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Symmetry breaking in mirror nuclei ^{55}Co and ^{55}Ni

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Abstract
Yrast states in mirror nuclei ^{55}Co and ^{55}Ni have been populated with a radioactive ion beam using the Isotope Separator On-Line method. A shielded array of 7 Compton suppressed germanium detectors recorded reaction gamma-rays. For channel selection, an array of 128 independent silicon detectors was used to differentiate exit channels with different number of proton and alpha particles emitted. From gamma-gamma and gamma-particle coincidences, three lines in ^{55}Co and one line in ^{55}Ni was obtained for the first time.

Keywords: Mirror nuclei, Radioactive Ion Beam, Coulomb Displacement Energies, Decay Schemes, Compound Nucleus, Fusion-Evaporation Reaction

1. Introduction
The structures of mirror nuclei (nuclei with the same mass number and the number of protons in one of them equals the number of neutrons in the other) are almost identical, except for the small effects due to Coulomb interaction where the symmetry is being broken. The study of this symmetry breaking reveals details of the nuclear structure. This shift in mirror symmetry will be observed mostly as a function of spin where the protons and/or neutrons rearrange themselves in new shell model orbits and hence cause changes in Coulomb energy differences. These effects, known as Coulomb Displacement Energies (CDE), have been the subject of several studies in nuclear structure physics. In two experiments at the beginnings of the 90's, the mirror pairs ^{49}Mn / ^{49}Cr and ^{47}Cr / ^{47}V were studied and an interesting breaking in the mirror symmetry was observed as a function of spin [1-3].

Up to now, the high spin study of the mirror nuclei has used stable beam/target combinations. Since the production of heavier mirror nuclei requires the formation of a compound nucleus which must be further away from the line of stability, one way to solve this problem is using a neutron-deficient radioactive ion beam (RIB). New combinations of colliding systems can allow for more systematic studies of the reaction mechanisms and structural effects (such as nuclear shape) as a function of proton or neutron number. The large available range in Z and N will be an important aspect in the study of such reactions.

In this way one can increase the cross-section of more neutron-deficient nuclei in comparison with reactions by stable beams. The first test of a fusion-evaporation compound nucleus by a radioactive ion beam was done at the Louvain-la-Neuve laboratory, Belgium, with the aims of studying the effects of CDE in the mirror nuclei ^{55}Co / ^{55}Ni, and obtaining information on the problems to be faced in using a radioactive beam for nuclear spectroscopy. As mentioned above, this experimental work was done at Louvain-la-Neuve and some results were published before [8,9]. Some of the experimental details are given here again for the information of the readers of this journal.

2. The Experiment
A radioactive ^{19}Ne beam was produced at Louvain-la-Neuve accelerator laboratory in a two-stage process using the Isotope Separator On-Line (ISOL) method [4,5]. Figure 1 shows a schematic outline of the experimental set-up used in the present work. Initially,

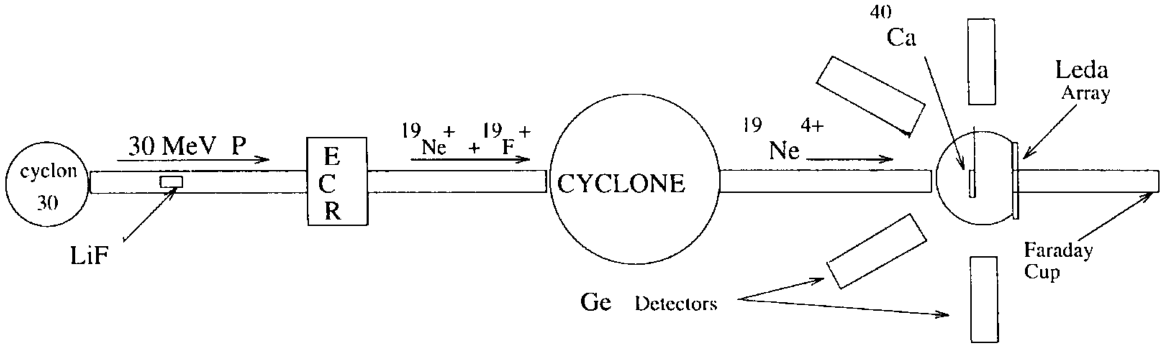

Figure 1. Schematic diagram of the experimental layout.

the CYCLONE 30 cyclotron produced 30 MeV protons with a beam current of 150 μA which bombards a thick Lithium Fluoride target to produce the radioactive atoms via the ^{19}F (p,n) ^{19}Ne reaction. The target was melted by the beam (melting point 1118 K) and was enclosed in a graphite cylinder which isolated the hot target material from the cold copper holder. The ^{19}Ne nuclei diffused out of the cylinder through the hot carbon window. These radioactive atoms, as well as a large number of stable ^{19}F isobaric contaminants, were then turned into positive ions in an Electron Cyclotron Resonance (ECR) ion source and injected into a second cyclotron accelerator named CYCLONE (see figure 1).

To achieve a high isotopic purity in the final beam, CYCLONE was tuned as a mass spectrometer so that the intensity of the ^{19}F contaminants was reduced far below (less than 1 part in 600) the radioactive beam intensity after acceleration. Using this method, beams of up to 150 ppA (9.4 X 10^8 particles per second) of $^{19}Ne^{4+}$ were accelerated to final beam energy of 70 MeV. The beam was pulsed to provide beam bursts separated by 73 ns. This beam pulsing was invaluable in the subtraction of random events (see below). The beam was incident on a 1.6 mg/cm^2 thick ^{40}Ca target which was prepared and kept in vacuum before use and then transferred to the chamber. This was important to avoid oxygen contamination of the target. The center of mass energy of the beam of 47.5 MeV was above the Coulomb barrier for this reaction allowing fusion-evaporation type reactions.

Gamma-rays were identified from residual nuclei formed in the ^{19}Ne + ^{40}Ca reaction using an array of 7 TESSA (Total Energy Suppression Shield Array)-style Ge detectors [6] with efficiencies between 20% and 25%, relative to a 76 mm X 76 mm NaI detector at 25 cm.

The Ge detectors were placed in the backward hemisphere because the forward hemisphere was expected to be swamped with scattered radioactive beam particles, even when using thin targets. The Ge detectors were supported in a framework such that three of them were at 90° while the others were at 145° to the beam direction. To reduce the amount of 511 keV annihilation radiation observed in the Ge detectors from the decay of the beam particles (The ^{19}Ne nuclei decay via β^+ emission to ^{19}F nuclei with a lifetime of 17 seconds), the detectors were collimated towards the target and 2 cm of Pb shielding was placed around all of the detectors and beam collimators. The beam stop was 2 m behind the target position and well shielded with a wall of lead bricks.

The micro strip silicon detectors known as the LEDA (Louvain-Edinburgh Detector Array) [7], which had been placed in the forward direction were used to detect evaporated proton and alpha particles from the reaction. The high granularity of this device and its thickness (300 μm) provided information on multiple charged particle events. The geometric efficiency of the LEDA array for detecting individual protons and alpha-particles was approximately 10% and was essentially insensitive to β and γ radiations produced in the reaction. As shown in figure 2, the silicon detectors were in eight sectors in an octagonal shape. The active area of this geometry is divided into 128 independent detector elements and this has the advantage of position resolution, high data throughput and high multiplicity event detection. This detector array was covered by a retractable 11.7 mg/cm^2 Al foil which stopped the scattered beam particles. A chamber housed all the components (except the Ge detectors) in a high vacuum (~1.7 X 10^{-5} mbar).

3. Data Analysis and Experimental Results

The raw singles spectrum from the gamma-ray detectors, measured in the reaction is shown in figure 3a. Despite the collimating of the Ge detectors towards the target and the 2 cm of Pb shielding around all detectors and beam collimators, the singles spectrum is totally dominated by 511 keV annihilation gamma-rays (the activity of ^{19}Ne was 47 MBq, i.e. 94 million 511 keV γ-rays per second). Since the beam stop was 2 m farther and well shielded, the 511 keV peak must almost certainly have been due to the scattered beam that stopped in the region of the target. This 511 keV due to annihilation of an electron-positron pair is mostly seen in opposite detector pairs. It has been shown that the rate of

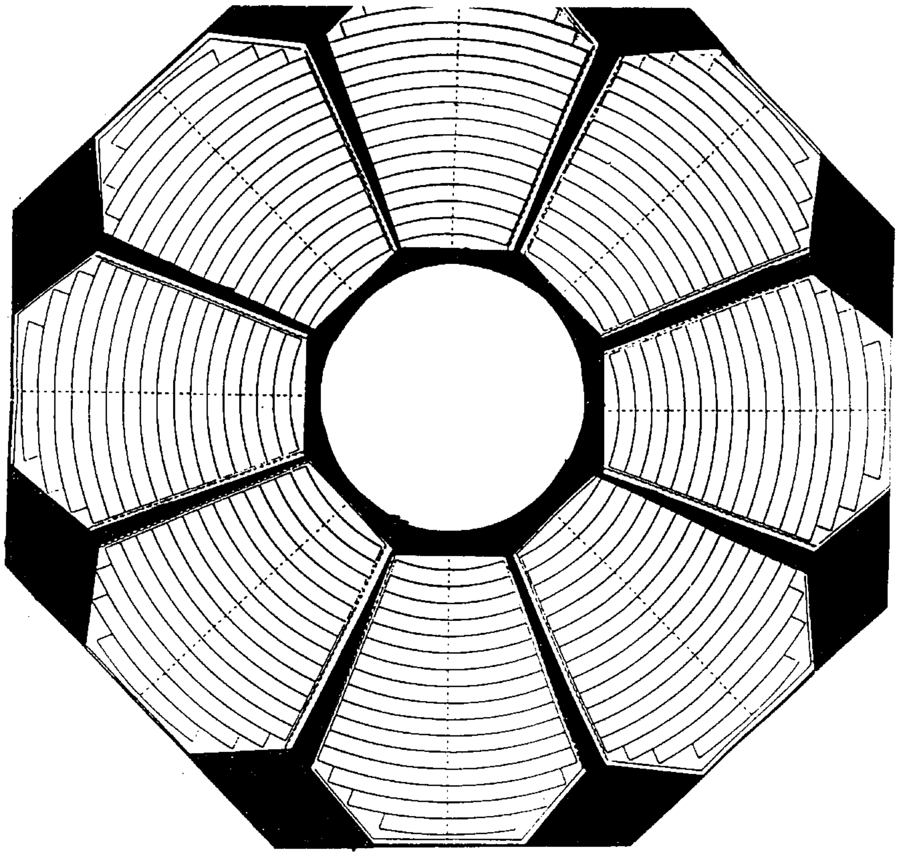

Figure 2. Layout of Edinburgh LEDA detector array.

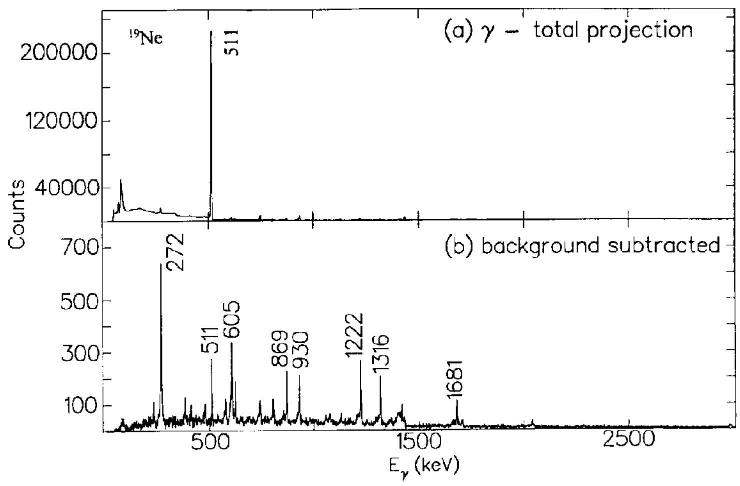

Figure 3. Total γ singles and background subtracted spectra.

511 keV radiation between opposite pairs is about 100 times greater than observed between adjacent detectors [8].

As figure 4 shows, by software gating on the in-beam regions A and C and out-of-beam regions B and D separately, a subtraction of the radioactive background {(A+C)-(B+D)} can be achieved giving a spectrum of the prompt gamma-rays (the two peaks in the figure) which are produced only in the fusion-evaporation reactions. The dominant 511 keV peak is almost completely eliminated and the unsuppressed Compton events below 511 keV are removed (figure 3b). In addition to the removal of the 511 keV gamma-rays, the background subtraction has also removed the peaks due

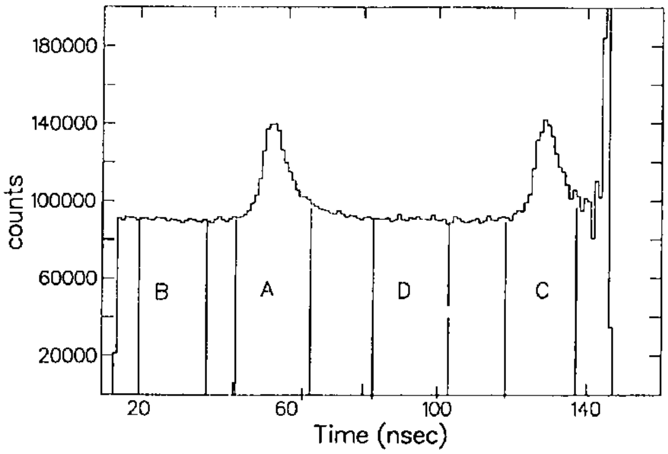

Figure 4. Pulse beam of the Cyclotron showing In-beam regions A and C and, out-of-beam regions B and D. The time interval between the two peaks is 73 ns.

to the radioactivity that continues between beam bursts [8,9].

A gamma-gamma coincidence means the cascade of related gamma-ray transitions in a specified excited nucleus, and a particle-gamma coincidence indicate the occurrence of a fusion-evaporation reaction. Any gamma-ray activity emitted between beam pulses or even during beam pulses in which no reaction was induced, should therefore be discriminated against by the LEDA detector array [8,9]. The effects of particle-gamma gating are shown in figure 5. This requirement is a good tool for selecting reaction gamma-rays.

4. Level Schemes of ^{55}Co/ ^{55}Ni Nuclei

By using gamma-gamma and particle-gamma coincidences, we were able to find three lines of ^{55}Co and one line for ^{55}Ni. We could not see the 1951 keV line in ^{55}Co which was reported previously in ref. [10]. Two point angular distributions were used to infer level spins. This information is summarized in table 1. The decay schemes of the two nuclei are shown in figure 6. The 2796 keV line was assigned to ^{55}Ni from the following information (figure 7): the peak is observed in the ^{19}Ne background subtracted singles data but not the ^{19}F (stable beam) induced reaction; within experimental uncertainties the peak has a two charged particle hit probability distribution in LEDA; and the energy of the line is close to that observed for the analogous transition in the ^{55}Co mirror nucleus (2973 keV).

5. Summary and Conclusions

It has been demonstrated that nuclear high spin studies can be performed successfully with a radioactive ion beam. It has proved to deal with the particular problems introduced by the radioactivity of the beam particles and the relatively low beam intensity (as compared with stable beams). The beam pulsing was the most important ingredient for producing high quality gamma-ray energy spectra. Charged particle detection proved to be a very useful on-line tool for identifying fusion-evaporation gamma-rays. The granularity of the LEDA array and the choice of their thickness were both beneficial. The moderate thickness of the silicon detectors allowed protons to be distinguished effectively from alpha particles.

The present experiment has provided three yrast states in ^{55}Co and one yrast state in ^{55}Ni. The symmetry breaking in the first excited states of the two nuclei is obvious. More transition lines in the two nuclei are required for a detail comparison at other excited states and spins. The increase in counting statistics required in order to study new nuclear structure in detail should be achievable with improvements in the detection system. For example, an array of 20 Ge detectors each with a 90% relative efficiency (at 1332 keV) would give two orders of magnitude increase in the gamma-gamma and gamma-particle coincidences compared to the present work.

Table 1. Energy and spin values for the mirror nuclei ^{55}Co and ^{55}Ni.

Nucleus	E_γ (keV)	E_i	E_f	J_i	J_f
$^{55}Co_{28}$	2973	2973	0	$11/2^-$	$7/2^-$
	801	3774	2973	$13/2^-$	$11/2^-$
	739	4513	3774	$15/2^-$	$13/2^-$
$^{55}Ni_{27}$	2796	2796	0	$11/2^-$	$7/2^-$

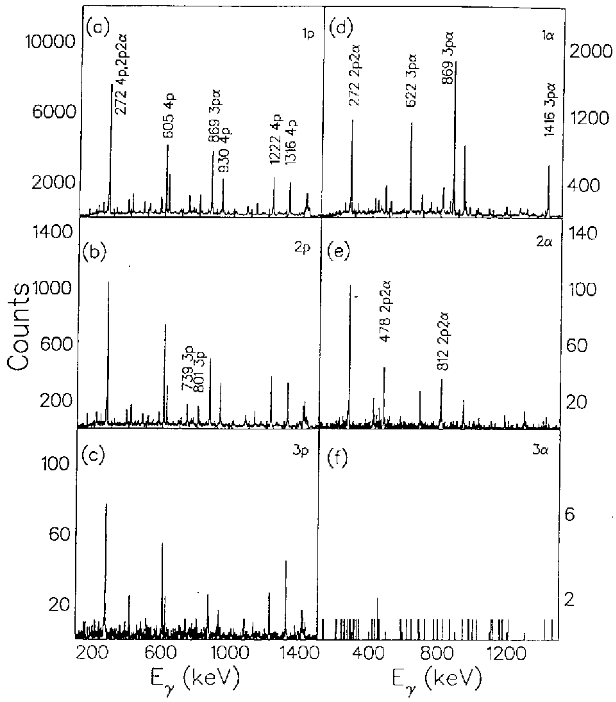

Figure 5. Gamma-ray energy spectra with full background subtraction and with specific gating requirements.

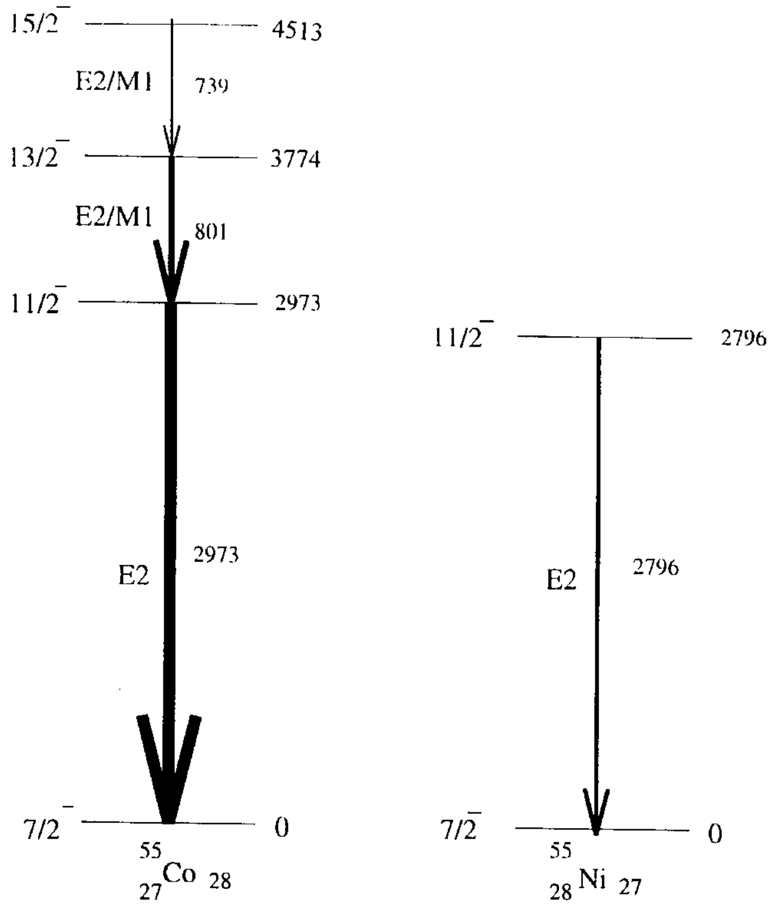

Figure 6. Decay schemes of the yrast states in mirror nuclei ^{55}Co and ^{55}Ni.

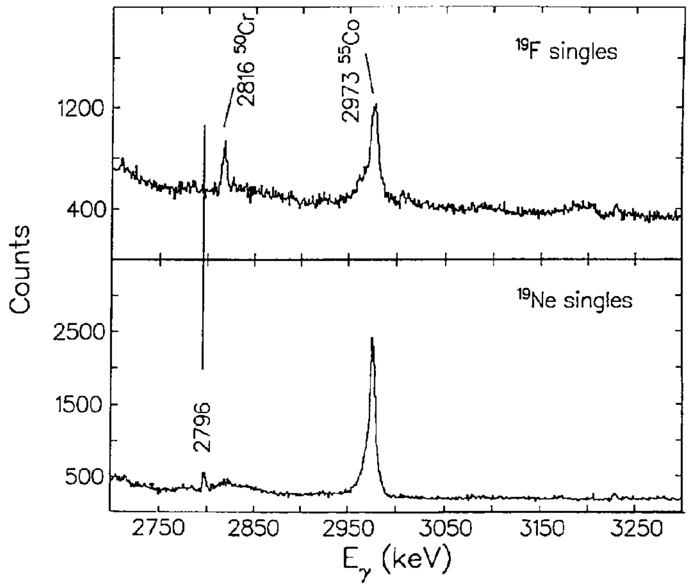

Figure 7. Spectra identifying the 2973 and 2796 keV lines, assigned to ^{55}Co and ^{55}Ni respectively.

Acknowledgments

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