

The Silicon Ball: a 4π Si detector array for reaction channel selection

T. Kuroyanagi, S. Mitarai, S. Suematsu, B.J. Min¹, H. Tomura, J. Mukai², T. Maeda
and R. Nakatani

Department of Physics, Faculty of Science, Kyushu University 33, Fukuoka 812, Japan

G. Sletten, J. Nyberg³ and D. Jerrestam⁴

The Niels Bohr Institute, University of Copenhagen, Risø, DK-4000 Roskilde, Denmark

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A 4π array of seventeen charged particle detectors (Si Ball) has been designed and constructed to provide selection of reaction channels for in-beam spectroscopy. The detector array, which consists of ΔE Si detectors of 170 μm thickness, is very compact to allow insertion into Inner Ball or Neutron Wall which may be a part of the NORDBALL γ -ray spectrometer. High spin states of neutron deficient nuclei around $A = 80$ have been studied using the Si Ball, and it has been proven that the Si Ball is a powerful tool in the in-beam spectroscopy of nuclei far from the β -stability line.

1. Introduction

In-beam spectroscopy with heavy ion reactions and use of large arrays of escape-suppressed germanium detectors has been in rapid progress during the last decade. The remarkable improvement of the detector efficiency of such instruments has results in a number of exciting discoveries, such as superdeformed bands [1] and strongly fragmented decay of K-isomeric states [2].

Further improvement of the sensitivity is in rapid progress and is developing along two general routes. One is an increase of the total germanium detector efficiency as in the Gammasphere [3], the Eurogam [4] and the Euroball [5] projects. The second is a development of selective devices which in conjunction with the germanium detector array might increase the sensitivity by large factors. The present paper aims at a

description of a selective device for use in reactions with high charged particle multiplicity.

In heavy ion fusion reactions at high excitation energy and spin and where the fused system is far from the β -stability line, many reaction channels are open. In particular, the large number of $p\alpha n$, $\alpha\alpha n$ and $p\alpha\alpha n$ reaction channels with proton and alpha multiplicity greater than 1 leads to such a fragmentation of the individual channel yields that a selection becomes imperative.

Most of the devices used so far have had rather small solid angle and consisted of only one or a few counter elements (low granularity) and were therefore unable to separate reaction channels clearly. The most successful so far, in our opinion, have been the phoswich arrays [6], ΔE Si-wafers [7,8] and a spherical device furnished with a large number of CsI scintillators [9].

The new charged particle multiplicity selector that will be described in the following has been designed for use in the NORDBALL [10] escape-suppressed germanium array and has therefore a geometry reflecting this relationship. Rather strong limitations on its size have been necessary since one wanted to combine it with the 60-element BaF_2 scintillator ball. Only a 100 mm diameter sphere is available inside this γ -ray calorimeter. The advantage would be a simultaneous measurement of both the γ -ray and the light charged particle multiplicity.

Present addresses:

¹ Design Analysis Department, Korea Atomic Energy Research Institute, PO Box 7, Daeduk-danji, Daejeon 305-353, Korea.

² Institute of Physics, University of Tsukuba, Tsukuba, Ibaraki 305, Japan.

³ The Svedberg Laboratory, Uppsala University, Box 533, S-751 21 Uppsala, Sweden.

⁴ University of Uppsala, UFL, Studsvik, S611 82 Nyköping, Sweden.

2. Description of the system

2.1. General criteria

The NORDBALL array has a general spherical geometry where the detector systems are positioned in concentric shells. The escape-suppressed germanium detectors are positioned 180 mm from the target. Inside that there is a shell of BaF_2 scintillators with 60 elements and finally the remaining inner sphere with a diameter of 100 mm is equipped with the shell of silicon detectors which will be discussed in this paper.

The most important design criteria for the Silicon Ball are:

- 1) A solid angle as close to 4π as possible.
- 2) Low probability of multiple hits in a detector; high granularity.
- 3) Good discrimination between protons and α particles.
- 4) Compact size to fit inside a 100 mm diameter reaction chamber.
- 5) Simple structure of each Si detector.
- 6) Simple geometry of the array of Si detectors.
- 7) Fast processing of the output signals at a high counting rate.
- 8) Simple electronics.
- 9) Small absorption and scattering of γ -rays by the device.
- 10) The same counting rate in every detector element.

2.2. Design of the Si Ball

A dodecahedron structure is one of the simplest geometries for fitting an array of identical silicon wafers inside a 100 mm diameter sphere. The silicon wafers have to be pentagonal and there will be twelve identical pieces of them. If a higher granularity than twelve is wanted, each counter element can easily be subdivided.

The thickness of the depletion layer of the Si detectors is an important quantity when optimizing the separation between protons and α particles. A thickness of 170 μm was chosen on the basis of simulation calculations where the energy loss of charged particles in silicon was studied. A variety of heavy ion reactions leading to rather different energy spectra and angular distributions of the protons and α particles were considered.

In the heavy ion fusion reactions, the evaporated particles concentrate in the forward angles to the beam axis by the kinematical effect, thus creating an increased multiple hit probability. In order to reduce this probability, the forward detectors should be smaller or be subdivided. A positive side effect of the subdivision is that the counting rate of the individual detector elements would be more equal.

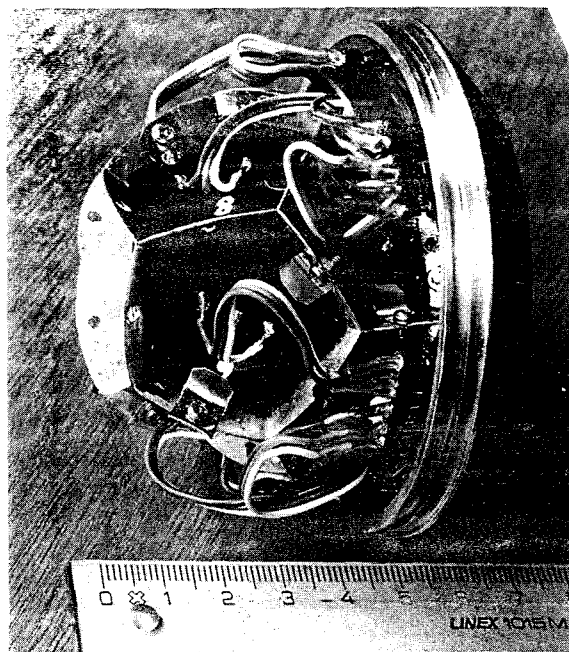


Fig. 1. Photograph of the Silicon Ball. The frame is made of aluminum sheet with a thickness of 0.15 mm. The structure to the right is a part of the vacuum chamber.

These considerations resulted in the following design of the Silicon Ball (Si Ball). The beam axis was chosen to be through the centre of two pentagons facing each other. The pentagonal silicon wafers were made such that they would be circumscribed by a circle of 50 mm diameter. A framework of 0.15 mm thick aluminum was designed to keep the wafers together. The resulting ball structure is shown in fig. 1.

In the version shown, the backwards pentagon is missing since the counting rate was estimated to be very small. In the other pentagonal surfaces, the silicon wafers were subdivided in two. In the six wafers of the forward hemisphere one therefore has twelve detectors. In the five wafers in the backward hemisphere, however, the two counter elements of each wafer were interconnected to provide only five detectors. Altogether the Si Ball shown in fig. 2 has seventeen counter elements. The geometrical efficiency of this device is about 90%.

The pentagonal p-n junction ion implanted detectors were made from n-type silicon and are shown in fig. 3. In operation a bias voltage of 100 V is supplied and a leakage current of less than 50 nA is measured at 300 K.

Since the beam is stopped inside the ball structure, precautions must be taken as to the scattered beam particles. First of all a small area Au-foil is placed as a beam stop in front of the forward wafers. Secondly,

absorber foils must be put in front of the other counter elements in order to stop scattered beam particles. These foils must be very carefully chosen for each reaction so that an optimum thickness for the penetration of protons and α particles can be obtained.

Fig. 4 shows energy spectra for protons and α particles detected in the reaction between a ^{28}Si beam and a ^{58}Ni target measured by the Si Ball. The five panels of the figure show the energy spectra obtained at different detector angles. Arrows indicate the discriminate levels L, H1 and H2. Alphas and protons are separated, but with a small overlap in the far end of the proton distribution. In figs. 4a and 4b there is an indication of a double proton hit between the H1 and H2 thresholds. In figs. 4c, 4d and 4e there are indications of low energy α particles in the same region.

2.3. The electronic circuit

An electronic circuit was designed on the basis of the experience obtained in the six-segment detector system described in ref. [8]. A diagram is presented in fig. 5. An improvement has been obtained by latching the charged particle signals by the γ or γ - γ signals from the germanium detectors. In this way, the spurious multiplicity signals produced by accidental summing up are largely reduced. In the circuit shown in fig. 5, the latched signals from the seventeen counter elements are presented to a summing amplifier which is coded to provide the number of protons and α particles detected per γ or γ - γ event.

3. Identification of reaction channels

The performance of the Si Ball in conjunction with the NORDBALL array was tested using the $^{58}\text{Ni} + ^{28}\text{Si}$ reaction at 110 MeV at the Tandem Accelerator Laboratory of the Niels Bohr Institute. The target was composed of two stacked self-supported ^{58}N foils, each with a thickness of $340 \mu\text{g}/\text{cm}^2$. The foils were mounted on 0.1 mm thick Mo rings. The amount of

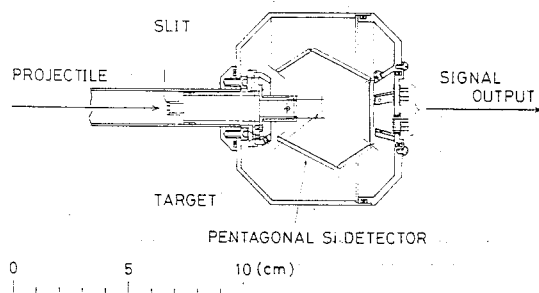


Fig. 2. The vacuum chamber including the Si Ball.

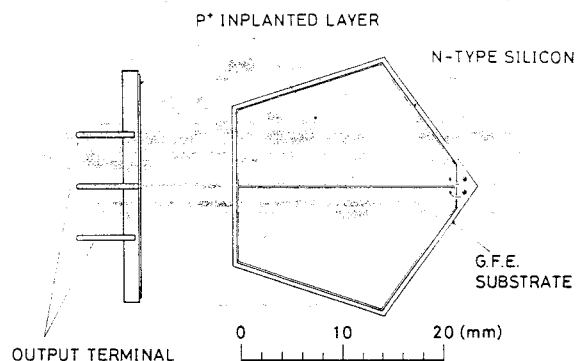


Fig. 3. A pentagonal Si detector segmented into two parts.

solid material in the target vicinity was reduced to a minimum in order to reduce unwanted scattering of beam and light charged particles.

The multiplicity identifier shown in fig. 5 was connected to the electronics of the NORDBALL array by three routes. One to provide a valid γ or γ - γ signal for the latch, the second to provide the signature of a charged particle coincidence to the NORDBALL trigger and as the third one, the output pulse from the multiplicity identifier which is recorded as a parameter in the NORDBALL event.

The event data from this experiment was sorted in software according to the various combinations of type and number of charged particles. A valid event was a twofold coincidence in the germanium detectors, a coincidence with a certain number of BaF_2 detectors and an output from the multiplicity identifier. A spectrum of the resulting identifier output is shown in fig. 6

In the lowest channels the spectrum shows the presence of events with α particles only and events with one and two α -particle coincidence are clearly seen. The next family of peaks are the combination of one proton with one or several α particles, respectively. To higher channel numbers the sequence is repeated with the combination of two, three and four protons with α particles.

Spectra of the type shown in fig. 6 (PID spectra) can now be used to sort out the corresponding germanium spectra. Examples are shown in fig. 7. Selecting on the $\alpha 3p$ and the $\alpha 2p$ in the PID spectrum (fig. 6) results in the spectra shown in figs. 7a and 7b, respectively. Germanium spectra resulting from a selection on the pure proton signals $4p$, $3p$ and $2p$ in the PID spectrum are shown in figs. 7c, 7d and 7e, respectively.

The selectivity of the instrument is very well demonstrated in figs. 7a and 8, both spectra being dominated by transitions in ^{79}Rb populated through the $\alpha 3p$ exit channel. This channel represents about 10% of the total cross section. The intruding transitions are from ^{80}Sr by the $\alpha 2p$ channel, ^{83}Y by the $3p$ channel and

^{82}Sr by the 4p exit channel. The overlap between reaction channels will be discussed in the following.

Fig. 7b shows the $\alpha 2p$ correlated exit channel which is dominated by transitions in ^{80}Sr , but transitions in the $\alpha 3p$ ^{79}Rb product can be clearly seen. Figs. 7c, 7d and 7e showing the 4p, 3p and 2p exit channels, respectively, contain some transitions that are common to all of them. An example is the 572.8 keV transition in the

4p product ^{82}Sr which is clearly seen in both the 3p and 2p gated spectra. It is important to compare the number of counts per channel for the different exit channels shown in fig. 7.

These overlaps are due to the fact that the total detection efficiency of the Si Ball is lower than 4π and that the single hit probability is different from 1. Transitions in the high multiplicity exit channels will there-

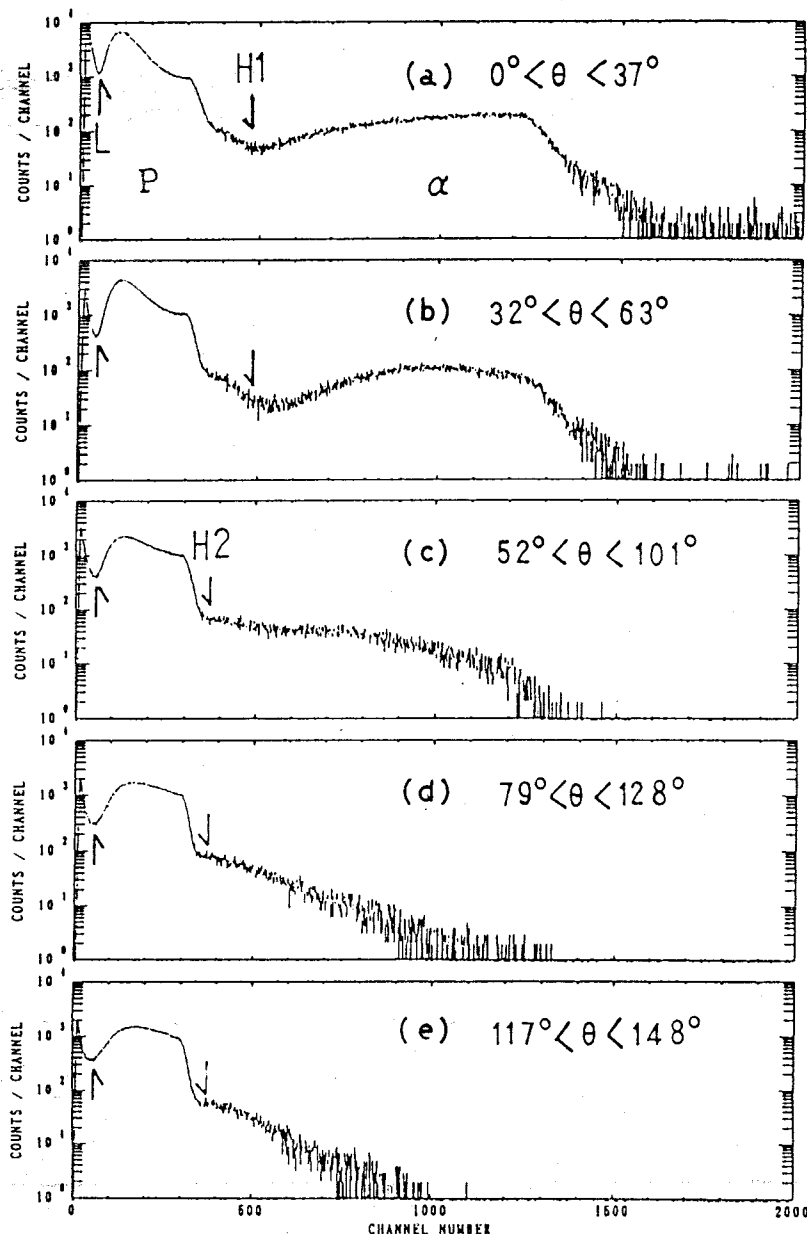


Fig. 4. Energy spectra of charged particles in the ($^{58}\text{Ni} + ^{28}\text{Si}$) reaction with a beam energy of 95 MeV. Positions of discrimination levels are shown by the arrows.

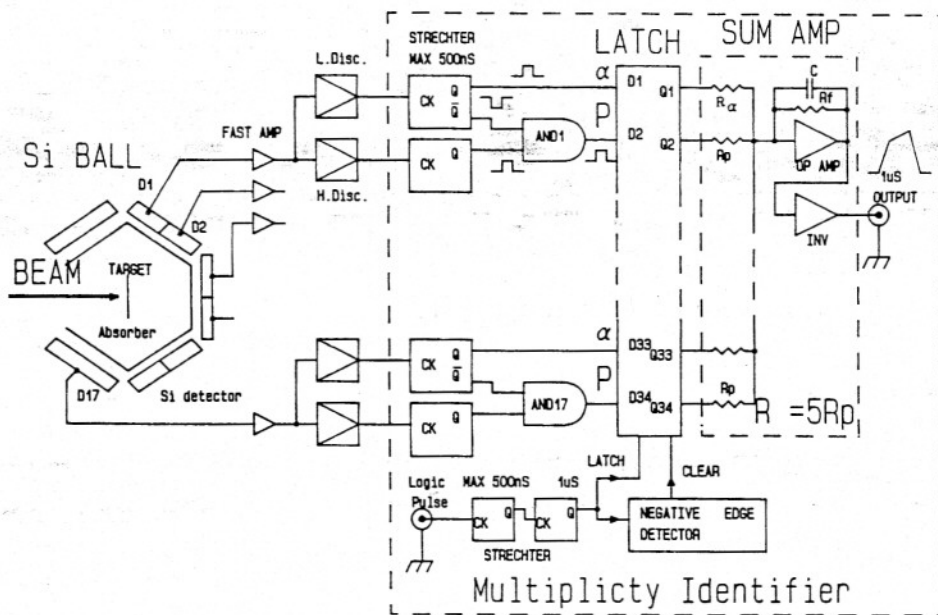
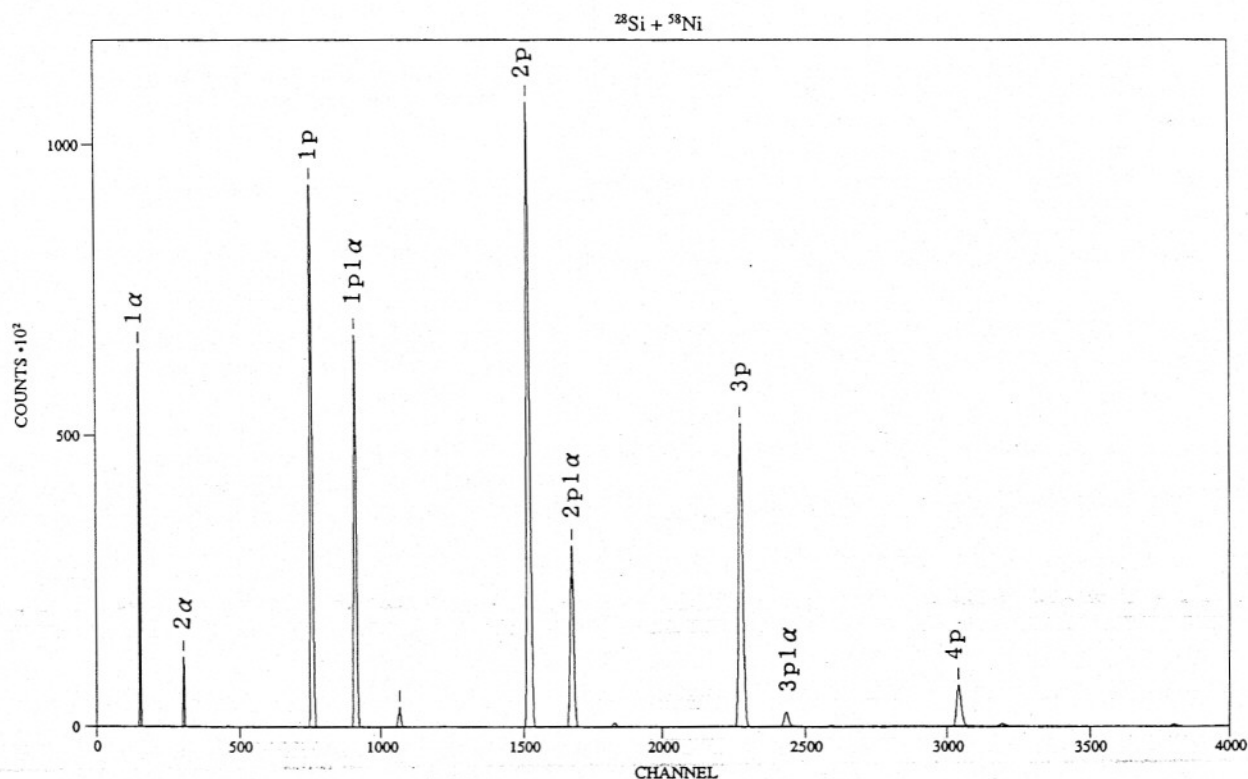


Fig. 5. Circuit diagram for the array of Si detectors.

Fig. 6. Particle identifier spectrum from the reaction $^{58}\text{Ni} + ^{28}\text{Si}$ at a Si beam energy of 110 MeV. The spectrum is gated by a twofold γ - γ coincidence. The detected multiplicity of charged particles is indicated on the strongest peaks.

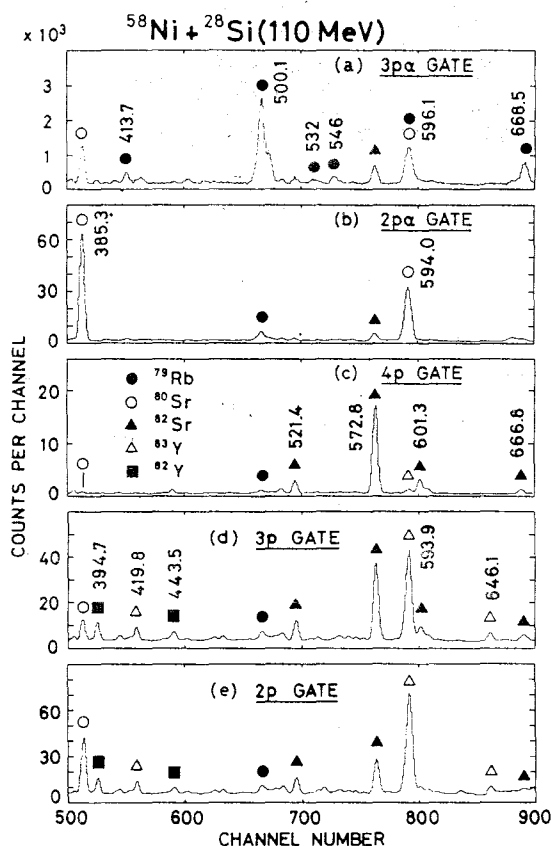


Fig. 7. Sections of γ spectra gated by various combinations of light charged particles following the $^{58}\text{Ni} + ^{28}\text{Si}$ reaction at a beam energy of 110 MeV. Dominating transitions in the various exit channels are indicated and overlaps discussed in the text. The gates for the individual spectra are: (a) $3p1\alpha$, (b) $2p1\alpha$, (c) $4p$, (d) $3p$, and (e) $2p$.

fore appear in the lower multiplicity channels if one or more particles remain undetected, or if more than one particle strike the same counter element.

3.1. Mixing of different reaction channels

The ability of discrimination between protons and α particles has been investigated by comparing germanium spectra from αp , $\alpha 2p$ and $\alpha 3p$ exit channels with $2p$, $3p$ and $4p$ channels. An inspection of the intensity ratio for the 385.3 keV transition in ^{80}Sr populated in the $\alpha 2p$ exit channel and the same transition appearing in the spectra of the $3p$ exit channel shows that 12% of the total α particles are misinterpreted as protons. See figs. 7b and 7d.

On the other hand, it is concluded from the intensity ratio of the 572.8 keV transition in ^{82}Sr ($4p$ channel) and the presence of it in the $\alpha 3p$ exit channel that only 0.9% of the proton signals are contaminating the

αs . This can be seen from a comparison of figs. 7a and 7c.

The amount of accidental coincidence was estimated to be less than 0.4% from a comparison of the yields of the 385.3 keV transition in ^{80}Sr ($\alpha 2p$ exit channel) with the presence of this line in the $4p$ gated spectra.

3.2. Total detection efficiency

The probability that transitions in the high multiplicity exit channel appear in the spectra gated by the lower multiplicity depends on the number of undetected particles, and therefore on the number of detectors and the total detection efficiency. Then the efficiency can, however, be deduced from the yields of γ peaks of a transition in the different PID spectra.

In order to estimate the total detection efficiencies of the Si Ball for the protons and α particles, yields of isolated γ -ray transitions of ^{82}Sr ($4p$ exit channel) or ^{80}Sr ($\alpha 2p$ exit channel) were compared with the yields of the same lines in the spectra gated by various other charged particle multiplicities. In this experiment, the total detection efficiencies of the protons and α particles were estimated to be at least 80% and 65%, respectively. In the estimate of the α -particle efficiency, the effect of the spectral overlap between the α particles and the protons has not been taken into account.

3.3. Comparison to a recoil mass spectrometer

A comparison of the spectroscopic purity and the efficiency when using the Si Ball as a reaction channel selector with the same quantities for the recoil mass spectrometer (RMS) of the Nuclear Structure Facility in Daresbury, UK, has been done for $A = 79$ in a study of ^{79}Rb [11].

A γ - γ spectrum gated by the $\alpha 3p$ exit channel in the PID spectrum (see fig. 6) is shown in fig. 8. It has a small feedthrough of higher multiplicity reaction channels corresponding to the relatively low cross section for channels with multiplicity larger than 4. Therefore, this spectrum shows the γ -rays of ^{79}Rb with a high ratio of peak to background and very high purity except for a few weak lines of ^{82}Sr ($4p$) and ^{80}Sr ($\alpha 2p$ exit channels).

The nucleus ^{79}Rb has also been studied by the reaction $^{24}\text{Rg}(^{58}\text{Ni}, 3p)^{79}\text{Rb}$ at Daresbury, at a bombarding energy of 190 MeV and using the RMS as a channel selector [11]. Fig. 1b of this reference shows a γ - γ spectrum in coincidence with recoil mass 79 selected by the RMS. A number of contaminating lines from ^{79}Sr , ^{76}Kr and ^{80}Sr are observed in this spectrum. These products have the same mass similar values of A/q or just having a very large yield next to a much

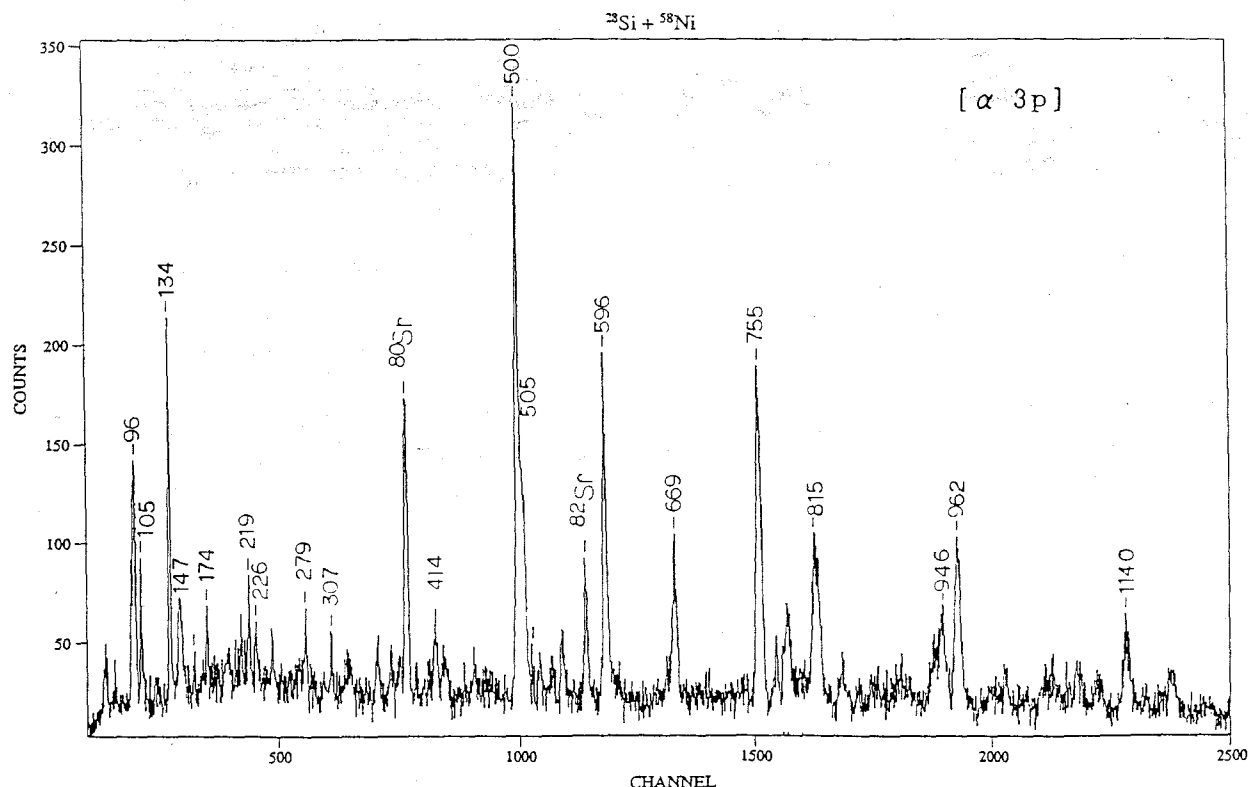


Fig. 8. A γ -ray spectrum in coincidence with three protons and one alpha particle. The $\alpha 3p$ reaction channel populates levels in ^{79}Rb .

smaller mass yield. The reported transmission efficiency is 2.5% for ^{79}Rb populated in the 3p exit channel. In comparison, the Si Ball as used in the NORDBALL experiment has an $\alpha 3p$ detection efficiency of 20%.

4. Conclusion

In this paper, we have reported on a Si Ball which provides excellent selection of reaction channels in in-beam γ -ray spectroscopy. It has been shown that the Si Ball installed inside the NORDBALL array is a very useful selective device for separating γ -ray spectra originating from various exit channels. A reaction channel selection on the basis of the light charged particle multiplicity has been demonstrated. A large solid angle and a high number of detector elements have provided a channel selector that gives small overlaps of reaction channels. A subtraction technique where the contribution of high multiplicity events is subtracted from the lower multiplicity events has been tested [6]. Very high purity spectra without loss of statistics in the low multiplicity are obtained.

The Si Ball can, because of its small size, be used together with the BaF_2 calorimeter of NORDBALL and a 2π neutron detector [12] so that gamma-gamma spectra can be obtained with three selective devices working at the same time. These spectra are simultaneously gated by γ -ray multiplicity, neutron multiplicity and charged particle multiplicity. Especially, the Si Ball in conjunction with the neutron detector is a powerful tool for the study of nuclei far from the β -stability line.

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