particles ejected in nuclear reactions. Data taken in the previous reporting period at Oak Ridge National Laboratory, in which the detector was exposed to particle beams of equal mass and two different atomic numbers, have now been analyzed. This involved developing software to process the list mode data tapes so as to utilize the timing information to plot intensities versus calculated mass and charge for different velocity cuts. Work also continued at the University of Florida [funded by the UF Division of Sponsored Research] using a Californium source [with known distributions of particles having various masses and charges] to measure detector performance in combination with coincident gamma-ray detection to assist in the analysis. In Spring 1989, a follow-up experiment was performed at the Holifield Heavy Ion Research Facility and analyzed with software developed during the course of the grant. The Ph. D. dissertation of Mr. Zoran Milosevich [UF Department of Chemistry] is based substantially on this work. Although the thin-film detector appears to have a number of potential advantages, additional development is required in order for it to be competitive with other systems. This conclusion will be discussed in Section 2.

The second activity of this reporting period was an experiment to calibrate the efficiency of the four-element Germanium polarimeter used in our previously-reported in-beam gamma-ray spectroscopy studies¹. Such devices employ coincidence circuitry to select those gamma-rays which Compton scatter from one active polarimeter element into another. This first Compton scattering will be either parallel to the particle beam axis or perpendicular to it, depending upon the polarization of the incoming gamma-rays [from a nuclear reaction, in our experiments]. The polarization can be reduced to a ratio of the difference between perpendicular and parallel scattering intensities to the sum of these quantities, leading to the cancellation of effects due to the low-order energy dependence of Compton scattering. The experiment described here was designed to verify this energy independence using the numerous, well-known gamma-rays from Europium-152. Gamma-rays from radioactive sources; however, do not appear polarized owing to the fact that the nuclei have all possible orientations. We obtained polarized radiation by requiring coincidences between events detected by both the polarimeter and an additional external detector, thereby establishing the orientation of the emitting ^{152}Eu nuclei. This experiment was performed at the Florida State University in order to duplicate, as closely as possible, the laboratory equipment and conditions [radiation background, etc.] of the in-beam polarimeter measurements. We can report modest success for the calibration effort: approximately 6% of the recorded counts were properly in coincidence with the gamma-rays determining the nuclear alignment. Although a larger number of significant events would have been

desirable, the successful fitting of a complete spectrum [^{152}Eu] down to noise level confirms the accuracy of our fitting code, ROBFIT, while also testing its various parameters and controls. This is discussed in Section 3.

The third project was an in-beam experiment on the reaction $^{16}\text{O} + ^{70}\text{Ge} \rightarrow ^{82}\text{Sr}$, following-up on work reported earlier¹. The principal objective was the determination of the polarization of gamma-rays from ^{82}Sr , leading to additional energy level spin/parity assignments. In this experiment, an 81-MeV beam of ^{16}O struck a ^{70}Ge target placed at about 45 degrees with respect to the beam axis. Along with the polarimeter, Ge(Li) detectors were placed at 0 and 90 degrees, respectively, to the beam axis; their outputs were used to sort polarimeter data into the ground-state, negative-parity, and positive-parity bands. The presence in the ^{82}Sr spectrum of gamma-rays at 508, 511, 513, and 522 keV, respectively, presented a major challenge in sorting out the multiple peak overlaps in this region. A portion of our results are shown in Figure 1.1 and a discussion is presented in Section 4. These results will be published in a followup paper to our earlier work on ^{82}Sr .

Figure 1.1. A portion of the Sr-82 Spectrum. The 522-keV peak, of most interest in this experiment, is seen here to the right of the larger peak. The relatively large number of counts permits determination of peak locations and widths even in regions of extreme overlap. Dots at the top of the figure represent point-by-point deviations of the fit from the data, the upper and lower lines marking two standard deviations.

Finally, there are our further developments of techniques for data analysis. ROBFIT is the present version of a spectrum fitting code written to analyze histogram data to the noise level. Work on this code has been supported in part by this DOE grant, an IBM grant, DARPA grants, and by the University of Florida.

The ROBFIT fitting code had its beginning as RLCFIT² when it was used to analyze angular distributions in ⁸²Sr¹. The code RLCFIT is relatively standard in that spectra are broken into short sections and fitted with polynomial backgrounds in each section. Its new features are: (1) the use of back-to-back cubic splines to represent a

standard peak which can then be fitted to all the rest of the peaks in the spectrum by varying only strengths and widths, and (2) an extended Newton-Raphson minimization scheme, SMSQ, which works well in most applications. RLCFIT was followed by PCFIT³ in which the widths of the peaks were constrained to follow the known patterns; errors were calculated much, much faster, and the entire background was fitted at once using Fourier transform techniques. During the course of this DOE grant, PCFIT became ROBFIT in which the background is fitted to the exponential of a cubic spline with the knots as parameters and the misses robustly treated so that the fit follows the background rather than the unfitted peaks. The code also allows for multiple standards; for the introduction of peaks constrained to certain positions [within errors] and other features. A book describing ROBFIT and its uses has been funded by DARPA and the manuscript is currently being prepared for publication⁴. Figure 1.2, and other figures appearing in the following discussions, are graphic evidence of the success of this effort.

Figure 1.2. In the fit to the difference between the perpendicular and parallel intensities in the polarimeter, the peak locations and widths are left as determined in Figure 1.1 and only the peak heights are allowed to vary.

2. LEHIFI: A Thin-Film Particle Detector/Mass Identifier

Much of the current research in experimental nuclear physics relies heavily on high-accuracy particle detectors capable of identifying nuclear charge Z and mass M ; the latter associated with mass number A . A combination thin film scintillator detector⁵ (TFD)-silicon surface barrier detector (SBD) has been shown to respond to transiting heavy ions and fission fragments such that approximate Z identification is possible on an event-by-event basis⁶⁻⁹.

We have dubbed the counter telescope assembly "Low Energy Heavy Ion Fragment Identifier" [LEHIFI]. The telescope consists of three

individual scintillator films for measuring specific luminescence of the transiting ion, followed by a surface barrier detector for residual energy measurement. Multiple ion velocity measurements can be made using timing pulses between various combinations of thin films. Each scintillator element is contained in a 3"x3"x3" housing and positioned perpendicular to the faces of two opposing photomultiplier tubes as shown in Figure 2.1. A drawing of the completed detector assembly is shown in Figure 2.2. The transiting ion passes through three scintillator detectors and is stopped in the surface barrier detector. The gain of each photomultiplier circuit may be matched to that of the others for equal amplification, using a ^{252}Cf fission fragment source. To accomplish this gain calibration, each TFD is individually exposed to the undegraded ^{252}Cf source by retracting it into an overhead compartment so that the following active element [TFD or SBD] "sees" the undegraded source. Initial tests of detector response to ^{252}Cf fission fragments were made at the University of Florida during the early stages of LEHIFI development.

Further testing was done in August, 1986, at the Holifield Heavy Ion Research Facility (HHIRF) at Oak Ridge National Laboratory. Beams of ^{58}Ni and ^{64}Ni ions with energies ranging from 0.75 MeV/nucleon to 2 MeV/nucleon were scattered from Pb, Au, and ^{64}Zn targets. The LEHIFI prototype was exposed to both the scattered particles and the recoiling target nuclei; the objective being to test detector response as a function of mass in an energy range similar to that of typical fission fragments. The M.S. thesis of Mr. Zoran Milosevich is based

Figure 2.1. Single Element of LEHIFI. The TFD is mounted on the brass plates and can be retracted with the plunger. The photomultiplier tubes and their shields fit into the holes at front and rear, at right angles to the TFD face and to the ion path.

Figure 2.2. Three-Element LEHIFI Assembly. This drawing shows the complete LEHIFI, assembled from three of the elements pictured in Figure 2.1, with SBD and calibration source in place.

substantially on this work.¹⁰ A response curve for a single TFD is shown in Figure 2.3. At the higher energy of 120 MeV the response [specific luminescence] for a given Z did not seem to depend on the mass. In the upper part of the figure it is seen that the response to ^{58}Ni and ^{64}Ni is essentially the same. At lower energy, mass dependence appeared [lower part of the figure] but this behavior was not confirmed in a follow-up experiment with different ions [see below]. Attempts to compare isobaric species [different Z] were inconclusive. Response to the three TFD elements of LEHIFI is shown in Figure 2.4; the mass dependence noted in the previous figure prevails in all three TFD's. Figure 2.5 illustrates further the response of the LEHIFI detector elements. The failure of the specific luminescence to retain its mass independence at lower energies remained a puzzle. The multiple-film detector data required further analysis, and additional experiments were considered.

The follow-up experiment took place in April, 1989, at HHIRF. To further investigate LEHIFI behavior with particles of different Z and M values at lower energies, the detector was exposed to ^{74}Se , ^{76}Se , ^{70}Ge , ^{74}Ge , and ^{76}Ge ions scattered off a gold target. LEHIFI response was measured at incoming particle energies ranging from 0.65 MeV/nucleon to 2 MeV/nucleon. Response to differing masses exhibited little variation, as shown in Figure 2.6. The low energy response differs somewhat from that of the previous experiment and does not confirm those results. The response variation with different Z values is not significant at the lower energies.

Figure 2.3. Single TFD Response. Specific luminescence for constant velocity $^{58,64}\text{Ni}$ ions is shown at 120 MeV [upper curve] and 45 MeV [lower curve]. Note the separation which appeared at the lower energies in this experiment.

Figure 2.4. Response of the Three TFD Elements. Specific luminescence of each element is shown for transiting ^{58}Ni and ^{64}Ni ions. Note the apparent mass independence of the TFD response.

Figure 2.5. Ion Time-of Flight and Detector Response.
 The velocity spectrum of 120-MeV ^{58}Ni and ^{64}Ni ions is shown at top, followed by energy spectra from the middle TFD and the SBD, respectively.

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Figure 2.6. LEHIFI Response to 120-MeV Selenium Ions.
The upper figure shows the specific luminescence of a single TFD to ^{74}Se ions of different charge states. Lower figure: LEHIFI response to transiting $^{74,76}\text{Se}$ ions.

A third experiment has been carried out more recently at the University of Florida. The detector response to ^{252}Cf fission fragments was recorded in coincidence with the prompt gamma rays emitted from the fragments in order to selectively identify the transiting particles. These data are currently undergoing analysis and should provide additional information on LEHIFI response to low-energy, heavy-mass ions.

3. Calibration of the 4-Element Polarimeter

The experimental setup is as shown in Figure 3.1.

Figure 3.1. Schematic Drawing of the Polarimeter Calibration Set-up. Note the slight difference in spacing of the left and right gating detectors from the ^{152}Eu source, which somewhat affected the results.

A coincident event between the R or L detectors and the polarimeter within a resolving time of 1 microsecond caused the event to be written to tape. Ten tapes were accumulated at the FSU Nuclear Laboratory (where this series of experiments was performed) for

later analysis at the University of Florida. Processing of the data included stripping into histogramming spectra for both the right and left gates of ground state, excited states, and background by sorting according to the gamma-ray energy signals from the NaI detectors.

It was found that there were insufficient data to make a foreground-background determination of the coincidences, owing to the fact that even slight energy shifts [as few as a couple of channels] in NaI detectors affect the background significantly. The energy dependence of the polarimeter was determined by fitting the entire ^{152}Eu spectrum at one time. By calibrating the Sm band with the Gd peaks and using the difference between the Sm intensities and the known values expected it was possible to determine the fraction of each peak actually in coincidence with the NaI detector. The quality of fit to a radiation spectrum which is possible with ROBFIT [and which is required for this type of analysis] is shown in Figures 3.2 through 3.7.

Figure 3.2. This is the full spectrum of counts in which two elements of the polarimeter fired during the same microsecond that the left NaI detector registered an energy pulse in the 121-keV range.

Figure 3.3. This shows the fit to the background of the Europium spectrum in Figure 3.2. It was this fit which enabled us to determine peak areas accurately enough to find the 6% excess in those in actual coincidence with the 121-keV gamma-ray.

Figure 3.4. Blow up of low energy region to show quality of data and fit.

Figure 3.5. This shows the fit in the 1085-keV region. The 1085 9-0 transition is background in both spectra and thus can be used to sort out the coincidence and background line. It needs to be separated from the 1084-keV containment for the best possible resolution.

Figure 3.6. The fit in the high energy region.

Polarizations of the five Eu-152 decay peaks have been obtained with about 33% standard deviations, demonstrating the nondependence of the polarization on energy. We believe that this work may represent one of the first occasions on which an entire spectrum of this complexity has been fit, at once, to a single background. In the polarimeter calibration and subsequent analysis, it became clear that a few ambiguities remain in the decay scheme of ^{152}Eu . The importance of a well-calibrated radioactive source of this type [many separated gamma-rays having a good range of energies] suggests further investigation of ^{152}Eu .

The principle difficulty in obtaining these peaks came from the fact that the coincidence data was nearly swamped by randoms. We extracted the coincidence part by assuming it to be proportional to

the total intensity of the peak in question. Then, an efficiency fit to known random peaks allowed the excess in the coincident peaks to be determined by comparing the intensity measured for them with those given in the 1989 Nuclear Data Sheets¹¹. For the Sm peaks $(4.28 \pm .56)\%$ was in coincidence, while for the Gd peaks $(8.3 \pm 1.1)\%$ was in coincidence.

This was confirmed by using ratios to the 344 keV peak in ^{152}Gd , between the data gated on the 121-keV peak in ^{152}Sm and that of the former, for the Sm calculation.

Table 1
¹⁵²Eu Polarizations

E (KeV)	Δ	Q	P _{exp}	P _{th}		
778	$.27 \pm .10$	.52	$.52 \pm .19$	.09	Gd 7-1	E1+(M2)
964	$-.49 \pm .12$	.45	$-1.09 \pm .27$	.20	Sm 9-1	M1+E2+EO
1090	$.17 \pm .24$	.41	$.41 \pm .59$	.32	Gd 10-1	E2 + (M1)
1112	$-.28 \pm .11$	.40	$-.70 \pm .28$	-.41	Sm10-1	M1+E2
1408	$-.42 \pm .11$	.33	$-1.27 \pm .33$	-.38	Sm 13-1	E1+(m2)

$$\Delta = (\text{per} - \text{par})/(\text{per} + \text{par})$$

$$Q = (1 + E/511)/(1 + (E/511) + (E/511)^2)$$

is the expected efficiency of a Compton Polarimeter after correcting for the angular dependence of Compton scattering.

P_{th} is calculated from Eqn II-36 in Stromwald¹² using the angular coefficients in Barrette et al¹³ Assuming H_k = 1 (no mixing).

In addition to the tabulated results, all our data consistently show the 1005-keV Sm 12->1 peak to have an intensity of 40 ± 1 rather than the 30 present in the nuclear data tables. This transition was not used in our coincident peak determination.

4. Polarization Measurements on Gamma-Rays from ^{82}Sr

This investigation was made in order to determine the polarizations of some of the lines in the ^{82}Sr decay scheme. These are of interest because of the peculiar structure of ^{82}Sr which tends to change shape as it decays. The experiment is essentially a repeat of an earlier one in which one of the four Germanium polarimeter elements failed. This failure both reduced the number of counts and made the ratio of counts determining the polarizability more energy sensitive. As stated in the Introduction, this experiment, like its predecessors, was carried out at the Nuclear Laboratory of Florida State University. Targets of enriched ^{70}Ge were bombarded with an 81-MeV beam of ^{16}O ions to produce excited states of ^{82}Sr for investigation. The experiment was set up as shown in Figure 4.1.

The data, fully analyzed, are the direct data in which beam hits target to produce a gamma ray which scatters into the polarimeter. The fit to the sum data (perpendicular plus parallel) is shown in Figures 4.2 and 4.3.

The fit to the difference data (perpendicular minus parallel) is shown in Figure 4.4. We have statistically significant polarizations for many peaks including the 522 KeV; one of most interest in this region. The 875 Kev peak occurs in these data in coincidence with another 875 KeV peak of no interest. Our gated data, which are much lower in counts, may shed some light on this transition, also.

Figure 4.1. Schematic drawing of the experimental setup used in the experiment to determine the polarization of gamma rays from ^{82}Sr .

Figure 4.2 Sum of perpendicular and parallel gates. All peaks, along with the fitted background which is the exponential of a cubic spline, contribute to the chi-squared of 8295 for the 8001 channels.

Figure 4.3 Detail of the fit in the 1085-keV region showing both the breakup of a typical doublet and the standard shape used with varying widths and heights to fit all of the peaks.

Figure 4.4 Fit to the difference data showing the polarization of the background, plotted in white. The background in this case is a cubic spline with 9 fitted constants.

Table 2
Polarization results on Sr-82

ENERGY	PER + PAR		PER - PAR	
85.08	173.29	+- 19.61	30.61	+- 15.18
269.92	3783.68	+- 436.90	-1131.65	+- 425.70
379.82	13240.00	+- 575.00	-53.38	+- 548.90
403.64	17000.10	+- 554.30	-988.08	+- 524.70
439.34	7140.50	+- 560.20	-973.56	+- 530.40
522.16	22892.80	+- 1267.00	445.74	+- 1233.00
534.43	6953.17	+- 527.20	844.80	+- 512.80
573.44	165503.00	+- 718.10	17756.60	+- 717.90
601.83	48541.50	+- 640.90	-3186.61	+- 642.00
606.69	27531.60	+- 658.30	-229.42	+- 659.50
693.90	16344.80	+- 547.00	1782.33	+- 546.80
754.99	170965.00	+- 758.90	23292.50	+- 742.00
786.00	55651.80	+- 702.70	5294.71	+- 658.40
800.80	38740.50	+- 578.60	4735.72	+- 541.80
820.16	25523.80	+- 609.60	2462.97	+- 571.30
840.34	52993.70	+- 745.70	5601.07	+- 684.00
875.13	46418.10	+- 598.00	5889.55	+- 548.70
900.69	73604.60	+- 597.20	9509.87	+- 568.20
941.54	24306.90	+- 672.10	1844.04	+- 638.80
950.98	11153.30	+- 538.80	25.35	+- 538.60
1003.00	48533.70	+- 804.70	5632.29	+- 805.00
1013.16	69392.80	+- 675.30	3999.47	+- 671.90
1107.33	13669.20	+- 518.40	-4.70	+- 515.00
1116.16	14277.40	+- 764.10	-2.88	+- 759.30
1136.01	9805.74	+- 633.10	183.29	+- 626.00
1175.32	9850.46	+- 500.30	498.86	+- 494.70
1180.56	6389.25	+- 540.10	451.01	+- 534.10
1296.57	18270.70	+- 538.10	1487.49	+- 531.90
1337.12	10198.90	+- 443.00	742.25	+- 437.30
1393.35	8380.07	+- 449.30	1891.68	+- 449.30
1489.35	23728.20	+- 569.30	1299.39	+- 566.70

The polarization is defined as $(PER - PAR)/(Q(E)f(PER + PAR))$ where $Q(E)$ is defined following Table 1 and f is a fraction on the order of .6 to account for the failure to detect all of the polarization.

5. Summary

We can report several favorable outcomes of these investigations:

- a) A substantial portion of the fitting code, ROBFIT, was developed and tested in several of these data analyses. Its further development and publication [through DARPA sponsorship] will make it increasingly useful to many workers in this and other research areas.
- b) A first pass at calibrating the four-crystal polarimeter met with modest success.
- c) Polarization of additional ^{82}Sr gamma-rays has been determined.
- d) The particle-identifier telescope LEHIFI has been conceived and development is under way.
- e) New research ideas have arisen from these studies; they will be actively pursued.

References

1. P.S. Haskins, F.E. Dunnam, R.L. Coldwell, A.C. Rester, R.B. Piercey, M.L. Muga, H.A. Van Rinsvelt, R.W. Smart, H.J.M. Aarts, J.D. Fox, L.C. Dennis and C.B. Saw, Phys Rev C 32, 1897 (1985).
2. R.L. Coldwell, *Radiative Properties of Hot Dense Matter*, pp 315-349, World Scientific, 1983.
3. R.L. Coldwell, Nucl. Instr. and Meth. **A242** (1986) 455.
4. R.L. Coldwell and G.J. Bamford, ROBFIT, A Code for the Analysis of Histogram Spectra, to be published.
5. M.L. Muga and H.E. Taylor, U.S. Patent #3567925, March 2, 1971.
6. M.L. Muga and G.L. Griffiths, Nucl. Instr. and Meth. 109, 289 (1973).
7. M.L. Muga, G.L. Griffiths, H.W. Schmitt and H.E. Taylor, *ibid.* 111, 581 (1973).
8. M.L. Muga, *ibid.* 125, 541 (1975).
9. J.M. Nicovich, A. Clem and M.L. Muga, *ibid.* 157, 93 (1978).
10. Z. Milosevich, Interaction of a Thru-Element Thin Film Detector with Selected Low-Energy Heavy Ions. Master's Thesis, University of Florida, 1988 (unpublished).
11. Nuclear Data Sheets 58, 93 (1989).
12. D.C. Stromswold, Linear Polarization Measurements on Gamma-Rays from ^{100}Pd , ^{102}Pd , ^{104}Pd , and ^{106}Pd , Dissertation, Johns Hopkins University (1976).
13. J. Barrette, M. Barette, A. Boutard, G. Lamoureaux, and S. Monaro, Can. J. Physics 48, 2011 (1970).

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