DirFis: A hybrid silicon and PPAC detector array for direct reaction and fission coincidence measurements

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Abstract

To further study the heavy-ion nuclear reaction mechanisms and fission of actinide nuclides by using the surrogate reaction method, a compact and efficient hybrid detector array for coincidence measurements of the beam-like particles and fission fragments has been developed and tested online. This detector array consists of four silicon strip detector telescopes and two parallel-plate avalanche counters. For the near-barrier (^{7}Li + ^{238}U) reaction, the fission fragments correlated with the beam-like (^{6}He) particles originating from the transfer reaction were confirmed by analyzing the folding angle. The fission barrier height for the short-lived actinide nucleus (^{239}Np), produced in the (1p) stripping channel, was extracted from its fission probability. The deduced value shows a good agreement with the existing literature data.

Full Text

Preamble

DirFis: A hybrid silicon and PPAC detector array for direct reaction and fission coincidence measurements∗ S.X. Zhu,1 H.M. Jia,1, † C.J. Lin,1, 2, ‡ J. Feng,1 Y.J. Qiu,1 S.L. Liu,1 Y. Yang,1 L. Yang,1 N.R. Ma,1 F. Yang,1 P.W. Wen,1 T.P. Luo,1 C. Chang,1 H.R. Duan,1 and H.Q. Zhang1

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To further investigate heavy-ion reaction mechanisms and the fission of actinide nuclei using the surrogate reaction method, a compact and efficient hybrid detector array for coincidence measurements of beam-like particles and fission fragments has been developed and tested online. This detector array consists of four silicon strip detector telescopes and two parallel-plate avalanche counters. For the near-barrier 7 Li + 238 U reaction, the fission fragments correlated with the beam-like 6 He particles originating from the transfer reaction were confirmed by analyzing the folding angle. The fission barrier height for the short-lived actinide nucleus 239 Np, produced in the 1p stripping channel, was extracted from its fission probability. The deduced value is in good agreement with the existing literature data.

Keywords

Hybrid detector array; Coincidence measurement; Transfer-induced fission; Fission barrier height; Fission fragment folding angle

INTRODUCTION

from the half-life restriction or uncertainty in γ-decay branching ratio, the coincidence with FF has the advantage of cover32 ing a wide excitation energy range and yielding more reliable 33 quantitative results [26, 28].

In addition to reaction mechanisms, fission-related studies 35 are also of considerable interest. Nuclear fission, since its dis36 covery about 90 years ago, remains one of the most challeng37 ing subjects in nuclear physics both experimentally [29–31] 38 and theoretically [29, 32, 33]. Fission is also widely utilized 39 in power reactors, which currently generate approximately 40 11% of the world' s electricity [34]. It also holds significant 41 application value in interdisciplinary fields such as nuclear 42 astrophysics, nuclear medicine and environment [35]. The 43 fission barrier height, introduced by Bohr and Wheeler [36], 44 is one of the most fundamental quantities describing nuclear 45 fission. To date, information on fission barriers in actinide 46 nuclei has been mainly obtained through direct neutron in47 duced fission and indirect transfer surrogate methods, includ3 48 ing (t, d) [37], (d, p) [38–40], (t, p) [41, 42], (He, d) [41-49 43] and (O,x) [44] reactions. Compared to neutron-induced 50 reactions, transfer-induced fission offers a significant advan51 tage of studying short-lived unstable nuclides, wherein the 52 natural decay not only makes sample handling difficult but 53 also generates intense background signals in measurements, 54 posing substantial challenges for neutron-induced reaction 55 studies.

To further investigate reaction mechanisms and fission re57 lated physics, a compact hybrid setup, named DirFis, con58 sisting of silicon strip detectors and parallel-plate avalanche 59 counters (PPACs) has been built and tested. The importance 60 of Np fission, which is a key intermediate nuclide in the 61 nuclear fuel cycle and has accumulated extensive experimen62 tal data on its fission barrier [42–44], makes it a suitable can63 didate for validating the reliability of the present detector ar64 ray.

In this work, coincidence measurements between fission 66 fragments and beam-like particles were performed for the 67 weakly bound Li +238 U system at the near-barrier energy 68 ELab = 36.8 MeV. The variation of the fission probability

Nuclear reactions with heavy-ions at energies around the Coulomb barrier are of great significance for studying the 4 interplay between nuclear structure and reaction dynamics. 5 Weakly bound nucleus induced reactions, owing to their low 6 separation energy thresholds [1] and cluster structures [2–4], 7 exhibit complicated reaction mechanisms of breakup, incom8 plete fusion and cluster transfers in the near-barrier energy 9 region. Over the past three decades, to thoroughly investi10 gate the reaction mechanisms induced by weakly bound nu11 clei, many silicon strip detector arrays have been developed 12 worldwide, such as MUST [5], LEDA [6], EXPADES [7], 13 GLORIA [8], MITA [9] and STARE [10]. These detector ar14 rays have greatly advanced the experimental research in this 15 field.

However, several key issues in weakly bound nuclear sys17 tems still remain.

Among them, the competition between 18 breakup-incomplete fusion and transfer reactions, as well 19 as the controversy over their relative contributions, has per20 sisted for decades [11–16]. From an experimental perspec21 tive, since both breakup and transfer processes can pro22 duce the same beam-like particles (BLP), it is difficult to 23 effectively distinguish between these two reaction mecha24 nisms from an inclusive measurement. To address this, var25 ious experimental techniques have been developed over the 26 years, including α decay measurements of target-like parti27 cles (TLP) [13, 15, 17], coincidence of BLP-γ [12, 16, 18–28 25], and BLP-fission fragment (FF) [26–28]. Compared to the 29 coincidence measurements with α-decay or γ, which suffer

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of the target-like nucleus 239 Np with excitation energy was 124 at 57 ∘ and 96 ∘ respectively, based on the folding angle disdetermined from the emitting BLP 6 He originating from 1p 125 tribution. The forward-angle PPAC detector (PPACF) was 71 stripping, and the fission barrier height of Np was ex- 126 placed at a distance of 187 mm from the target center, while 72 tracted. The design of the hybrid detector array is described in 127 the backward-angle one (PPACB) was placed at a distance of 73 Section II. Section III presents the offline test results. Section 128 152 mm. The covered polar angle θ ranges from 20.2 74 IV discusses the in beam test results followed by the summary 129 96.2

and from 52.5 to 140.2 , respectively. The total solid 130 angle covered by the two PPAC detectors (ΩPPAC) amounts 75 in Section V. 131 to 0.85π.

Four PIN silicon detectors were placed at fixed forward 133 angles of $±$15 and $±$20 ∘ relative to the beam direction as II. THE HYBRID DETECTOR ARRAY 134 monitors. They were used to monitor the beam direction and The detector array is illustrated in Fig. 1 [Figure 1: see original paper], where the arrow 135 spot size, as well as to normalize reaction cross sections via 136 Rutherford scattering. 78 indicates the beam direction. Four ΔE-E silicon strip de69

tector telescopes Si0−3 were placed at backward angles of 112 ∘ and 155 ∘ relative to the beam direction to identify the 81 beam-like particles. Each telescope consists of three layers 82 of 50 × 50 mm silicon detectors: the first layer is a single83 sided silicon strip detector (SSSD) with a nominal thickness 84 of 20 µm, the second layer is an SSSD with a thickness of 85 300 µm, and the third layer is a quadrant silicon detector 86 (QSD) with a thickness of 1000 µm. Each SSSD is segmented 87 into 16 strips with the strip orientations of the first two layers 88 perpendicular to each other, forming 256 pixels with areas of 89 3.0 × 3.0 mm . All the SSSDs and QSDs were manufactured 90 by the Micron Semiconductor Ltd [45]. The first and second 91 layers are used to detect heavier particles such as Li and He 92 isotopes, while the second and third layers are used to detect 93 lighter particles like p, d and t.

The distances from the target to the detectors are 162.7 mm 95 for Si0,1 and 167.5 mm for Si2,3 , with an angular coverage of 96 $±0.55*perpixel.Thetotalsolidanglecoveredbythefour97silic* A 0.5 µm thick Mylar 98 film was installed in front of each silicon telescope to mini99 mize the influence of low-energy electrons on the first layer 100 silicon detectors during online experiments. All silicon detecmainly consisting of four ΔE-E silicon strip detector telescopes and 101 tors were coupled with self-made integrated charge-sensitive two PPAC detectors. The long arrow indicates the beam direction. 102 preamplifiers [46] in vacuum, working in a cooled condition 103 to optimize the energy resolution and ensure performance sta104 bility. These preamplifiers have been applied in several exper105 iments and exhibit excellent and stable performance [10, 47-III. OFFLINE TESTS 106 50].

Two PPACs, each with an active area of 296 × 200 mm2 , Good energy and position resolutions are essential for kine108 were employed to detect the fission fragments. Both the en- 138 109 trance and exit windows are 2.0-µm-thick Mylar film. Both 139 matic measurements, which are crucial for characterizing the 110 PPACs adopt a conventional three-electrode structure, con- 140 reaction processes of weakly-bound nuclei. Therefore, offline 111 sisting of an X anode, a cathode, and a Y anode. The distance 141 performance tests were conducted using a three-component α Cf fission source for 112 from the anode plane to the cathode plane is 3.0 mm. The 142 source for the silicon detectors and a detectors, order obtain their performance and 113 anode wires are 20-µm-diameter gold-plated tungsten wires determine optimal operating conditions. 114 with a spacing of 1.0 mm between every two wires and cou115 pled to delay lines. Two adjacent wires in the X direction 116 were read out together as one channel, while three adjacent A. Silicon detector performance with a three-component α 117 wires in the Y direction were read out together as one. There-145 source 118 fore, each PPAC has 146 position information in X direction 119 and 66 position information in Y direction. More detailed 120 description of the PPAC can be found in [51]. The electron- 147 The three-component α source consists of 239 Pu, 241 Am 121 ics system was used to acquire TDC time signals and ADC 148 and Cm. The 20-µm thick silicon layer is too thin for com122 energy signals.

To maximize the detection efficiency with 149 plete energy deposition of these αs, and the α particles will 123 appropriate counting rates, the two PPACs were positioned 150 hit the 300-µm layer. A typical E1 -E2 energy spectrum of α

particles detected in a pixel of Si0 is shown in Fig. 2 Figure 2: see original paper. The 166 of 4.5 Torr and a high voltage of −550 V for both PPACs. large variation in the energy loss observed in the first silicon 167 A typical result obtained for 252 Cf fission fragments under 153 layer is mainly attributed to the thickness non-uniformity of 168 these conditions is shown in Fig. 3 [Figure 3: see original paper]. Panels (a) and (b) show 154 the thin silicon detector. The total energy E1 +E2 spectrum 169 the typical position resolution spectra of PPACB in the X 155 is shown in Fig. 2(b). The three separate groups correspond 170 and Y directions, respectively. The position calibration was 156 to the three components. A Gaussian fit to the peak of 5.486 171 obtained from the linear proportional relationship between 157 MeV α particles emitted from Am yields an energy reso- 172 the time signal difference and the geometric position. From 158 lution of 1.2% for the total energy E1 +E2 , as shown by the 173 Gaussian fits to the position peaks, the average FWHM of 174 the detector in the X and Y direction are 0.94 ± 0.03 mm and 159 solid line. 175 2.21\$±\$0.08 mm, respectively. It can be seen that good position 176 resolution was achieved from both the X and Y directions.

(MeV)

Counts

X (mm)

E (MeV)

Counts

Counts

Y (mm)

source. (a) Position spectrum in the X direction. (b) Position spectrum in the Y direction.

FWHM =

67(2) KeV

E +E (MeV)

IV. IN BEAM TEST tector telescope tested with a three-component α source. (a) E1 -E2 spectrum of the α particles from the decay of the three-component The experiment was conducted at the HI-13 tandem accelα source. (b) Total energy E1 +E2 spectrum. The Gaussian fitting 178 (solid line) for the middle group gives an energy resolution of 1.2% 179 erator of the China Institute of Atomic Energy. The 238 U for the 5.486 MeV α peak. 180 target was selected considering the high fissility of its target-

like particles after transfer reactions. The 238 U target with a 182 thickness of 370 µg/cm was sandwiched between a 33 nm 183 aluminum foil and a 50 µg/cm carbon backing. The target 184 was fixed at the center of the hybrid detector array with a B. PPAC position resolution with a 252 Cf source 185 normal angle of 30 relative to the beam direction, in order to 186 minimize the energy loss of fission fragments in the target and The position resolution of the PPAC detector mainly de- 187 the dead area caused by the target frame. The reaction energy U is Elab = 36.8 MeV. The irradiation time was 162 pends on the nature of the incident ions, the working gas, 188 for Li + 163 and the applied high voltage.

Isobutane gas with a purity 189 20 hours with a beam intensity of 10 enA. The low-energy Br + 238 U elastic scattering was selected to calibrate the 164 of 99.99% was used as the working gas of PPAC detectors. 190 165 The optimal operating conditions were achieved at a pressure 191 geometrical alignment of the two PPACs.

Calibration of the PPACs by using 79 Br + 238 U elastic scattering

Elastic scattering of 79 Br + 238 U at a beam energy 170 195 MeV was used to calibrate the geometry of the two PPACs. 196 The obtained folding angle distribution of the Br + 238 U 197 elastic scattering is shown in Fig. 4 [Figure 4: see original paper]. The red solid line repre198 sents the scattered beam component, while the green dashed 199 line represents the recoiled target nucleus component. The 200 good agreement of the experimental data with the kinematic 201 calculations confirms the good position calibration and instal202 lation geometry.

E = 36.8 MeV

E (MeV)

(degree)

E +E (MeV)

E (MeV)

= 155°

(degree)

E (MeV)

U elastic scattering at 170 MeV. The X-axis shows the θ coverage angle of the PPACs, and the Y -axis shows the folding angle of the two simultaneously emitted fragments. The lines represent kinematic calculations, where the red solid line corresponds to the scattered beam component (Sc), and the green dashed line corresponds to the recoiled target nucleus component (Rc).

charged particles in 7 Li + 238 U at Elab = 36.8 MeV and θlab = 155 ∘ . (a) Identification of the heavier particles using the first and second layers. (b) Identification of the lighter particles using the second and third layers.

He-gated fission fragment folding angle distribution

The 6 He exit channel in the 7 Li + 238 U system was firstly 221 selected to test the performance of the detector array consid203 B. Identification of beam-like particles 222 ering its following advantages: 1) For measurement, the en7 223 ergy loss of scattered Li particles in PPAC is small, which A typical inclusive ΔE-E particle identification spectrum 224 reduces the counting rate of PPAC especially in the angular 205 measured by the silicon strip detector telescope Si0 in Li + 225 region with small θ relative to the beam direction and hence U at Elab = 36.8 MeV and θlab = 155 is shown in Fig. 5 [Figure 5: see original paper]. 226 reduces the dead time for data acquisition. 2) For the emitting 207 In Fig. 5(a), E1 is the energy loss in the first layer, and E1 +E2 227 channel, the origin of He from 1p stripping should be dom208 is the sum of the energy loss in the first layer and the resid- 228 inant compared to the breakup mechanism due to the large Li. 3) For 6 He, 209 ual energy deposited in the second layer. He and Li isotopes 229 proton separation energy of 9.97 MeV for 210 are well identified in this spectrum. The band correspond- 230 it has no bound excitation states, thus avoiding the ambiguity 211 ing to He is prominent, and these particles are completely 231 associated with excitation energy partition in the exit channel. 212 stopped in the second layer. Specifically, the observation of 232 He indicates the occurrence of the 1p-stripping process in 233 complementary fission fragments obtained from the cathodes 214 the Li-induced reaction. In Fig. 5(b), E2 is the energy loss 234 of the two PPACs in 7 Li + 238 U at Elab = 36.8 MeV, where 215 in the second layer, and E3 is the residual energy deposited in 235 EF and EB correspond to the energy signals obtained from 216 the third layer. In this spectrum, the hydrogen isotopes p, d, 236 PPACF and PPACB , respectively. It can be observed that the 217 and t are well identified. The d and t particles are completely 237 heavy fragments produced in the reaction are mainly concen238 trated in the channel range of 1000-3000. Consequently, the 218 stopped in the third layer.

E (Channel)

considering that the measured 6 He particles emitted in the 266 backward angular region will transfer larger linear momen267 tum to the target nucleus compared to situation in CF events.

He-gated

Counts

E (Channel)

complementary fission fragments measured by PPACF and PPACB in 7 Li + 238 U at Elab = 36.8 MeV. The red dashed contour indicates the selected fission events used for further analysis.

(degree)

triangles) obtained in 7 Li + 238 U at Elab = 36.8 MeV. The doubleGaussian fitting curve is for the total fission, where the higher peak corresponds the CF components in accordance with the arrow position calculated by assuming Viola kinematics [52], and the lower peak corresponds to the non-complete momentum transfer components. The solid line is the summed one. The fitting for 6 Hecoincident one is shown as the dash-dotted line.

clean fission events selected for subsequent analysis are enclosed within the red contour.

The folding angle distribution is a sensitive probe to se242 lect the non-complete momentum transfer events. The fold243 ing angle distribution for all events in which both fission frag7 244 ments were detected by PPACF and PPACB in Li + 245 Elab = 36.8 MeV is shown in Fig. 7 [Figure 7: see original paper] as solid circles. These 246 events correspond to the total fission (TF) yield, including 247 both complete-fusion fission and fission following direct re268 D. Fission probability of 239 Np as a function of excitation 248 actions. It shows an obvious deviation from a Gaussian shape. energy obtained from the 238 U(7 Li,6 He)239 Np reaction 249 A double-Gaussian fitting, shown as the solid line, was used channel 250 to roughly fit the shape. The main component concentrating 251 at 173 agrees with the Viola systematics [52] assuming The fission barrier height corresponds to the excitation en252 fission from the complete fusion (CF) with full-momentum 271 where the fission probability is half of the maximum of 253 transfer. In addition, a pronounced lower angle component 254 centered at 168 is observed, corresponding to the non- 273 the first-chance fission probability [53]. Experimentally, the 274 method based on the variation of the fission probability with 255 complete fusion events.

A total of 1790 triple coincidence events of 6 He particles 275 excitation energy has been widely used to obtain the fission 257 with both fission fragments detected by PPACF and PPACB 276 barrier height of a nuclide [41, 43, 44, 54]. 258 were obtained, yielding the folding angle distribution shown 277 In the present case, the measured 6 He particles can only 259 in Fig. 7 as the solid triangles. It can be seen that the peak 278 populate the ground state, so all the excitation energy in the 260 position of the He correlated fission fragments shows obvi- 279 exit channel is imparted to the TLP Np. By measuring the 261 ous deviation from the peak position of 173 . It is roughly 280 energy Eb and emission angle θ of He, the excitation energy Np can be unambiguously determined by applying the 262 reproduced by the single Gaussian fitting with a smaller peak 281 of 263 angle compared to the CF, shown as the dash-dotted line in 282 conservation laws of energy and momentum [54]:

Ea (Ma − MB) − Eb (Mb + MB) + 2 Ma Mb Elab Eb cos θ E = Qgg −

where a, b and B represent the beam, beam-like and target- 288 emitting particles. like particles, respectively. Mi represents the mass of each 289 The fission probability PFis , extracted from the double co286 nucleus involved in the reaction, Qgg is the Q-value of the 290 incidence between the BLP and either FF, is defined as the 287 transfer reaction populating the ground states for the two 291 ratio of the fission cross section σ Fis to the reaction cross

section σr for forming the compound nucleus in the specific transfer channel [44, 54]. For PPACi , the corresponding 294 quantity P Fis is given by

where NBLP is the count of the outgoing beam-like 6 He par297 ticles detected by the silicon strip detectors, corresponding 298 to TLP events; NBLP−FFi is the count obtained from coinci299 dence between BLP and any fission fragment detected by ei300 ther PPAC detector, corresponding to events where the TLPs 301 undergo fission; ϵi is the fission detection efficiency defined 302 as [41]

2ΩPPACi

NBLP−FFi (E ∗) NBLP (E ∗)ϵi (E ∗)

P /0.3 MeV

(E ∗) =

= 5.81(13) MeV

E (MeV)

The factor of 2 in the numerator is due to producing two fission fragments in a fission event. This is the so-called as a function of the excitation energy E ∗ for 239 Np by using the 306 geometrical efficiency.

This definition has been widely U(7 Li,6 He)239 Np at Elab = 36.8 MeV. The solid circles represent 307 used [41, 43, 44] and confirmed reliable within a deviation the experimental data, and the solid line is the fitting curve by using 308 of 10%-level recently for Am(3 He,t)243 Cm within an exEq. 4. 309 citation energy range of 5.5-15.0 MeV by comparing with a 310 Monte Carlo simulation result based on a high statistical meamax 311 surement of the fission fragment angular distribution [54]. In and BFis for 239 Np from 312 addition, corrections for both the intrinsic efficiency and the U(7 Li,6 He)239 Np reaction channel by using coincidence with random 313 random coincidence efficiency (P) were applied. The PPACF or PPACB . random 314 intrinsic efficiency was determined by comparing the number Method PFis 315 of backward fission fragments identified in coincidence with BLP-FFF 0.01 0.57(4) 5.81(13) 316 the forward PPAC within a confined angular region expected BLP-FFB 0.01 0.63(4)

5.82(12) 317 to be covered by the backward PPAC, and was found to be aprandom 318 proximately 99.6% in the present experiment. P 319 estimated from the correlation between elastically scattered 345 nuclei typically exhibit a complex double-humped fission bar7 Li particles and fission fragments, for which no real fission 346 rier structure, it is well known that the use of a single-humped 347 Hill-Wheeler approximation allows for a consistent deriva321 is expected, and was found to be approximately 0.01.

The experimentally extracted fission probability PFis ob- 348 tion of the barrier height corresponding to the higher one de323 tained from coincidence with PPACF as a function of excita- 349 termined by the double-humped fission barrier model [56]. 324 tion energy E for the target-like nucleus 239 Np is shown in 350 The Hill-Wheeler fitting formula is expressed as [57]: 325 Fig. 8 [Figure 8: see original paper] as solid circles, where the error bars represent only staP max 326 tistical uncertainties. The measurement covers a wide excita- 351 h Fis PFis (E $*$) = $-$E $*$) 327 tion energy range below 12.5 MeV, and the obtained P 1 + exp 2π(BFis Fis is 328 0.57(4), averaged over all pixels of the silicon detector telemax 329 scopes. The result obtained from coincidence with PPACB 352 where P Fis , BFis , and ω are adjustable parameters repremax 330 is similar, giving P Fis = 0.63(4). A significant discrepancy 353 senting the maximum fission probability for the first-chance 331 is observed between the present (P Fis) result and the litera- 354 fission, fission barrier height, and fission barrier curvature, 332 ture value reported by JAEA [44]. The lower value reported 355 respectively. 333 by JAEA is attributed to the strong horizontal tail of elasti- 356 Using Eq. 4, the fit was carried out over the sub-barrier and 334 cally scattered particles produced in the above-barrier O + 357 first-chance fission energy region. The fitting result, shown Np reaction, which strongly affects the extraction of the 358 by the green solid curve in Fig. 8, reproduces the rising part 336 fission probability in the excitation energy region near the fis- 359 of the fission probability curve well, and the extracted fission 337 sion barrier, as well as to the use of a relatively large 0.8 MeV 360 barrier heights BFis are listed in Table 1 . As shown in the 338 bin width, resulting from poor energy resolution. 361 table, the extracted values of P Fis and BFis are consistent For the fitting to the fission barrier, it should be pointed out 362 for different fission fragment emission angles. This provides 340 that due to the fact that the rising part of the fission probabil- 363 experimental evidence that the effect of angular anisotropy on 341 ity curve in Fig. 8 contains only a few data points, this limited 364 the extracted results is minor [54]. 342 energy resolution precludes the observation of any resonance 365 The comparison of the average value of the extracted fis239 343 (class-II) sub-barrier structures, which are sensitive to both 366 sion barrier height 5.82 ± 0.13 MeV for Np from this work 344 the inner and outer barrier heights [55]. Although actinide 367 with the literature data [42–44] is shown in Table 2 . It can be

U system at Elab = 36.8 MeV. Benefiting from the good

work in comparison with the literature data [42–44]. 385 for He, a good excitation energy resolution for the excitation Reaction BFis (MeV) Refs. 386 energy of Np was obtained. The folding angle distribu238

U(7 Li,6 He)239 Np 5.82 ± 0.13 This work Np(18 O,16 O)239 Np 5.86 ± 0.09 U(3 He, d)239 Np 5.85 ± 0.30 U(3 He, d)239 Np 5.70 ± 0.20

tion gives further support for incomplete momentum transfer in the beam-like 6 He emitting channel. Furthermore, the

389 BFis of

Np was extracted from the dependence of fission 390 probability on excitation energy. The result is in good agree391 ment with the available results. The reliability of extraction 392 of the fission barrier height based on nucleon transfer reac368 seen that the present experimental result is in good consis393 tions induced by light projectiles by using the present setup 369 tence with the available data [42–44], validating the feasibil394 has been validated. This opens up the possibility of supple370 ity of determining fission barrier heights via transfer-induced 395 menting experimental fission data for more short-lived and 371 fission using the present detector array. 396 highly radioactive actinide nuclides. On the other hand, the 397 quantitative extraction of breakup- or transfer-induced fission 398 in the α- and t- emitting channels by using the obtained data V. SUMMARY 399 is in progress.

In this work, a hybrid detector array for coincidence measurements of the direct reaction products and the fission AUTHOR CONTRIBUTIONS 375 fragments has been designed and fabricated. The combina376 tion of large-area silicon strip detectors and large-sensitiveAll authors contributed to the study conception and design. 377 area PPAC detectors provides a large solid-angle coverage of 401 378 0.95π for the detector array, significantly improving the coin- 402 Material preparation was performed by C.J. Lin, H.M. Jia, J. 379 cidence detection efficiency and hence enabling the extension 403 Feng, and Y.J. Qiu. Data analysis and the first draft of the 404 manuscript were prepared by S.X. Zhu.

All authors com380 to the reaction channels with smaller cross sections.

The present hybrid detector array has been applied to FF- 405 mented on previous versions of the manuscript and approved 382 BLP coincidence measurement for the weakly bound Li + 406 the final version.

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