Extending the Application of DSAM to Atypical Stopping Media

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Abstract

A methodology that manifolds the possibilities of level lifetime measurements using the Doppler Shift Attenuation Method (DSAM), and extends its application beyond the conventional thin-target-on-thick-elemental-backing setups, is presented. This has been achieved primarily through application of the TRIM code to simulate the stopping of the recoils in the target and the backing media. Using the TRIM code, primarily adopted in the domain of materials research, in the context of lifetime analysis require rendition of the simulation results into a representation that appropriately incorporates the nuances of nuclear reaction along with the associated kinematics, besides the transformation from an energy-coordinate representation to a velocity-direction profile as required for lifetime analysis. The present development makes it possible to practice DSAM in atypical experimental scenarios such as those using molecular or multi-layered target and / or backing as the stopping medium. These aberrant cases, that were beyond representation in the customary Doppler shape analysis can, in the light of the present work, be conveniently used in the DSAM based investigations. The new approach has been validated through re-examination of known lifetimes measured both in the conventional as well as in the deviant setups.

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32 1. Introduction

33 Measurement of level lifetimes is of much significance in nuclear structure
34 research, since they provide information on the microscopic structure of the
35 states and facilitate constraining as well as refining the associated models. Sev-
36 eral procedures [1] of lifetime measurements have been practiced for decades
37 and the choice of the same depends on the range of lifetimes being addressed /
38 expected in a particular investigation. The Doppler Shift Attenuation Method
39 (DSAM) is one that is adopted for measurement of level lifetimes in the range
40 of $\sim$ few tens of fs (10^{-15} s) to $\sim$ few ps (10^{-12} s) and is widely used in nuclear
41 structure investigations. Several efforts dedicated to different developments [2–
42 4] in the context of this method have been carried out in the last few decades.
43 The analysis for level lifetimes following DSAM measurements commences with,
44 as is well known, the simulation of the slowing down process of the recoils in
45 the target and the backing media. One of the principal uncertainties in such
46 analysis has been identified to be the stopping powers that govern this slowing
47 down phenomenon. The problem is further compounded in case of lifetime mea-
48 surements that use molecular target and / or backing wherein the estimation
49 of stopping powers, using theoretical models, is even more difficult. Extensive
50 efforts have, however, been undertaken in the domain of stopping power studies
51 for over a century. Starting from the pioneering studies by Bragg *et al.* [5] and
52 later investigations by Alexander *et al.* [6], for instance, there have been signif-
53 icant strides in the last couple of decades, by the contemporary researchers like
54 Ziegler *et al.* [7] and Paul *et al.* [8], in compilation of the vast amount of ex-
55 perimental data and developing theoretical models therefrom in order to better
56 estimate the stopping powers. These recent developments have gone a long way
57 in reducing the (stopping) uncertainties such that the contemporary softwares
58 like SRIM [7] claims an uncertainty of a modest $\sim 5\%$ [7] in the heavy-ion stop-
59 ping power calculations, that is expected to still improve with the progress in
60 the measurements and the corresponding refinements in the theory. It is natural
61 to envisage the use of these state-of-the-art tools for an adequate description

of the slowing down process and a subsequent reduction in the uncertainties associated with the DSAM measurements.

Extensively used codes for analyzing the DSAM data, such as LINESHAPE [9], typically allow only elemental media as the target and the backing. Stopping powers are calculated using one of the earlier models by Ziegler [10] or by Northcliffe and Schilling [11] that are based on the proton and the α stopping data and that use a different scaling algorithm for the heavy-ions. The approach is reasonable for a conventional DSAM measurement that customarily uses a thin target on a thick elemental backing such that the energy loss of the recoils in the target can be neglected and the stopping process can be perceived to be occurring entirely in the backing medium wherein the stopping powers, calculated from the above models, can be claimed to be accurate within 15-20%.

Certain lifetime measurements, however, require setups that are incongruent with the traditional scenario. For instance, the neutron rich ^{18}O target, extensively used in the spectroscopy of *sdpf* nuclei [12–17], come in the form of metallic oxides, such as Ta_2O_5 . The target elements chosen in the rare-earth region are also often oxidized, such as Sm_2O_3 and Nd_2O_3 . Moreover, depending on the method of target fabrication, the oxide layer can be substantially thick [17] to operate both as the target as well as the backing. For such a target medium, the energy of the beam decreases while traversing the thickness of the target and consequently the yield of the residue exhibit a variation. In fact, only a part of the target thickness may actually contribute in the production of the residue while the remaining can only act as a stopping medium. Such media, owing to the molecular nature as well as the thickness, are beyond the description allowed in the conventional analysis. These experimental conditions require the use of simulation packages such as TRIM [7] that allow for a wide range of stopping media to carry out the stopping simulations using Monte Carlo techniques with updated and experimentally benchmarked stopping powers. It is required that the results of these simulations be incorporated into the lifetime

analysis. Such implementation of cutting-edge simulation techniques in DSAM measurements is expected to provide greater flexibility in the choice of the target and/or backing medium that can now be elemental or molecular, thin or thick, single or multi-layered depending on the requirement of the specific measurement. However, it is imperative that these simulations appropriately include the details of the nuclear reaction and the associated kinematics, such as the energy dependent angular distribution of the residues, in order to calculate the stopping parameters, such as the stopping time, number of time steps etc., that have a bearing on the Doppler shift / shape of the observed γ -ray transitions.

This paper presents a set of developments to assimilate the stopping simulations obtained using the TRIM code, to incorporate the relevant details of the nuclear reactions, and to use these in the analysis following DSAM measurements. The method has been validated with the lifetime measurements of levels with previously reported lifetimes using conventional as well as atypical target / backing configurations.

2. Programming and Methodology

The TRIM, acronymed for TRAnsport of Ion in Matter, program finds extensive usage in the domain of material science research wherein it is applied to investigate the effects of energetic ions passing through a medium that might be elemental or molecular and might consist of multiple layers of varying depths. It is an efficient simulation tool through the use of statistical algorithms and is an alluring option for simulating the slowing down process of the recoiling nuclei in the target and the backing media as is required in analysis for lifetime measurements using DSAM. In fact there is precedence of using TRIM in nuclear physics simulations such as by Sagaidak *et al.* [18] who used the code to simulate energy and angular distributions of the residues following heavy-ion induced fusion-evaporation reactions.

122

123 The output of the TRIM simulations, however, cannot be naively used for
124 DSAM studies. A set of programs have been developed to process the TRIM
125 generated output for catering to the requirements of lifetime analysis. These
126 pertain to correcting the trajectories with the reaction kinematics associated
127 with the production of the residue, to extracting the velocity profile (variation
128 of β with time) of the residues moving in the target-backing media, and to in-
129 corporating the possible change in the cross section for residue formation along
130 the target thickness.

131

132 The TRIM code characteristically assigns the origin, (0,0,0), as the common
133 starting point for all the simulated trajectories. The actual experimental sce-
134 nario of lifetime measurements with thick target is, however, different. In case
135 of a thick target, as pointed out before, the cross section for production of the
136 residue of interest evolves along the thickness of the target with decreasing beam
137 energy. Thus, varying number of residues are produced at different target depths
138 and these would have different starting points for their respective trajectories.
139 In the current analysis, the cross section dependence of the residue of interest on
140 the beam energy was determined either based on available experimental data or
141 statistical model calculations [19]. The change in beam energy, along the thick-
142 ness of the target, was calculated using the SRIM code. It is understood that
143 for a thick target, only a part of the same would contribute to the production
144 of the residue of interest while the remaining thickness will only operate as a
145 stopping medium. The effective thickness of the target, contributing to popula-
146 tion of the residue, was divided into bins representing the changing beam energy
147 and the evolving cross section therein as illustrated in the lower panel of Fig. 1.
148 In the conventional DSAM analysis, the residues are uniformly distributed over
149 the entire target thickness which is a reasonable approximation for a thin target
150 setup. The variation in the yield of the residue within a thick target is rather
151 substantial. In correspondence with the decreasing beam energy, the minimum
152 yield can be as low as 5-10% of the maximum yield. This variation needs to

Figure 1: (Upper panel) Typical energy-angle distribution of residues generated in the statistical model calculations using the PACE4 code [19]. (Middle panel) Schematic representation of a nuclear fusion-evaporation reaction producing residue (of interest) following particle evaporation from the compound nucleus. The TRIM trajectories, initiating aligned to the X-direction are rotated to match the angle of the residue chosen under the constraint of the energy-angle distribution. (Lower panel) Schematic representation of the decreasing beam energy accompanied by evolving yield of the residue in case of a thick target. The evolution is represented by up to 10 bins in the present analysis, as detailed in the text. Each bin is characterized by the respective beam energy ($E_{lab,i}$), yield (Y_i) of the residue and the corresponding energy-angle distribution.

153 be represented in the lifetime analysis and the same has been implemented in
 154 the present work. The cross-sections (for the residue of interest) at different
 155 beam energies, along the target, were calculated using the PACE4 [19] code in
 156 the current analysis. However, in case the cross-section measurements for the
 157 particular reaction, at relevant energies, exist in the literature, the same can be
 158 used for the purpose.

159

160 The residues produced in each bin would have a different initial energy-angle
 161 distribution and different starting points for their trajectories. The distribution
 162 in the initial energy and angle of the residues follows from the evaporation of
 163 the particles (p, n, α) , de-exciting the compound nucleus (Fig. 1), that has to be
 164 incorporated at the starting point of the trajectories in the stopping medium.
 165 The trajectories obtained from TRIM simulations, however, initiate aligned to
 166 the X-direction, with direction cosines (1,0,0), and does not include this dis-
 167 tribution. The two-dimensional energy-angular distribution of the residues was
 168 calculated using the statistical model code PACE4 [19] for each individual bin,
 169 characterized by a beam energy, along the depth of the target. For each residue,
 170 an energy and an angle is chosen under the constraint of the probability dis-
 171 tribution of the respective bin. The corresponding TRIM trajectory, chosen
 172 sequentially from the set of trajectories generated with identical incident en-
 173 ergy (greater than maximum possible energy) of all the ions, is inspected for
 174 the point where the energy of the residue is nearly equal to the chosen energy
 175 from the distribution. This point in the trajectory is then perceived as the origin
 176 of the trajectory of this particular residue in the stopping medium. The origin
 177 is appropriately offset to initiate at the center of the respective cross section
 178 bin. In conjunction, the angle chosen from the distribution is used to modify
 179 the trajectory through application of a rotation matrix, so as to incorporate the
 180 angular entry of the residue, deviated from the beam direction (following par-
 181 ticle evaporation), into the stopping medium. The incorporation of the initial
 182 (distribution of) energy and angle of entry, obtained from the PACE4 calcula-
 183 tions, is an important aspect of the present analysis. It is understood that this

184 distribution is characteristic to the particular reaction that is used to populate
 185 the residue of interest and it is thus difficult to derive a general quantitative
 186 impact of including this in the lifetime analysis. For instance, a residue angle
 187 (initial) of 15° (which has considerable residue distribution in some of the reac-
 188 tions used in the present study) will lead to an increase in the path length by $\sim$
 189 3.5% compared to an undeviated trajectory, thus influencing the stopping time
 190 of the residue and consequently the lifetime results. Similarly, residues with dif-
 191 ferent initial kinetic energies will have different stopping times that, once again,
 192 will impact the analysis.

193

194 The trajectory information obtained from TRIM, in the form of energy and
 195 coordinates dumped at certain energy interval, and modified with inclusion of
 196 the nuclear reaction aspects, was converted into a description wherein a trajec-
 197 tory is represented by the time profile of the β and the direction cosines, logged
 198 in uniform time steps, in compliance with the requirements of lifetime analysis.
 199 The size of the time step is user specified and is typically ~ 0.001 - 0.002 ps.

200

201 In case of the more conventional scenario of a thin target on a thick backing,
 202 the working with the TRIM simulations is slightly different from that described
 203 above. This is particularly relevant if the residues loose an amount of energy in
 204 the target medium, before reaching the backing, that cannot be neglected. In
 205 this case, the TRIM simulation is separately executed for the target and for the
 206 backing and the processed trajectories in the target medium and the backing
 207 medium are then combined into a common file.

208

209 The output of the exercise were simulated trajectories, that were used in the
 210 subsequent analysis for extracting the level lifetimes. This was carried out us-
 211 ing the LINESHAPE package and is similar to the standard practice discussed
 212 and detailed, for example in Ref. [17]. The uncertainty on the quoted lifetime
 213 is that from the χ^2 minimization, resulting from the fitting of the calculated
 214 Doppler shape / shift to the experimental spectrum, and does not include un-

215 certainty on the stopping powers used for the simulation of the slowing process
 216 of the residues in the target and the backing media ($\sim 5\%$ [7], on the average).
 217 It may be noted that the uncertainties on the stopping powers in the SRIM
 218 database, that are used for the TRIM simulations, are benchmarked with re-
 219 spect to the experimental data on heavy-ion stopping in a wide variety of media.
 220 The overlap of the SRIM calculated stopping powers with the measured values,
 221 for heavy-ions, is presently quoted around 5% with 69% of the data within 5%
 222 of the TRIM calculated value and 86% within 10% [7]. This is significantly
 223 better than the stopping powers calculated using the models of Ziegler [10] and
 224 Northcliffe-Schilling [11], used in the conventional LINESHAPE program, that
 225 can have uncertainty as high as 15-20% [20, 21].

226

227 It should also be noted that the LINESHAPE package has been referred here
 228 in a very generic sense. The result of the stopping simulations can well be made
 229 compatible with any code for DSAM analysis that may use these trajectory
 230 information for determination of the level lifetimes.

231

232 3. Results

233 Lifetime analysis using the new prescription was carried out for levels in dif-
 234 ferent nuclei, populated in varied experimental scenario. These lifetimes were
 235 known from previous studies and re-examined in the current investigation for
 236 validation of the analysis methodology presented herein. The results are pre-
 237 sented in this section and summarized in Table 1.

238

239 3.1. Thick Elemental Target

240 The current methodology was first used for analysis of data acquired with
 241 thick elemental target that is presumably a simpler medium for stopping simula-
 242 tions compared to a molecular one. The reaction was $^{27}\text{Al}(^{16}\text{O},xny\text{p}\alpha)$ at E_{lab}

Figure 2: (Color online) Fitted Doppler shape observed for the 2167 keV transition, de-exciting the 2167 keV level, in the ^{38}Ar nucleus.

Figure 3: (Color online) The upper panel represents the stopping powers of ⁴¹Ca in aluminum, calculated using the Ziegler heavy-ion and the shell corrected Northcliffe-Schilling stopping power models, that are used in the conventional LINESHAPE code, along with the stopping powers used in the TRIM simulations, as in the present analysis. The middle and the bottom panel illustrates the lifetime results obtained in the ⁴¹Ca and ³⁸Ar nuclei, with thick elemental target setup (see text) and different stopping power models as compared to the literature value. An uncertainty of 5% on the stopping power has been included for the TRIM results while that in the results obtained using the Ziegler and the Northcliffe-Schilling models has been assigned to be 15% [20, 21].

243 = 34 MeV, with a thick (~ 200 mg/cm²) elemental ²⁷Al foil as the target and
 244 ¹⁶O beam provided by the 15UD Pelletron at the Inter University Accelerator
 245 Center (IUAC), New Delhi. The emitted γ -ray transitions were detected using
 246 the Indian National Gamma Array (INGA) then consisting of 16 Compton sup-
 247 pressed Clover detectors [22]. Level lifetimes of the ⁴¹Ca and the ³⁸Ar nuclei,
 248 populated in the aforementioned reaction were determined for the purpose. It is
 249 noted that the uncertainties quoted on the present results does not include the
 250 contribution of the stopping powers used from the SRIM code, that is estimated
 251 to be $\sim 5\%$.

252

253 Fig. 2 illustrates the fitted Doppler shape of the 2167 keV transition de-
 254 exciting the 2167 keV level in the ³⁸Ar nucleus. The resulting lifetime $\tau = 641$
 255 ± 14 fs is in reasonable agreement with the recently reported value of $710 \pm$
 256 30 fs by Speidel *et al.* [23] where the quoted uncertainty does not include the
 257 systematic uncertainties in the stopping powers that can be as high as 10-20%.
 258 There have been several other measurements of the level lifetime for the 2167
 259 keV state and the current adopted [24] value is 671 ± 30 ps [24] in excellent
 260 overlap with the present result. In order to benchmark the current analysis with
 261 respect to the existing stopping algorithms, the Doppler shape of the 2167 keV
 262 γ -ray transition was also analyzed with the conventional LINESHAPE package
 263 using the stopping models of Ziegler [10] and Northcliffe *et al.* [11], available
 264 therein. A comparison of the lifetimes obtained from this exercise is illustrated
 265 in Fig. 3.

266

267 The same analysis was also carried out for the 3915 keV level of the ⁴¹Ca
 268 nucleus and the results are also depicted in Fig. 3. The lifetime of the level from
 269 the present analysis is $\tau = 2.24 \pm 0.11$ ps that is in overlap with the adopted
 270 value of $\tau = 2.17 \pm 0.43$ ps [24]. The latter is a weighted average of the results
 271 of Lieb *et al.* [25], 2600 ± 800 fs, using Recoil Distance Method and of Lister *et*
 272 *al.* [26], 1750 ± 450 that includes an uncertainty of 25% from the stopping pow-
 273 ers. The lifetime values extracted using different stopping theories, presented

274 in Fig. 3, overlap within the quoted uncertainties, affirming the accuracy of the
275 present methodology, albeit with lower uncertainty on the stopping power in
276 the latter.

277

Table 1: Lifetimes of selected states in the nuclei studied in the present work. The results are compared to the previously reported values to validate the current analysis. The quoted uncertainty on the present results does not include that for the stopping powers. This uncertainty, as discussed in the text and as per Ref. [7] is $\sim 5\%$.

Target	Nucleus	E_x (keV)	E_γ (keV)	τ (fs)		Previous Work		
				Previous Work	Present Work	Stopping Uncertainty	Stopping Model	Reference
Thick Elemental Al	^{41}Ca	3915	545	2600 ± 800^1	2243 ± 108			[25]
				1750 ± 450^2		25%	Lindhard	[26]
	^{38}Ar	2167	2167	710 ± 30^3	641 ± 14	10-15%	Ziegler	[23]
	^{26}Mg	1809	1809	693 ± 75^4	634 ± 2	5%	Forster	[27]
		2939	1130	204 ± 12^5	201 ± 4	5%	Forster	[28]

Continued in next page

Table1 – continued from previous page

Target	Nucleus	E_x (keV)	E_γ (keV)	τ (fs)		Previous Work		
				Previous Work	Present Work	Stopping Uncertainty	Stopping Model	Reference
Thick Molecular Ta ₂ O ₅	²⁹ Si	2028	2028	442±14 ⁶	430±10	5%	Forster	[29]
		3624	1596	3760±190 ⁷	2478±76	7%	Ziegler	[30]
				3740±190 ⁸		5%	Forster	[29]
		5255	1631	80±4 ⁷	106±2	7%	Ziegler	[30]
				100±20 ⁹		15%	Lindhard	[31]
	³⁰ Si	2236	2236	310±40 ¹⁰	290±11	20%	Northcliffe, Lindhard	[32]
Thin Elemental	¹⁰⁴ Ag	3301	481	300±60 ¹¹	395±1	10%	Northcliffe	[33]
⁷⁶ Ge on		3808	508	320±60 ¹¹	349±4	10%	Northcliffe	[33]
Thick Au backing								

¹Measurement by Lieb *et al.* [25] using the Recoil Distance Method (RDM) technique. ²Measurement by Lister *et al.*

279 [26]. The uncertainty includes that of 25% from the stopping power, calculated using the theory of Lindhard *et al.* [34].
 280 ³Measurement by Speidel *et al.* [23]. The uncertainty (probably) does not include that from the stopping power which was
 281 calculated [35, 36] using the formalism by Ziegler [37] and can be as high as 10-15%. ⁴Measurement by Kozub *et al.* [27]. The
 282 uncertainty includes that from the stopping power which was adopted from the experimental electronic stopping power data
 283 by Forster *et al.* [38] with uncertainty $\sim 5\%$. . It may be noted that a number of lifetime measurements in the $A \sim 30$ region
 284 used the stopping powers of Forster *et al.*. However, these were based on data in a small number of elemental stopping media,
 285 with light mass projectiles and are of limited applicability. ⁵Measurement by Dybdal *et al.* [28]. The uncertainty does not
 286 include that from the stopping powers which was taken from Forster *et al.* and had an uncertainty of $\sim 5\%$. ⁶Measurement by
 287 Scherpenzeel *et al.* [29]. Weighted average of four measurements using four different stopping media. Stopping powers from
 16 288 Forster *et al.*. Uncertainties on individual measurements $\sim 5\%$. ⁷Measurement by Tikkannen *et al.* [30] using stopping powers
 289 from Ziegler *et al.* [10] and quoting the uncertainty from the same to be 7%. The uncertainty on the lifetime probably does not
 290 include this. ⁸Measurement by Scherpenzeel *et al.* [29] from a single stopping medium. ⁹Measurement by Bardin *et al.* [31]
 291 and includes 15% uncertainty on stopping powers that were calculated from the theory of Lindhard *et al.* [34]. ¹⁰Measurement
 292 by Bitterwolf *et al.* [32] and includes 20% uncertainty on the stopping powers that were calculated from the experimental
 293 stopping powers of Northcliffe and Schilling [11] and the theory of Lindhard *et al.* [34]. ¹¹Measurement by Datta *et al.* [33]
 294 and does not include stopping power uncertainty that can be, as quoted, as high as 10%.

3.2. Thick Molecular Target

The method was then extended to lifetime analysis in the *sdpf* nuclei populated using $^{18}\text{O}(^{18}\text{O},xpynz\alpha)$, $^{18}\text{O}(^{16}\text{O},xpynz\alpha)$ and $^{18}\text{O}(^{13}\text{C},xpynz\alpha)$ reactions at $E_{lab} = 30\text{-}34$ MeV. The beam was provided by the Pelletron-LINAC Facility at the Tata Institute of Fundamental Research (TIFR), Mumbai and the Pelletron Facility at the Inter University Accelerator Center (IUAC), New Delhi. The neutron-rich ^{18}O target was in the form of thick molecular Ta_2O_5 prepared by heating a Ta foil of thickness ~ 50 mg/cm², in an enriched ^{18}O atmosphere, resulting in the formation of 9.25 mg/cm² thick Ta_2O_5 layer on either side of the foil. For the experiment with the ^{18}O beam, an array of seven Compton suppressed Clover detectors was used as the detection system while that in the experiments with the ^{13}C and the ^{16}O beams was the Indian National Gamma Array (INGA), then consisting of 15-16 Compton suppressed Clovers. Further details on the experimental setups can be found in Ref. [13, 17]. The particular nuclei studied include ^{26}Mg , $^{29,30}\text{Si}$ ($Z = 14$), $^{33,34}\text{P}$ ($Z = 15$) and ^{33}S ($Z = 16$). We present here some of the lifetime results as representative cases to establish the methodology presented herein. It is noted that the uncertainties quoted on the present results does not include the contribution of the stopping powers used from the SRIM code, that is estimated to be $\sim 5\%$.

In the ^{29}Si nucleus, the lifetime of the 2028 keV level, de-populated by the 2028-keV transition, has been analyzed with the present technique and found to be 430 ± 10 fs, in excellent agreement with the literature value of 442 ± 14 fs reported by Scherpenzeel *et al.* [29] using the stopping powers by Forster *et al.* [38]. A number of lifetime measurements in this mass region ($A \sim 30$) used the stopping powers from Forster *et al.* that were based on measurements with certain specific projectiles ($9 \leq Z \leq 17$) incident on six (Ti, Fe, Ni, Cu, Ag, Au) specific elemental stopping media and subsequent scaling to projectiles in the range $8 \leq Z \leq 20$. Scherpenzeel *et al.* used four of these stopping media to measure the lifetime of the 2028 keV state in ^{29}Si and the above value is a weighted average of the individual results each with uncertainty $\sim 5\%$. While

Figure 4: (Color online) Fitted Doppler shape and shift of the 1596 keV and the 1631 keV transitions, respectively de-exciting the 3624 keV and the 5255 keV levels, in the ^{29}Si nucleus.

326 the experimental determination of the stopping powers is expected to favorably
 327 restrict the uncertainties on the same, such a measurement as by Forster *et*
 328 *al.* with particular projectile-target combinations might only be of limited use.
 329 Fig. 4 illustrates the observed Doppler shape / shift and the corresponding fit
 330 of the 1596- and the 1631-keV transition peaks in the same ^{29}Si nucleus. The
 331 resulting lifetime (Table 1) of the 5255-keV level, de-exciting by the 1631-keV
 332 transition, is 106 ± 2 fs, in close compliance with the previously reported val-
 333 ues of 80 ± 4 fs by Tikkannen *et al.* [30], that does not include uncertainties
 334 on the stopping power, and 100 ± 20 fs by Bardin *et al.* [31], that includes a
 335 15% stopping power uncertainty. However, the lifetime of the 3624-keV level,
 336 de-excited by the 1596-keV transition, comes out to be 2.48 ± 0.08 ps, which is
 337 at variance with the literature values of 3.76 ± 0.19 ps reported by Tikkannen
 338 *et al.* [30], that probably does not include the uncertainties in the stopping
 339 powers of Ziegler [10], or 3.74 ± 0.19 ps by Scherpenzeel *et al.* [29], using the
 340 stopping powers of Forster *et al.* [38]. It may be noted that this discrepancy
 341 in the lifetime of the 3624-keV state, with respect to the previously measured
 342 values, has also been reported by our group [39], using an independent set of
 343 developments, reported elsewhere [17]. The level lifetime of the 3624-keV state
 344 was found, therein, to be $2.54^{+0.23}_{-0.19}$ ps which agrees well with the result from the
 345 current analysis. It needs to be stressed that fitting of the completely shifted
 346 1631-keV peak and the Doppler shaped 1596-keV peak, simultaneously, has been
 347 a stringent test of the present methodology and the results therefrom have quite
 348 authenticated the same.

349
 350 For the ^{26}Mg nucleus, the lifetimes of the 1809 and the 2939 keV levels have
 351 been analyzed in the present efforts. The lifetime of 1809 keV level, de-excited
 352 by 1809 keV γ -ray transition, was determined as 634 ± 2 fs which is in overlap
 353 with the value reported by Kozub *et al.* [27], 693 ± 75 fs, using the stopping
 354 powers of Forster *et al.*. The lifetime of the 2939 keV state, deexcited by the
 355 1130 keV transition, was analyzed to be 201 ± 4 fs in agreement with the value
 356 of 204 ± 12 reported by Dybdal *et al.* [28] once again using the stopping powers

Figure 5: (Color online) Fitted Doppler shape and shift of the 481 keV transition, de-exciting the 3301 keV level in the ^{104}Ag nucleus.

of Forster *et al.*.

Thus, it may be observed that the present methodology has been effective in extracting lifetime results from data acquired with thick molecular stopping medium. It is also worth noting that such molecular media could not be represented within the purview of the conventional DSAM analysis carried out using programs such as the LINESHAPE code.

3.3. Thin Elemental Target on Thick Elemental Backing

In order to test the methodology in a conventional setup, the lifetimes of levels in the ^{104}Ag nucleus were analyzed. The nucleus was populated using

368 $^{76}\text{Ge}(^{32}\text{S},p3n)$ reaction at $E_{lab} = 110$ MeV, using $500\mu\text{g}/\text{cm}^2$ isotopically en-
 369 riched ^{76}Ge target on a $26\text{ mg}/\text{cm}^2$ gold backing. The beam was provided by
 370 the Pelletron LINAC Facility at TIFR, Mumbai and INGA, then consisting of
 371 15 Compton suppressed Clover detectors, was used as the detection system.

372
 373 Lifetimes of 3301 and 3808 keV levels in the ^{104}Ag nucleus have been ex-
 374 tracted in the present study and summarized in Table 1. A representative fit to
 375 the Doppler shape on the 481 keV transition, de-exciting the 3301 keV level, is
 376 illustrated in Fig. 5. It is noted that the lifetimes from the present investigation
 377 are in excellent overlap with the previously reported values [33], though with
 378 lesser uncertainties. This exercise carried out for a typical setup for DSAM
 379 and the results obtained therefrom, indicate the general validity of the present
 380 programs in DSAM analysis.

381 382 **4. Conclusions**

383 A new approach of lifetime analysis in DSAM has been developed by using
 384 the TRIM code to simulate the slowing down of the residues in the target and
 385 the backing media, along with appropriate inclusion of the details of nuclear
 386 reactions and associated kinematics. The results have been subsequently used
 387 in the LINESHAPE program in order to extract the level lifetimes. Use of the
 388 LINESHAPE code, however, is only generic and, in principle, can be replaced by
 389 any other program. The methodology has been applied to determine the level
 390 lifetimes of nuclei populated in varied experimental scenario, both typical as well
 391 as unconventional, and the successful reproduction of the known lifetimes has
 392 validated the technique. The present development is expected to improve the
 393 accuracy of lifetime results following DSAM through use of updated stopping
 394 powers as well as to extend the applicability of the method to unconventional
 395 target setups which can be faithfully represented in the modern simulation codes
 396 like TRIM. Finally, this methodology also spells out the prospect of further re-

duction in the uncertainties on DSAM results with the availability of better
 experimental data and associated theoretical modelling that is expected to be
 adopted in the continuously improving codes like TRIM.

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 III).

413

- 414 [1] P. J. Nolan, J. F. Sharpey-Schafer, Rep. Prog. Phys. 42 (1979) 1.
- 415 [2] P. Petkov, A. Dewald, P. von Brentano, Nucl. Instr. Meth. Phys. Res.
 416 A 560 (2006) 564.
- 417 [3] P. Petkov, M. Yavahchova, D. Tonev, N. Goutev, A. Dewald, Nucl. Instr.
 418 Meth. Phys. Res. A 711 (2013) 96.
- 419 [4] P. Petkov, A. Dewald, D. Tonev, N. Goutev, G. Asova, B. Dimitrov,
 420 G. Gavrilov, M. Mineva, M. S. Yavahchova, Nucl. Instr. Meth. Phys.
 421 Res. A 783 (2015) 6.
- 422 [5] W. H. Bragg, R. Kleeman, Phil. Mag. 10 (1905) 318.
- 423 [6] T. K. Alexander, J. S. Forster, Adv. Nucl. Phys. 10 (1978) 197.

- 424 [7] www.srim.org.
- 425 [8] <https://www-nds.iaea.org/stopping/>.
- 426 [9] J. C. Wells, N. R. Johnson, ORNL Report 6689 (1991) 44.
- 427 [10] J. F. Ziegler, The Stopping and Ranges of Ions in Matter, Pergamon Press,
428 1980.
- 429 [11] L. C. Northcliffe, R. F. Schilling, At. Data Nucl. Data Tables 7.
- 430 [12] P. C. Bender, C. R. Hoffman, M. Wiedeking, J. M. Allmond, L. A. Bern-
431 stein, J. T. Burke, D. L. Bleuel, R. M. Clark, P. Fallon, B. L. Goldblum,
432 T. A. Hinnners, H. B. Jeppesen, S. Lee, I. Y. Lee, S. R. Leshner, A. O. Mac-
433 chiavelli, M. A. M. D. Morris, M. Perry, L. Phair, N. D. Scelzo, S. L.
434 Tabor, V. Tripathi, A. Volya, Phys. Rev. C 80 (2009) 014302.
- 435 [13] R. Chakrabarti, S. Mukhopadhyay, Krishichayan, A. Chakraborty,
436 A. Ghosh, S. Ray, S. S. Ghugre, A. K. Sinha, L. Chaturvedi, A. Y. Deo,
437 I. Mazumdar, P. K. Joshi, R. Palit, Z. Naik, S. Kumar, N. Madhavan, R. P.
438 Singh, S. Muralithar, B. K. Yogi, U. Garg, Phys. Rev. C 80 (2009) 034326.
- 439 [14] R. Chakrabarti, S. Mukhopadhyay, R. Bhattacharjee, S. S. Ghugre, A. K.
440 Sinha, A. Dhal, L. Chaturvedi, M. K. Raju, N. Madhavan, R. P. Singh,
441 S. Muralithar, B. K. Yogi, U. Garg, Phys. Rev. C 84 (2011) 054325.
- 442 [15] P. C. Bender, S. L. Tabor, V. Tripathi, C. R. Hoffman, L. Hamilton,
443 A. Volya, R. M. Clark, P. Fallon, A. O. Macchiavelli, S. Paschalis, M. Petri,
444 M. P. Carpenter, R. V. F. Janssens, T. Lauritsen, E. A. McCutchan,
445 D. Seweryniak, S. Zhu, C. J. Chiara, X. Chen, W. Reviol, D. G. Sarantites,
446 Y. Toh, Phys. Rev. C 85 (2012) 044305.
- 447 [16] S. S. Bhattacharjee, R. Bhattacharjee, R. Chakrabarti, R. Raut, S. S.
448 Ghugre, A. K. Sinha, T. Trivedi, L. Chaturvedi, S. Saha, J. Sethi, R. Palit,
449 Phys. Rev. C 89 (2014) 024324.

- [17] R. Bhattacharjee, S. S. Bhattacharjee, K. Basu, P. V. Rajesh, R. Raut,
S. S. Ghugre, D. Das, A. K. Sinha, L. Chaturvedi, U. Garg, S. Ray, Phys.
Rev. C 90 (2014) 044319.
- [18] R. N. Sagaidak, V. K. Utyonkov, F. Scarlassara, Nucl. Instr. Meth. Phys.
Res. A 700 (2013) 111.
- [19] A. Gavron, Phys. Rev. C 21 (1980) 230.
- [20] J. J. Valiente-Dobón, C. E. Svensson, A. V. Afanasjev, I. Ragnarsson,
C. Andreoiu, D. E. Appelbe, R. A. E. Austin, G. C. Ball, J. A. Cameron,
M. P. Carpenter, R. M. Clark, M. Cromaz, D. Dashdorj, P. Fallon, S. J.
Freeman, P. E. Garrett, A. Görgen, G. F. Grinyer, D. F. Hodgson, B. Hy-
land, D. Jenkins, F. Johnston-Theasby, P. Joshi, N. S. Kelsall, A. O. Mac-
chiavelli, D. Mengoni, F. Moore, G. Mukherjee, A. A. Phillips, W. Re-
viol, D. Sarantites, M. A. Schumaker, D. Seweryniak, M. B. Smith, J. C.
Waddington, R. Wardsworth, D. Ward, Phys. Rev. C 77 (2008) 024312.
- [21] S. Aydin, M. Ionescu-Bujor, F. Recchia, S. M. Lenzi, M. Bouhelal, D. Baz-
zacco, P. G. Bizzeti, A. M. Bizzeti-Sona, G. de Angelis, I. Deloncle,
E. Farnea, A. Gadea, A. Gottardo, F. Hass, T. Huyuk, H. Laftchiev, S. Lu-
nardi, D. Mengoni, R. Menegazzo, C. Michelagnoli, D. R. Napoli, A. Poves,
E. Sahin, P. P. Singh, D. Tonev, C. A. Ur, J. J. Valiente-Dobón, Phys. Rev.
C 89 (2014) 014310.
- [22] S. Muralithar, K. Rani, R. Kumar, R. P. Singh, J. J. Das, J. Gehlot, K. S.
Golda, A. Jhingan, N. Madhavan, S. Nath, P. Sugathan, Nucl. Instr. Meth.
Phys. Res. A 622 (2010) 281.
- [23] K. -H. Speidel, S. Schielke, J. Leske, J. Gerber, P. Maier-Komor, S. J. Q.
Robinson, Y. Y. Sharon, L. Zamick, Phys. Lett. B 632 (2006) 207.
- [24] www.nndc.bnl.gov.
- [25] K. P. Lieb, M. Uhrmacher, J. Dauk, A. M. Kleinfeld, Nucl. Phys. A 223
(1974) 455.

- 478 [26] C. J. Lister, A. J. Brown, L. L. Green, A. N. James, P. J. Nolan, J. F.
479 Sharpey-Schafer, J. Phys. G 2 (1976) 577.
- 480 [27] R. L. Kozub, B. J. Fields, C. B. C. Jr., T. K. Alexander, G. C. Ball, J. S.
481 Forster, H. B. Mak, W. Mclatchie, Nucl. Phys. A 403 (1983) 155.
- 482 [28] K. Dybdal, J. S. Forster, P. Hornshøj, N. Rud, C. A. Straede, Nucl. Phys.
483 A 359 (1981) 431.
- 484 [29] D. E. C. Scherpenzeel, G. A. P. Engelbertink, H. J. M. Aarts, C. J. V. D.
485 Poel, H. F. R. Arciszewski, Nucl. Phys. A 349 (1980) 513.
- 486 [30] P. Tikkanen, J. Keinonen, A. Kuronen, A. Z. Kiss, E. Koltay, E. Pintye,
487 B. H. Wildenthal, Nucl. Phys. A 517 (1990) 176.
- 488 [31] T. T. Bardin, J. A. Becker, T. R. Fisher, A. D. W. Jones, Phys. Rev. C
489 4 (1971) 1625.
- 490 [32] E. Bitterwolf, P. Betz, A. Burkard, F. Glatz, F. Heidinger, T. Kern,
491 R. Lehmann, S. Norbert, J. Siefert, H. Röpke, Z. Phys. A 298 (1980)
492 279.
- 493 [33] P. Datta, S. Chattopadhyay, P. Banerjee, S. Bhattacharya, B. Dasmahap-
494 atra, T. K. Ghosh, A. Goswami, S. Pal, M. S. Sarkar, S. Sen, H. C. Jain,
495 P. K. Joshi, Amita, Phys. Rev. C 69 (2004) 044317.
- 496 [34] J. Lindhard, M. Schraff, H. E. Schiott, Mat. Fys. Med. Dan. Vid. Selsk.
497 33.
- 498 [35] O. Kenn, K. -H. Speidel, R. Ernst, S. Schielke, S. Wagner, J. Gerber,
499 P. Maier-Komor, F. Nowacki, Phys. Rev. C 65 (2002) 034308.
- 500 [36] K. -H. Speidel, O. Kenn, F. Nowacki, Prog. Part. Nucl. Phys. 49 (2002)
501 91.
- 502 [37] F. J. Ziegler, J. Biersack, U. Littmark, The Stopping and Ranges of Ions
503 in Solids (Vol. 1), Pergamon Press, 1985.

- 504 [38] J. S. Forster, D. Ward, H. R. Andrews, G. C. Ball, G. J. Costa, W. G.
505 Davies, I. V. Mitchell, Nucl. Instr. Meth. Phys. Res. 136 (1976) 349.
- 506 [39] S. S. Bhattacharjee, R. Bhattacharjee, R. Raut, S. S. Ghugre, A. K. Sinha,
507 T. Trivedi, L. Chaturvedi, U. Garg, S. Ray, B. K. Yogi, M. K. Raju,
508 R. Chakrabarti, S. Mukhopadhyay, A. Dhal, R. P. Singh, N. Madhavan,
509 S. Muralithar, S. Saha, J. Sethi, R. Palit, Phys. Rev. C 91 (2015) 044306.