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Determination of absolute internal conversion coefficients using the SAGE spectrometer

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Abstract

A non-reference based method to determine internal conversion coefficients using the SAGE spectrometer is carried out for transitions in the nuclei ^{154}Sm , ^{152}Sm and ^{166}Yb . The Normalised-Peak-to-Gamma method is in general an efficient tool to extract internal conversion coefficients. However, in many cases the required well-known reference transitions are not available. The data analysis steps required to determine absolute internal conversion coefficients with the SAGE spectrometer are presented. In addition, several background suppression methods are introduced and an example of how ancillary detectors can be used to select specific reaction products is given. The results obtained for ground-state band E2 transitions show that the absolute internal conversion coefficients can be extracted using the methods described with a reasonable accuracy. In some cases of less intense transitions only an upper limit for the internal conversion coefficient could be given.

Keywords: electron spectroscopy, background subtraction, energy reconstruction, internal conversion coefficient, silicon detector

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1. Introduction

The analysis methods described in this paper have been developed primarily for use with the SAGE (Silicon And GERmanium) spectrometer located at the Accelerator Laboratory of the University of Jyväskylä (JYFL). The spectrometer was constructed with the aim of performing simultaneous in-beam gamma ray and internal conversion electron spectroscopic studies by combining the JUROGAMII germanium array [1] with an electron spectrometer. Detailed discussions of the construction and performance of the SAGE spectrometer can be found in Refs. [2–4]. Further combination of the SAGE spectrometer with the RITU [5, 6] gas-filled recoil separator and the GREAT [7] focal plane spectrometer allows the use of the recoil-decay tagging technique [8–10]. The primary beam from the JYFL K-130 cyclotron is used to induce nuclear reactions at the target. Depending on the experiment, the reaction products enter RITU and are either dumped or transported to the GREAT spectrometer at the focal plane. The prompt γ -rays emitted in the de-excitation of the populated nuclei are detected with the germanium detectors of the JUROGAMII array and conversion electrons are transported upstream from the target position by an electromagnetic solenoid and detected with a segmented silicon detector. The electrons travel along a helical path following the magnetic field lines in the solenoid, the radius of which is dependent the electron velocity perpendicular to the magnetic field and the magnetic field strength. A high voltage barrier is used to reduce the extremely high flux of δ -electrons produced by interactions of the ion beam with the atomic electrons of the target material. The silicon detector segments have small average size, which has a drawback at high electron energies. The electron interaction volume grows large and many of the detected electrons deposit energy in more than one segment. An algorithm designed to reduce background generated by scattering between segments is discussed later in the paper. In addition, the fact that the radius of the helical path followed by the electrons is energy dependent provides an opportunity to perform further background filtering. An algorithm exploiting these properties is also presented.

31 2. Experiment details

32 The nuclear structure properties of ^{154}Sm were recently discussed by Small-
33 combe *et al.* [11]. The main goal of the experiment (here referred to as S06) was
34 to determine internal conversion coefficients from the excited rotational bands of
35 ^{154}Sm in order to test the hypothesis that the bands have vibrational (β -band)
36 structure. Coulomb excitation was used to populate the excited energy levels in
37 ^{154}Sm by using an enriched target of ^{154}Sm which was irradiated with a beam of
38 ^{16}O . Subsequent to the experiment S06, an additional test experiment ST1 was
39 performed. For the ST1 test run the pre-amplifier signals of the outer segments
40 of the SAGE Si-detector were fed through voltage dividers that increased the
41 maximum detectable energy up to 30-40 MeV from the original 2-2.5 MeV. The
42 reasons for this modification and discussion of the results obtained are presented
43 later in this manuscript. The various parameters related to S06 and ST1 exper-
44 iments are summarised in table 1. In the aforementioned work by Smallcombe
45 *et al.*, the analysis of the electron-gamma coincidence data and extraction of the
46 internal conversion coefficients relies on the Normalised-Peak-to-Gamma (NPG)
47 method [12]. The NPG method is based on the observation of known transi-
48 tions and therefore can not be applied to cases where these reference points are
49 missing. A standalone procedure to determine internal conversion coefficients
50 (ICCs) from in-beam data along with methods to reduce the underlying elec-
51 tron background are introduced in this paper. The discussion relies on the same
52 dataset (S06) as that used by Smallcombe *et al.* and the data-analysis param-
53 eters such as trigger conditions, event widths etc. are kept as close as possible
54 to those introduced in Ref. [11] in order to enable direct comparison between
55 results. Partial level schemes of studied nuclei are shown in figure 1.

56 2.1. Determination of the gamma-ray and electron detection efficiencies

57 In order to reduce the total counting rate, it is usual that Sn (0.1 mm)
58 and Cu (0.5 mm) absorbers are placed between the target and the germanium
59 detectors of JUROGAMII. In S06 experiment, the absorbers were removed in

Table 1: Summary of various parameters used in the two experiments presented in this work. U_{HV} is the voltage applied to HV barrier and I_{coils} is the current through the SAGE magnetic coils.

Run	Target		Beam		SAGE	
	Element	Thickness [mg/cm ²](enrich.)	Ion	Energy [MeV]	U_{HV} [kV]	I_{coils} [A]
S06	¹⁵⁴ Sm	1.5 (99%)	¹⁶ O	65	-20	800
ST1	¹⁵⁴ Sm	1.1 (98.69%)	¹⁶ O	35/65	-20	800
	¹⁵⁴ Gd	4.16 (80 _≲ %) ^a	¹⁶ O	65	-20	0

^a Estimated from γ -ray spectrum.

60 order to improve the detection of Sm X-rays. The absolute gamma-ray detec-
61 tion efficiency was measured using calibrated ¹³³Ba, ¹⁵²Eu and ²⁰⁷Bi sources.
62 The resulting γ -ray detection efficiency curve is presented in figure 2. Note that
63 the curve deviates from the one shown in Ref. [4] as S06 was run without ab-
64 sorber foils of the JUROGAMII array. For both the SAGE γ -ray and conversion
65 electron efficiency curves the data are fitted with a function of the form

$$\epsilon(E) = Exp\left[\sum_{i=0}^n a_i \times \ln\left(\frac{E}{E_0}\right)\right], \quad (1)$$

66 where a_i and E_0 are fitted coefficients and E is the energy of the γ -ray or internal
67 conversion electron. The electron detection efficiency was determined by using
68 calibrated open ¹³³Ba and ²⁰⁷Bi conversion electron sources. The resulting
69 electron detection efficiency curve is shown in figure 3. It can be seen from
70 the figure 3 that it is possible to improve the efficiency for detection of higher
71 energy electrons by using an add-back procedure. Details of this procedure
72 are discussed later in the text. The calibration runs during the experiment were
73 made with no voltage applied to the HV barrier. The effect of the barrier shown
74 in detail in figure 4 is an average behaviour deduced by fitting data obtained
75 from several measurements carried out subsequent to the S06 experiment. As
76 can be seen from figure 4, the effect of the HV barrier is negligible for electron
77 energies over 200 keV, even when the voltage applied to the barrier is -35 kV.

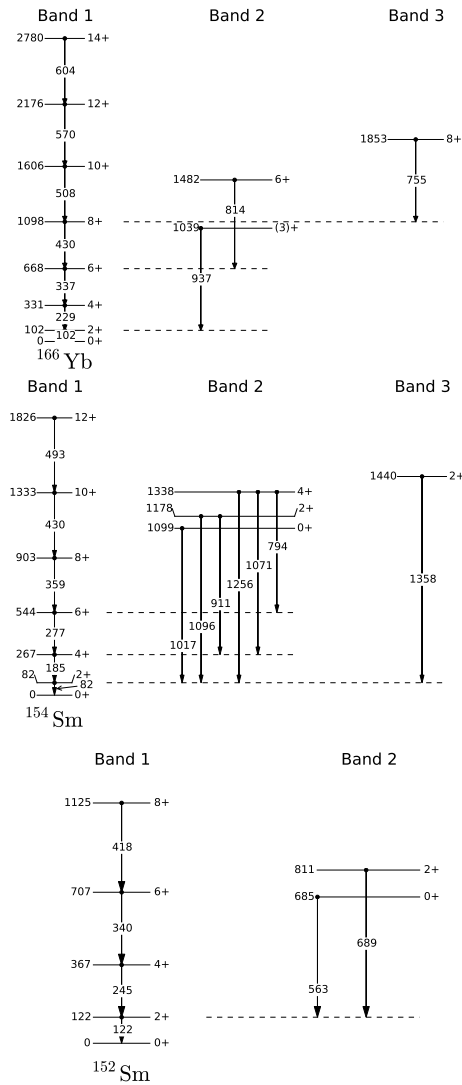


Figure 1: Partial level schemes of ^{166}Yb , ^{154}Sm and ^{152}Sm . The level and transition energies are rounded to the nearest keV. Data from Ref [13].

78 **3. Data analysis procedures**

79 *3.1. Electron add-back/veto*

80 *3.1.1. Description*

81 Around 1 MeV energy the range of the electrons in silicon approaches and
 82 exceeds the typical segment dimensions of the SAGE silicon detector (1 mm

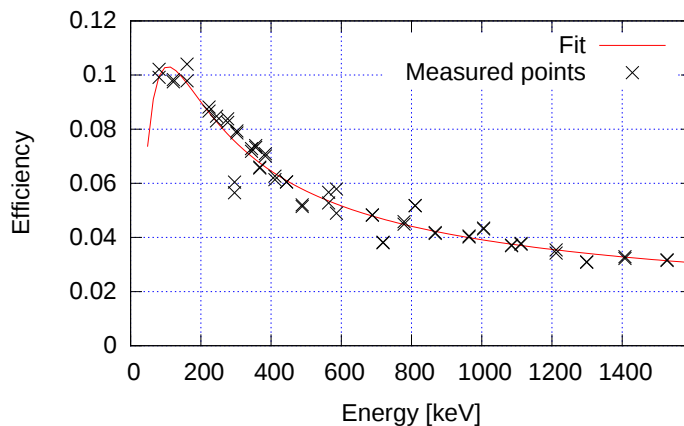


Figure 2: Detection efficiency for single γ -rays in JUROGAM II. The measured points are from calibration runs before and after the experiment. Typical errors on the measured points are $\pm 1\%$ of the value. Error bars have been omitted for clarity.

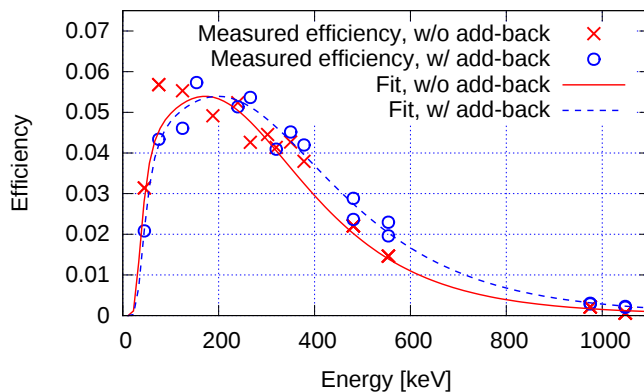


Figure 3: Absolute electron detection efficiency with and without add-back. Typical errors on the measured points are $\pm 3\%$ of the value. Error bars are omitted for clarity.

83 thick, 1-2 mm wide radially). The calculated 99% stopping range for a 1 MeV
 84 electron in silicon is 1.98 mm. A number of the high energy electrons simply
 85 punch through the 1mm thick detector and deposit only a fraction of their full

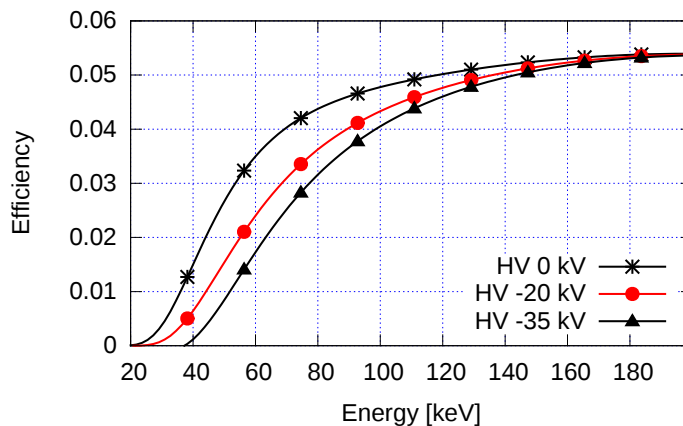


Figure 4: Effect of the HV barrier on the absolute electron detection efficiency. The lowest reliably achieved voltage in experimental conditions is -35 kV.

86 energy. Moreover, a significant fraction of the high energy electrons scatter to
 87 adjacent segments and thus deposit energy in two or more segments. These
 88 events can be either recovered by summing the energies (add-back) or can be
 89 removed (vetoed) from the data with a simple algorithm. The outline of the add
 90 back/veto algorithm is shown in figure 5. An example of a typical spectrum
 91 generated by the add-back algorithm is shown in figure 6. In the cases where
 92 two or more pixels are hit, the energy deposited in a single pixel is found to
 93 have any value up to the maximum for the transition. The inset in figure 6
 94 shows the effect of the add-back on the resulting peak shape. Unfortunately,
 95 due to the structure of the Si-detector, some electrons lose energy in the inactive
 96 area between segments which cannot be detected and a spurious lower energy
 97 component is observed in the spectrum. Due to technical issues with bias source
 98 the silicon detector bias was limited to 90 V during the measurements and based
 99 on the detector I-V curves there is reason to believe that the detector is not
 100 completely depleted. This may explain the apparent high energy loss between
 101 segments shown as a difference in energy between peaks A and B in figure 6.
 102 Note that summing events that first scatter between segments and then escape
 103 the detector would yield a continuous tail below the full energy peak and cannot

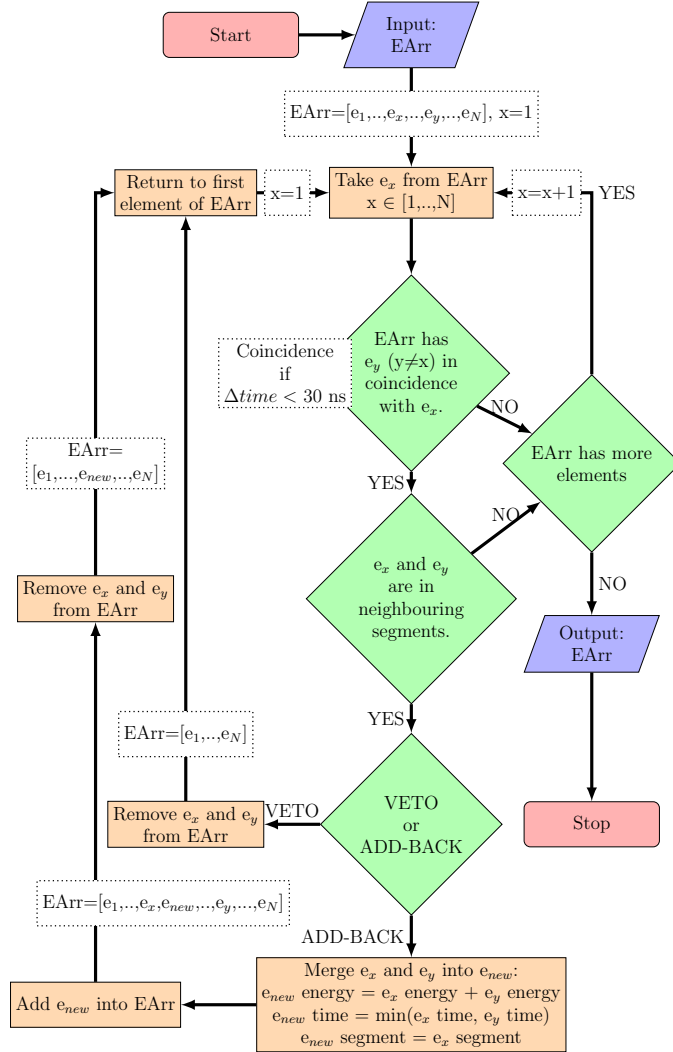


Figure 5: Outline of the add back/veto algorithm. EArr is an iterable data structure where all the elements (electrons) have energy, time and position (segment) attributes.

104 be the main process generating the secondary peak. Tests conducted during the
 105 commissioning phase showed that the detector does not suffer from cross talk
 106 between signal strip wires or electronics that could explain the secondary peak.
 107 High energy, "punch through" events that effect the common ground behind the
 108 silicon detector can be also ruled out as a source of the secondary peak as the

effect in common ground dissipates over all the silicon segments.

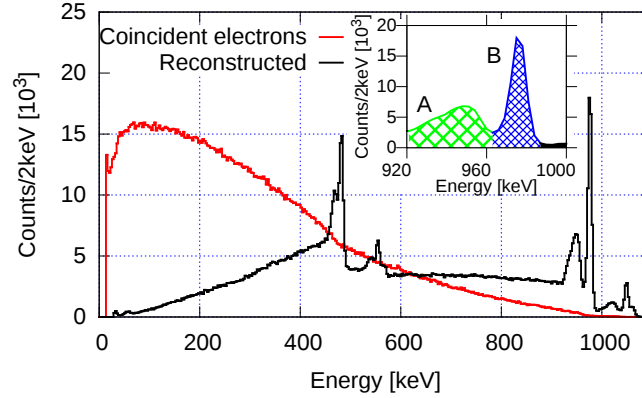


Figure 6: Conversion electron energy spectrum measured with ^{207}Bi source reconstructed by the add-back algorithm along with the original energy spectrum for events where two or more electrons are detected simultaneously in neighbouring segments. *Inset* A typical peak shape in the reconstructed spectrum. Peak A corresponds to electrons that are scattered through the inactive part of the detector which separates the segments. Peak B corresponds to the full energy peak.

109

110 3.1.2. Neighbouring segments

111 The SAGE detector is segmented in 90 individual segments and there are
 112 several different ways in which it is possible to associate the segments within
 113 the add-back procedure. A number of different schemes were tested and the
 114 optimal scheme was found to be where all the neighbouring segments within the
 115 central region of the detector are grouped together and thereafter those with
 116 the longest common borders. The emphasis in determining the best scheme
 117 was placed on maximizing the full energy peak areas while at the same time
 118 keeping the summing of full energy events with background to a minimum.
 119 An outline of the SAGE silicon detector which shows how the different segment
 120 types are searched for coincident events is illustrated in figure 7. A comparison
 121 of spectra of electrons emitted from ^{207}Bi after application of the add-back
 122 and veto algorithms is shown in figure 8. As can be seen from figure 8(a), at
 123 energies around 550keV the add-back algorithm has little effect on the efficiency

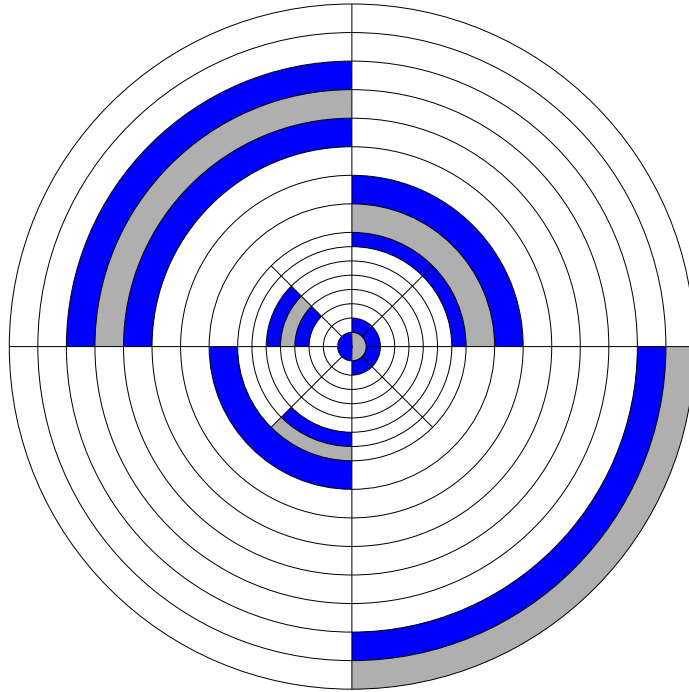


Figure 7: Add-back search patterns for six different segment types. The gray color (lighter color) shows the segment where the event with algorithm index x is detected (see fig. 5), the adjacent blue segments are those which are searched for coincident events.

124 (electron ranges are shorter) but the use of vetoing significantly reduces the
 125 background under the peaks. In figure 8(b) it can be seen that the add-back
 126 algorithm increases the efficiency at higher energies, but the effect of vetoing is
 127 rather limited. The overall effect of the add-back procedure on the detection
 128 efficiency is shown in figure 3. The veto algorithm does not have an effect
 129 on the detection efficiency, but can be used to reduce the background in the
 130 spectrum. A similar add-back method has been devised for the SPICE electron
 131 spectrometer [14].

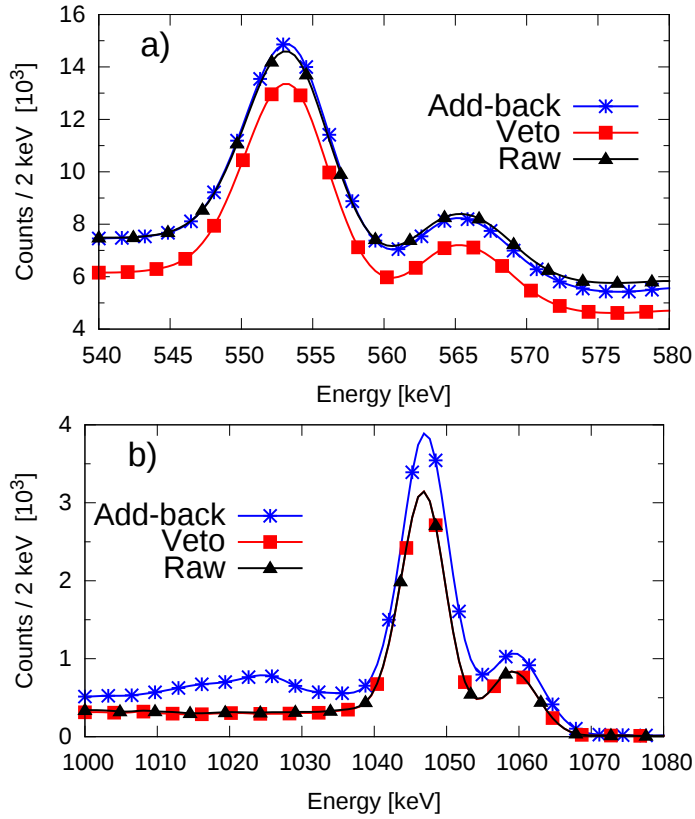


Figure 8: A comparison of the results of applying the veto and add-back algorithms on the conversion electron peaks from ^{207}Bi . a) 554 and 566 keV peaks. b) 1048 and 1060 keV peaks. Data is smoothed to allow better differentiation between the cases.

132 3.2. Filtering with detection radius

133 As mentioned in the introduction, the operational principle and the design of
 134 the SAGE spectrometer gives an opportunity to filter the predominant electron
 135 background by studying the detection radius of the electrons as a function of
 136 energy. In order to develop the filter, the electron transport properties of SAGE
 137 were first probed with standard open electron sources. By using the source data
 138 the maximum allowed radius for electrons of a certain energy can be deduced.
 139 The source data was used to determine the maximum radius as a function of
 140 energy, which was subsequently used to fit a curve based on the function for

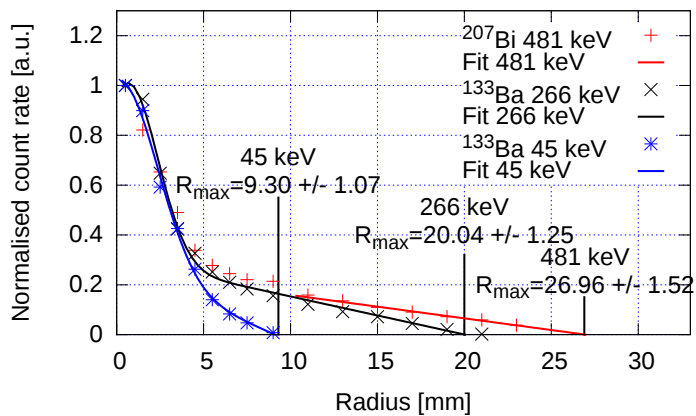


Figure 9: Distributions of electrons with various energies over the SAGE Si-detector. Fits are made according to equation 3 except that only the tail end of 481 keV fit is shown for clarity. Note that the outer radius of the SAGE Si-detector is 24 mm.

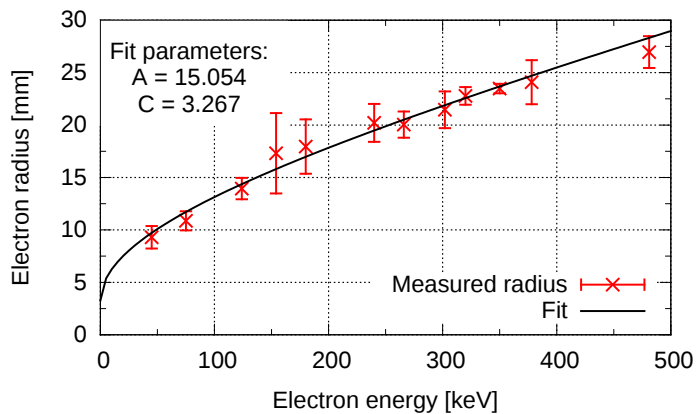


Figure 10: Measured maximum radius as a function of electron energy.

141 the Larmor radius. Using the relativistic form of the Larmor radius with the
 142 assumption that electron velocity is perpendicular to the magnetic field we get

$$R_e(E) = \frac{\beta c \gamma m_e}{eB} = \frac{m_e c \gamma \sqrt{1 - 1/\gamma^2}}{eB}$$

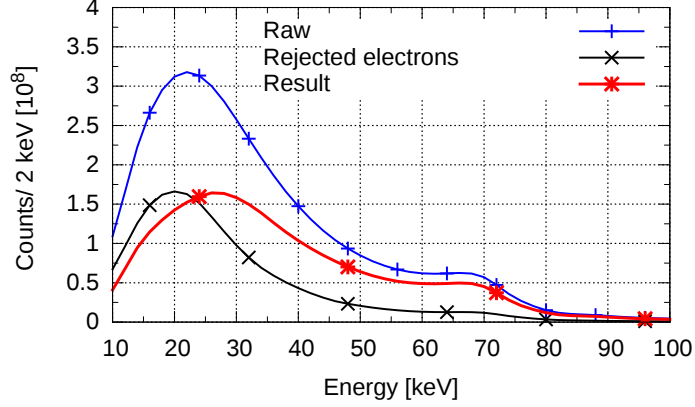


Figure 11: Effect of radial filtering on electron singles spectrum obtained from the S06 in-beam data.

$$= \frac{m_e c \sqrt{\gamma^2 - 1}}{eB} = A \sqrt{\left(1 + \frac{E}{m_e c^2}\right)^2 - 1} + C, \quad (2)$$

143 where m_e is the electron mass, v is the velocity of the electron, c is the speed of
 144 light, $\beta = v/c$, $\gamma = 1/\sqrt{1 - \beta^2}$, E is the kinetic energy of the electron, e is the elec-
 145 tron charge and B the magnetic field. The fitting parameters are A ($=m_e c/eB$)
 146 and C . As the direction and the strength of the magnetic field are not clearly
 147 defined close to the SAGE silicon detector the last form of equation 2 is used
 148 as a basis for fitting. If the electron distribution is well centred electrons with
 149 energy E and higher radius than $R_e(E)$ are assumed to have been scattered or
 150 generated by beam halo effects and considered to contribute in the background
 151 and can be filtered. An example of electron distributions with different energies
 152 is shown in figure 9. The fit function used to describe the electron distribution
 153 over the radius of the Si-detector has the form

$$n(r) = a \times \text{Exp}(-b(r - r_0)^2) + cr + d, \quad (3)$$

154 where a , b , c , d and r_0 are fitted parameters and r is the radius in mm. To avoid
 155 artefacts arising from radial segmentation of the Si-detector the electron radius is
 156 randomized within the radial segment limits. For example electron hitting one of
 157 the two center segments gets radius within range of $[0,1]$ mm. In an experiment,

158 the position of the beam spot on the target must be carefully adjusted in order
159 to centre the electron count rate distribution at the detector. Note that the
160 beam spot size and the active spot size in the calibration sources is roughly the
161 same ($\varnothing \sim 3$ mm). Originally the magnetic configuration of SAGE caused the
162 electron distribution to systematically veer down and right from the Si-detector
163 center (looking from the target). This was corrected by modifying magnetic
164 shielding around the magnetic coils (see details in Ref's [3, 15]). The δ -electron
165 background is not directly filtered because it is generated in the correct position.
166 The measured maximum radius behaviour determined using the various electron
167 energies from ^{133}Ba and ^{207}Bi sources is shown in figure 10 along with a fit using
168 equation 2. The filter is shown to reduce low energy background below 50 keV
169 by approximately 10% when using source data. The effect of radial filtering on
170 in-beam data is much more prominent as seen in the figure 11. The majority of
171 the background is from δ -electrons produced by interaction of the beam with the
172 target. As in general, the current work focuses on internal conversion coefficients
173 with transition energies higher than 50 keV the effect on the present results is
174 limited. Nevertheless, the filter is employed as it reduces the number of events
175 in the γ - e^- coincidence matrix thus easing the analysis. Note that if the add-
176 back/veto algorithm is used in the same analysis process with radial filtering the
177 add-back/veto must be performed first in order to avoid errors with the radial
178 filtering arising from scattered events.

179 *3.3. Definition of coincidence time gates*

180 In order to extract accurate absolute internal conversion coefficients, the
181 time gates for γ - γ and γ - e^- coincidences must be carefully selected. In the
182 present work, the γ - γ and γ - e^- time differences were found to be energy de-
183 pendent. The common practice of selecting a single time independent time gate
184 from γ - γ and γ - e^- time difference spectra can be lacking in this case. The cor-
185 rect time gate can be found by slicing the time spectra in sections and studying
186 the relative number of coincident events within this slice compared to the total
187 number of counts in the coincident peak. As an example, relative peak curves

188 from ^{154}Sm 82-185 keV, 185-277 keV, ^{166}Yb 102-430 keV and random ^{154}Sm
 189 82- ^{152}Sm 122 keV coincidences are presented in figure 12. The time gate is
 190 defined to be the time interval where the relative coincidence peak area is larger
 191 than random peak area. As an example the ^{154}Sm 82-185 keV coincidence gives
 192 a high limit of 100ns and a low limit of -60ns (points are circled in figure 13).
 193 Due to the experimental timing logic the low limit is related to de-excitation
 194 observed first and the high limit to the second in the coincidence cascade in
 195 the γ - γ data. Timing of electrons is less affected by electron energy and the
 196 gate limits can be set as a function of γ -ray energy with γ - e^- data. Time gates
 197 defined from ^{133}Ba , ^{207}Bi , ^{154}Sm and ^{166}Yb data are shown in figures 13 and 14.
 198 The fits presented in figures 13 and 14 have a general form of

$$f(E) = A1 \times \text{Exp}\left(\frac{B1}{\sqrt{E}}\right) + C1, \quad (4)$$

where E is the energy in keV and A1, B1, C1 are the fitted parameters.

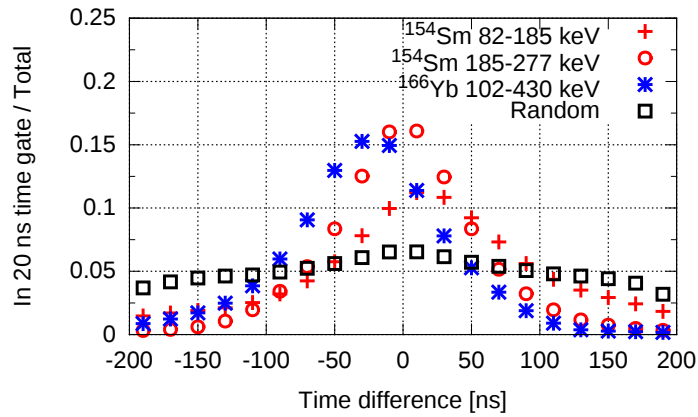


Figure 12: Relative coincident peak size curves compared to total number of coincident counts within [-200:200]ns time gate.

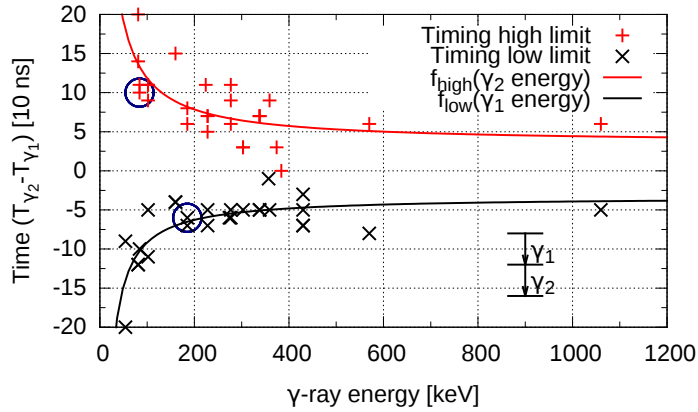


Figure 13: Energy-dependent time gate limits for γ - γ coincidences.

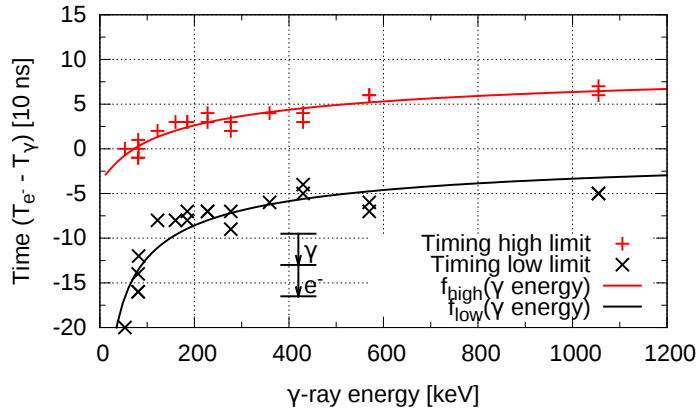


Figure 14: Energy-dependent time gate limits for γ - e^- coincidences. Both limit fits are functions of γ -ray energy.

200 4. Results

201 4.1. Extraction of internal conversion coefficients

202 In this work the internal conversion coefficient α_{exp} is determined from

$$\alpha_{exp} = \frac{N_e \times \epsilon_\gamma}{N_\gamma \times \epsilon_e}, \quad (5)$$

203 where N_e is the number of detected electrons, N_γ is the number of detected
 204 γ -rays, ϵ_γ and ϵ_e are the detection efficiencies for γ -rays and electrons, respec-
 205 tively. In this work, the effect of angular correlations is neglected. Using the

206 data obtained in the S06 experiment, a large number of experimental internal
 207 conversion coefficients could be determined. The measured absolute internal
 208 conversion coefficients for ^{154}Sm , ^{152}Sm and ^{166}Yb ground state band transi-
 209 tions that are all considered to be pure E2 character as a function of electron
 210 energy are shown in figure 15. The results derived from the raw (no algorithms
 211 applied and unfiltered) matrices differ from the reference tabulated values ob-
 212 tained using BrIcc [16] conversion coefficient calculator. It can be seen that no
 213 single normalisation constant would yield agreement throughout the full energy
 214 range and without a common factor the NPG method cannot be used. After
 215 application of time gates, either add-back or veto and radial filtering for the
 216 electron events in the silicon detector the overall result is much more agreeable.
 217 A more detailed plot of the final result is shown in figure 16. As can be seen in
 218 figure 16 the measured ICCs below 200 keV are systematically lower than the
 219 tabulated values. The difference is thought to be the result of the interactions
 220 of the electrons with the thick target. The values deduced indicate that ^{166}Yb
 221 is less affected. The difference can arise from the fact that ^{166}Yb is produced
 222 in a fusion-evaporation reaction, meaning that ^{166}Yb has a kinetic energy of
 223 only ~ 6 MeV and range in samarium of ~ 0.9 mg/cm² with beam (^{16}O) energy
 224 of 65 MeV. This should be compared with that for excited ^{154}Sm which is ~ 4
 225 mg/cm². As the beam particles pass through the target matter they lose energy
 226 and therefore creation of sub-barrier fusion products deeper in the target mat-
 227 ter is less likely. As the electrons emitted from ^{166}Yb travel through less target
 228 matter the energy loss is smaller and probability of scattering is lower hence
 229 it is more likely that the emitted electrons contribute to the full energy peaks.
 230 According to the rule-of-thumb given in Ref [17] the optimal target thickness
 231 for measurements of conversion electrons in an energy range of 100 to 500 keV
 232 would be 0.3-0.7 mg/cm². This is significantly less than the 1.5 mg/cm² target
 233 used in this case and negative effects on the spectrum quality can be expected.
 234 The relative effect of the target on electron transmission is shown figure 17. If
 235 we process the ICCs measured below 200 keV with the rough assumption that
 236 samarium conversion electrons originate evenly throughout the target depth

237 and ytterbium conversion electrons just from the first half of the target we get
 238 attenuation factors shown in table 2. Applying these estimated target attenu-
 239 ation values to measured ICCs yield values close to those calculated by BrIcc.
 240 In ^{166}Yb the analysis is further complicated by the overlap of LMN conversion
 lines and K conversion lines from different transitions. The standard timing

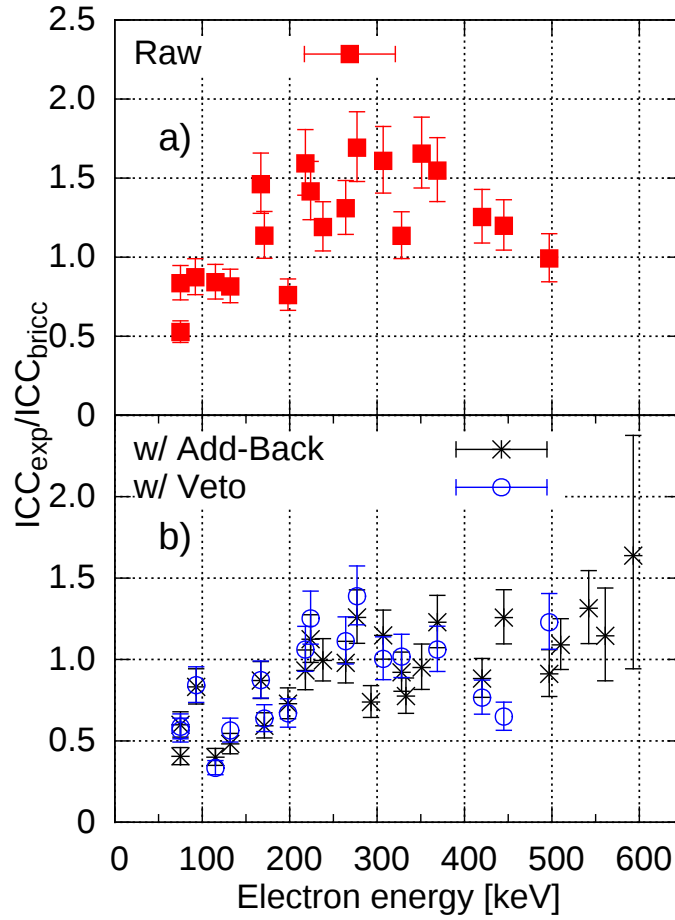


Figure 15: Experimental internal conversion coefficients relative to tabulated values extracted from the data obtained in the S06 experiment. a) Result from raw matrices. b) Results after time gating, electron add-back or veto and radial filtering.

241

242 method where only time independent γ - γ and γ - e^- time gates are used results
 243 in a γ - γ gate of $[0,60]\text{ns}$ and a γ - e^- gate of $[-100,60]\text{ns}$ [11]. Compared to these

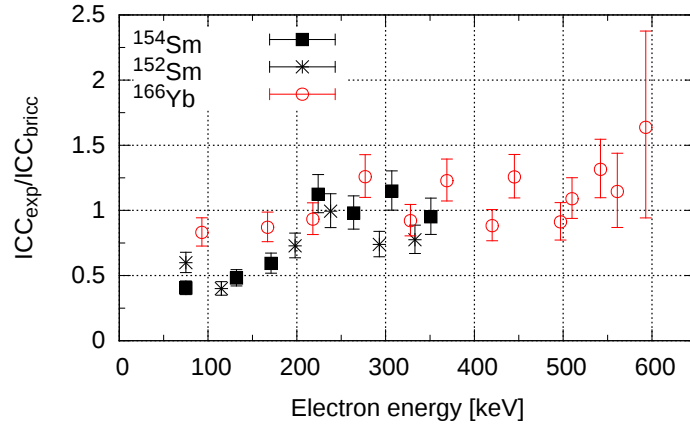


Figure 16: Comparison of the experimental ICCs relative to tabulated values for isotopes of Samarium and ^{166}Yb obtained with add-back algorithm. The better agreement for ^{166}Yb below 200 keV can be understood in terms of the reaction kinematics and the interactions of electrons with the target.

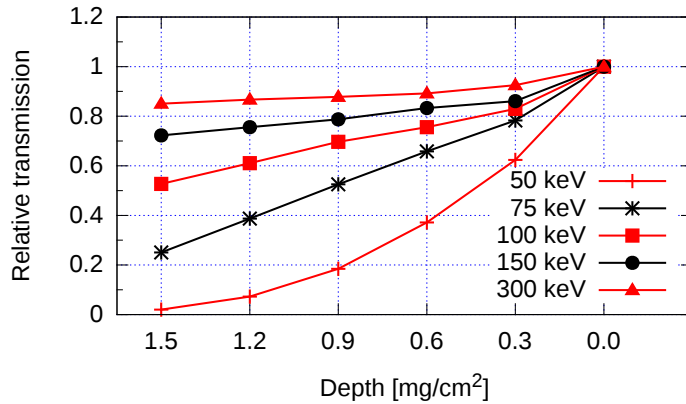


Figure 17: Effect of Sm target on electron transmission. Simulation result taking account of energy loss, scattering and SAGE electron acceptance.

244 the energy dependent gates shown in figures 13 and 14 are significantly different.
 245 If we consider the energy range between 200-400 keV the γ - γ time independent
 246 gate is roughly half the width of the energy dependent time gate. According to
 247 equation 5 this would yield ICCs approximately a factor of 2 too large as N_γ is
 248 halved. This would explain why the measured ICCs obtained in Ref [11] were

Table 2: Approximate attenuation coefficients for ICCs below 200 keV and resulting relative ICCs with results obtained with add-back algorithm.

Origin	e^- energy [keV]	α_{Rel}^a	Attenuation coefficient ^b	Corrected α_{Rel}
¹⁵² Sm	75	0.59(7)	0.6(1)	1.0(2)
	115	0.39(5)	0.7(1)	0.6(4)
	198	0.73(9)	0.8(1)	0.9(2)
¹⁵⁴ Sm	75	0.41(5)	0.6(1)	0.7(3)
	132	0.48(6)	0.7(1)	0.7(3)
	171	0.59(7)	0.8(1)	0.7(3)
¹⁶⁶ Yb	93	0.83(9)	0.8(1)	1.0(2)
	167	0.87(9)	0.9(1)	1.0(2)

^a $\alpha_{Rel} = \alpha_{exp}/\alpha_{BrIcc}$

^b Approximated from figure 17

249 1.8 times the literature value².

250 4.2. Internal conversion coefficients of high-energy transitions

251 The main goal of the S06 ¹⁵⁴Sm Coulomb excitation experiment was to study
 252 inter-band transitions between the excited side bands and the ground state band.
 253 The results for these higher energy transitions are shown in table 3. In several
 254 cases only an upper limit could be given due to the lack of statistics. The
 255 partial level schemes showing the transitions investigated are shown in figure 1.
 256 Data for level schemes are from Ref [13]. The measured ICC for the 4_3^+ to 6_1^+
 257 transition in ¹⁵⁴Sm suggests E2 character. However, a M1+E2 transition with
 258 a mixing ratio $\delta \lesssim 0.5$ is possible within the error limits.

²J. Smallcombe, private communication

Table 3: Experimental results for α_K ICCs in ^{154}Sm , obtained by using energy dependant time gates, either the veto or add-back algorithm and filtering. The level and multipolarity assignments are as listed in NNDC [13] if not otherwise stated. The upper limits are deduced with a 90% confidence limit according to Ref [18]. The measured value of the mixing ratio (δ) is given where available.

Origin	γ energy [keV]	e^- energy [keV]	I_i^π	I_f^π	σL	δ	$\alpha_{K,exp}$ add-back	$\alpha_{K,exp}$ veto	$\alpha_{K,lit}$
^{152}Sm	563	516	0_2^+	2_1^+	E2	-	0.006(4)	0.005(3)	0.0069(34) ^a
	689	642	2_2^+	2_1^+	E0+M1+E2	8_{-3}^{+6d}	0.003(2)	0.04(2)	0.0297(75) ^a
^{154}Sm	795	748	4_3^+	6_1^+	(E2) ^b	-	0.0030(27)	$\leq 0.021(1)$	0.00345(5) ^c
	911	864	2_3^+	4_1^+	E2	-	0.0023(20)	0.003(2)	0.0034(16) ^a
	1017	970	0_3^+	2_1^+	E2	-	$\leq 0.038(1)$	$\leq 0.018(1)$	0.00204(3) ^c
	1071	1024	4_3^+	4_1^+	M1+E2	$>50^e$	$\leq 0.025(1)$	$\leq 0.038(1)$	$0.0079_{-0.0073}^{+0.0087}$ ^a
	1096	1050	2_3^+	2_1^+	M1+E2	$30(21)^f$	$\leq 0.036(1)$	$\leq 0.043(1)$	$\leq 0.0067(6)^a$
	1256	1209	4_3^+	2_1^+	E2	-	$\leq 0.061(1)$	$\leq 0.051(2)$	0.001329(19) ^c
	1358	1311	2_4^+	2_1^+	[M1+E2]	$19(10)^f$	$\leq 0.036(1)$	$\leq 0.032(1)$	0.0014(3) ^c
^{166}Yb	755	694	8_3^+	8_1^+	E0+M1+E2	-	0.03(2)	0.005(4)	0.0158(45) ^a
	814	753	6_2^+	6_1^+	M1	-	0.008(3)	0.008(3)	0.0069(28) ^a
	937	876	$(3)_2^+$	2_1^+	E2	-	0.014(6)	$\leq 0.49(2)$	0.00351(5) ^c

^a Experimental result from Ref [11].

^b Not available in NNDC, own assignment based on the experimental ICC value.

^c BrIcc result. ^d From Ref [19]. ^e From Ref [13]. ^f From Ref [20].

259 4.3. Observation of high-energy events in the silicon detector

260 As can be seen in figure 18, the electron spectrum measured from the
261 $^{16}\text{O}+^{154}\text{Sm}$ Coulomb excitation reaction shows a significant number of events
262 that lie outside the dynamic range of the analogue to digital converters in the
263 data acquisition system. The number of these events far exceeds that which is
264 expected based on the behaviour and shape of the electron spectrum at high
265 energies. In a test experiment (ST1), these ‘‘overflow’’ events were shown to be
266 due to the detection of backscattered ^{16}O beam in the SAGE silicon detector.

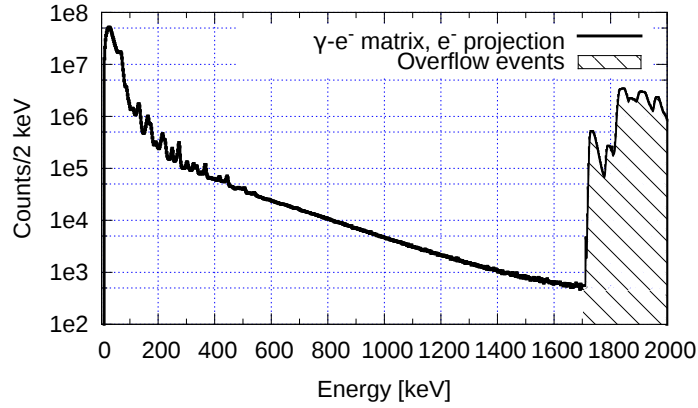


Figure 18: A projection of the electron spectrum from the γ -electron coincidence matrix produced in the $^{16}\text{O}+^{154}\text{Sm}$ Coulomb excitation reaction. Note the abundance of “overflow” events observed at high energies.

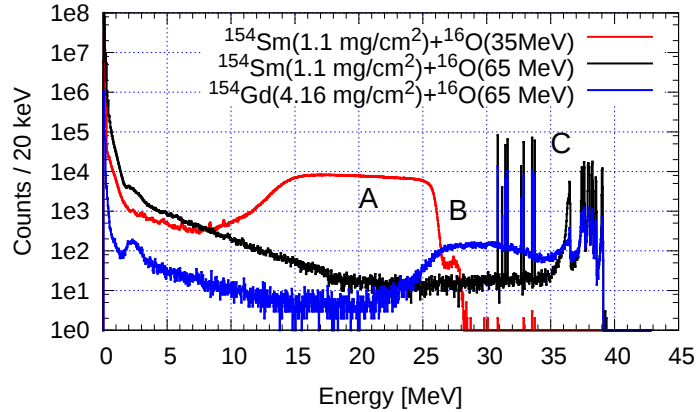


Figure 19: Spectra from the SAGE silicon detector with increased dynamic range from the ST1 test run with a ^{154}Sm target bombarded by a beam of ^{16}O at an energy of 35 MeV and 65 MeV and ^{154}Gd target bombarded with 65 MeV energy. (A) Backscattered ^{16}O from samarium. (B) Backscattered ^{16}O from gadolinium. (C) Overflow events.

267 In the ST1 test experiment, the gain in amplification of the outer seg-
 268 ment (59 to 90) signals of the SAGE silicon detector were reduced by voltage
 269 dividers allowing increased dynamic range and detection of backscattered ^{16}O
 270 beam particles. An alpha source was used for energy calibration confirming
 271 that the maximum energy range had increased to $\sim 30\text{-}40$ MeV from the orig-

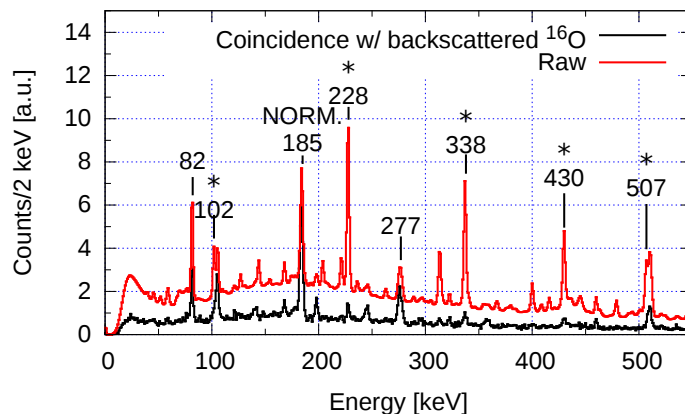


Figure 20: Gamma-projections from γ -electron matrices. Normalized with the area of 185 keV peak. From ST1 test run with 65 MeV beam energy. Peaks marked with asterisk originate from ^{166}Yb .

272 inal ~ 2 -2.5 MeV. The original Coulomb excitation experiment was repeated
 273 with beam energies of 35 and 65 MeV. For validation purposes scattering from
 274 4.16 mg/cm^2 ^{154}Gd target with 65 MeV beam energy was also studied. In the
 275 resulting spectrum shown in figure 19 backscattered ^{16}O is clearly observable.
 276 The energy distribution of the scattered particles correspond with calculated
 277 distribution from a 1.1 mg/cm^2 ^{154}Sm target. The identification of backscat-
 278 tered ^{16}O was further confirmed when the beam energy was changed, resulting
 279 in a corresponding shift in the energy of the backscattered particles. Selecting
 280 events in coincidence with backscattered ^{16}O , the events arising from sub-barrier
 281 fusion such as ^{166}Yb can be removed. A normalized γ -ray projection coincident
 282 with backscattered ^{16}O ions is shown in figure 20. After demanding the coin-
 283 cidence, the contribution from ^{166}Yb (102, 228, 338, 430 and 507 keV peaks)
 284 is significantly smaller compared to that from ^{154}Sm (82, 185 and 277 keV).
 285 However, the peak areas are significantly reduced. In the raw projection of the
 286 γ - e^- matrix the peak area of the 185 keV transition is in the order of 10^8 but
 287 in the gated projection only on the order of 10^3 . Since the statistics obtained in
 288 the short test run were rather low, the data were not analysed further. However,
 289 with a longer run and improved detection system demanding a coincidence with

290 scattered particles could produce exceptionally clean data for the extraction of
291 ICCs.

292 **5. Conclusions**

293 Experimental internal conversion coefficients have been successfully extracted
294 with non-reference based methods. The crucial step in order to determine ab-
295 solute ICC values with reasonable accuracy is the creation of energy-dependent
296 time gates. The result obtained through demanding coincidence with backscat-
297 tered ions (Fig 20) resembles greatly the results obtained with recoil gating or
298 recoil-decay tagging in γ -ray spectroscopic studies (see for example Ref [21]). In
299 order to fully exploit the possibilities of this method plans to instrument SAGE
300 with an additional heavy ion detector have been made. One notable detector
301 based on recent developments with optical fibres such as presented in Ref [22]
302 is under consideration.

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