

# Warsaw macro-micro model and random walk method for calculating the fusion probability of superheavy elements

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# Superheavy elements

- Only man-made
- $Z > 103$  (transactinides)
- Produced in nuclear reactions:
  - Cold fusion
  - Hot fusion

IUPAC Periodic Table of the Elements

<div><div>1</div><div>1</div><div>H</div><div>hydrogen</div><div>1.0080</div><div>± 0.0002</div></div>												<div><div>2</div><div>2</div><div>He</div><div>helium</div><div>4.0026</div><div>± 0.0001</div></div>											
<div><div>3</div><div>3</div><div>Li</div><div>lithium</div><div>6.94</div><div>± 0.06</div></div>												<div><div>4</div><div>4</div><div>Be</div><div>beryllium</div><div>9.0122</div><div>± 0.0001</div></div>											
<div><div>11</div><div>11</div><div>Na</div><div>sodium</div><div>22.990</div><div>± 0.001</div></div>												<div><div>12</div><div>12</div><div>Mg</div><div>magnesium</div><div>24.305</div><div>± 0.002</div></div>											
<div><div>19</div><div>19</div><div>K</div><div>potassium</div><div>39.098</div><div>± 0.001</div></div>												<div><div>20</div><div>20</div><div>Ca</div><div>calcium</div><div>40.078</div><div>± 0.004</div></div>											
<div><div>37</div><div>37</div><div>Rb</div><div>rubidium</div><div>85.468</div><div>± 0.001</div></div>												<div><div>38</div><div>38</div><div>Sr</div><div>strontium</div><div>87.62</div><div>± 0.01</div></div>											
<div><div>55</div><div>55</div><div>Cs</div><div>caesium</div><div>132.91</div><div>± 0.01</div></div>												<div><div>56</div><div>56</div><div>Ba</div><div>barium</div><div>137.33</div><div>± 0.01</div></div>											
<div><div>87</div><div>87</div><div>Fr</div><div>francium</div><div>[223]</div></div>												<div><div>88</div><div>88</div><div>Ra</div><div>radium</div><div>[226]</div></div>											
<div><div>104</div><div>104</div><div>Rf</div><div>rutherfordium</div><div>[261]</div></div>												<div><div>105</div><div>105</div><div>Db</div><div>dubnium</div><div>[268]</div></div>											
<div><div>106</div><div>106</div><div>Sg</div><div>seaborgium</div><div>[269]</div></div>												<div><div>107</div><div>107</div><div>Bh</div><div>bohrium</div><div>[270]</div></div>											
<div><div>108</div><div>108</div><div>Hs</div><div>hassium</div><div>[277]</div></div>												<div><div>109</div><div>109</div><div>Mt</div><div>meitnerium</div><div>[277]</div></div>											
<div><div>110</div><div>110</div><div>Ds</div><div>darmstadtium</div><div>[281]</div></div>												<div><div>111</div><div>111</div><div>Rg</div><div>roentgenium</div><div>[282]</div></div>											
<div><div>112</div><div>112</div><div>Cn</div><div>copernicium</div><div>[285]</div></div>												<div><div>113</div><div>113</div><div>Nh</div><div>nihonium</div><div>[286]</div></div>											
<div><div>114</div><div>114</div><div>Fl</div><div>flerovium</div><div>[290]</div></div>												<div><div>115</div><div>115</div><div>Mc</div><div>moscovium</div><div>[290]</div></div>											
<div><div>116</div><div>116</div><div>Lv</div><div>livermorium</div><div>[293]</div></div>												<div><div>117</div><div>117</div><div>Ts</div><div>tennessine</div><div>[294]</div></div>											
<div><div>118</div><div>118</div><div>Og</div><div>oganesson</div><div>[294]</div></div>												<div><div>119</div><div>119</div><div>Uue</div><div>unbinilium</div><div>[295]</div></div>											
<div><div>120</div><div>120</div><div>Uuh</div><div>unbihunium</div><div>[296]</div></div>												<div><div>121</div><div>121</div><div>Uuq</div><div>unbibium</div><div>[297]</div></div>											
<div><div>122</div><div>122</div><div>Uub</div><div>unbibism</div><div>[298]</div></div>												<div><div>123</div><div>123</div><div>Uut</div><div>unbiunium</div><div>[299]</div></div>											
<div><div>124</div><div>124</div><div>Uuq</div><div>unbibism</div><div>[300]</div></div>												<div><div>125</div><div>125</div><div>Uup</div><div>unbihexium</div><div>[301]</div></div>											
<div><div>126</div><div>126</div><div>Uuh</div><div>unbihectium</div><div>[302]</div></div>												<div><div>127</div><div>127</div><div>Uus</div><div>unbioctium</div><div>[303]</div></div>											
<div><div>128</div><div>128</div><div>Uuo</div><div>unbiunium</div><div>[304]</div></div>												<div><div>129</div><div>129</div><div>Uuq</div><div>unbibism</div><div>[305]</div></div>											
<div><div>130</div><div>130</div><div>Uuh</div><div>unbihectium</div><div>[306]</div></div>												<div><div>131</div><div>131</div><div>Uus</div><div>unbioctium</div><div>[307]</div></div>											
<div><div>132</div><div>132</div><div>Uuo</div><div>unbiunium</div><div>[308]</div></div>												<div><div>133</div><div>133</div><div>Uuq</div><div>unbibism</div><div>[309]</div></div>											
<div><div>134</div><div>134</div><div>Uuh</div><div>unbihectium</div><div>[310]</div></div>												<div><div>135</div><div>135</div><div>Uus</div><div>unbioctium</div><div>[311]</div></div>											
<div><div>136</div><div>136</div><div>Uuo</div><div>unbiunium</div><div>[312]</div></div>												<div><div>137</div><div>137</div><div>Uuq</div><div>unbibism</div><div>[313]</div></div>											
<div><div>138</div><div>138</div><div>Uuh</div><div>unbihectium</div><div>[314]</div></div>												<div><div>139</div><div>139</div><div>Uus</div><div>unbioctium</div><div>[315]</div></div>											
<div><div>140</div><div>140</div><div>Uuo</div><div>unbiunium</div><div>[316]</div></div>												<div><div>141</div><div>141</div><div>Uuq</div><div>unbibism</div><div>[317]</div></div>											
<div><div>142</div><div>142</div><div>Uuh</div><div>unbihectium</div><div>[318]</div></div>												<div><div>143</div><div>143</div><div>Uus</div><div>unbioctium</div><div>[319]</div></div>											
<div><div>144</div><div>144</div><div>Uuo</div><div>unbiunium</div><div>[320]</div></div>												<div><div>145</div><div>145</div><div>Uuq</div><div>unbibism</div><div>[321]</div></div>											
<div><div>146</div><div>146</div><div>Uuh</div><div>unbihectium</div><div>[322]</div></div>												<div><div>147</div><div>147</div><div>Uus</div><div>unbioctium</div><div>[323]</div></div>											
<div><div>148</div><div>148</div><div>Uuo</div><div>unbiunium</div><div>[324]</div></div>												<div><div>149</div><div>149</div><div>Uuq</div><div>unbibism</div><div>[325]</div></div>											
<div><div>150</div><div>150</div><div>Uuh</div><div>unbihectium</div><div>[326]</div></div>												<div><div>151</div><div>151</div><div>Uus</div><div>unbioctium</div><div>[327]</div></div>											
<div><div>152</div><div>152</div><div>Uuo</div><div>unbiunium</div><div>[328]</div></div>												<div><div>153</div><div>153</div><div>Uuq</div><div>unbibism</div><div>[329]</div></div>											
<div><div>154</div><div>154</div><div>Uuh</div><div>unbihectium</div><div>[330]</div></div>												<div><div>155</div><div>155</div><div>Uus</div><div>unbioctium</div><div>[331]</div></div>											
<div><div>156</div><div>156</div><div>Uuo</div><div>unbiunium</div><div>[332]</div></div>												<div><div>157</div><div>157</div><div>Uuq</div><div>unbibism</div><div>[333]</div></div>											
<div><div>158</div><div>158</div><div>Uuh</div><div>unbihectium</div><div>[334]</div></div>												<div><div>159</div><div>159</div><div>Uus</div><div>unbioctium</div><div>[335]</div></div>											
<div><div>160</div><div>160</div><div>Uuo</div><div>unbiunium</div><div>[336]</div></div>												<div><div>161</div><div>161</div><div>Uuq</div><div>unbibism</div><div>[337]</div></div>											
<div><div>162</div><div>162</div><div>Uuh</div><div>unbihectium</div><div>[338]</div></div>												<div><div>163</div><div>163</div><div>Uus</div><div>unbioctium</div><div>[339]</div></div>											
<div><div>164</div><div>164</div><div>Uuo</div><div>unbiunium</div><div>[340]</div></div>												<div><div>165</div><div>165</div><div>Uuq</div><div>unbibism</div><div>[341]</div></div>											
<div><div>166</div><div>166</div><div>Uuh</div><div>unbihectium</div><div>[342]</div></div>												<div><div>167</div><div>167</div><div>Uus</div><div>unbioctium</div><div>[343]</div></div>											
<div><div>168</div><div>168</div><div>Uuo</div><div>unbiunium</div><div>[344]</div></div>												<div><div>169</div><div>169</div><div>Uuq</div><div>unbibism</div><div>[345]</div></div>											
<div><div>170</div><div>170</div><div>Uuh</div><div>unbihectium</div><div>[346]</div></div>												<div><div>171</div><div>171</div><div>Uus</div><div>unbioctium</div><div>[347]</div></div>											
<div><div>172</div><div>172</div><div>Uuo</div><div>unbiunium</div><div>[348]</div></div>												<div><div>173</div><div>173</div><div>Uuq</div><div>unbibism</div><div>[349]</div></div>											
<div><div>174</div><div>174</div><div>Uuh</div><div>unbihectium</div><div>[350]</div></div>												<div><div>175</div><div>175</div><div>Uus</div><div>unbioctium</div><div>[351]</div></div>											
<div><div>176</div><div>176</div><div>Uuo</div><div>unbiunium</div><div>[352]</div></div>												<div><div>177</div><div>177</div><div>Uuq</div><div>unbibism</div><div>[353]</div></div>											
<div><div>178</div><div>178</div><div>Uuh</div><div>unbihectium</div><div>[354]</div></div>												<div><div>179</div><div>179</div><div>Uus</div><div>unbioctium</div><div>[355]</div></div>											
<div><div>180</div><div>180</div><div>Uuo</div><div>unbiunium</div><div>[356]</div></div>												<div><div>181</div><div>181</div><div>Uuq</div><div>unbibism</div><div>[357]</div></div>											
<div><div>182</div><div>182</div><div>Uuh</div><div>unbihectium</div><div>[358]</div></div>												<div><div>183</div><div>183</div><div>Uus</div><div>unbioctium</div><div>[359]</div></div>											
<div><div>184</div><div>184</div><div>Uuo</div><div>unbiunium</div><div>[360]</div></div>												<div><div>185</div><div>185</div><div>Uuq</div><div>unbibism</div><div>[361]</div></div>											
<div><div>186</div><div>186</div><div>Uuh</div><div>unbihectium</div><div>[362]</div></div>												<div><div>187</div><div>187</div><div>Uus</div><div>unbioctium</div><div>[363]</div></div>											
<div><div>188</div><div>188</div><div>Uuo</div><div>unbiunium</div><div>[364]</div></div>												<div><div>189</div><div>189</div><div>Uuq</div><div>unbibism</div><div>[365]</div></div>											
<div><div>190</div><div>190</div><div>Uuh</div><div>unbihectium</div><div>[366]</div></div>												<div><div>191</div><div>191</div><div>Uus</div><div>unbioctium</div><div>[367]</div></div>											
<div><div>192</div><div>192</div><div>Uuo</div><div>unbiunium</div><div>[368]</div></div>												<div><div>193</div><div>193</div><div>Uuq</div><div>unbibism</div><div>[369]</div></div>											
<div><div>194</div><div>194</div><div>Uuh</div><div>unbihectium</div><div>[370]</div></div>												<div><div>195</div><div>195</div><div>Uus</div><div>unbioctium</div><div>[371]</div></div>											
<div><div>196</div><div>196</div><div>Uuo</div><div>unbiunium</div><div>[372]</div></div>												<div><div>197</div><div>197</div><div>Uuq</div><div>unbibism</div><div>[373]</div></div>											
<div><div>198</div><div>198</div><div>Uuh</div><div>unbihectium</div><div>[374]</div></div>												<div><div>199</div><div>199</div><div>Uus</div><div>unbioctium</div><div>[375]</div></div>											
<div><div>200</div><div>200</div><div>Uuo</div><div>unbiunium</div><div>[376]</div></div>												<div><div>201</div><div>201</div><div>Uuq</div><div>unbibism</div><div>[377]</div></div>											
<div><div>202</div><div>202</div><div>Uuh</div><div>unbihectium</div><div>[378]</div></div>												<div><div>203</div><div>203</div><div>Uus</div><div>unbioctium</div><div>[379]</div></div>											
<div><div>204</div><div>204</div><div>Uuo</div><div>unbiunium</div><div>[380]</div></div>												<div><div>205</div><div>205</div><div>Uuq</div><div>unbibism</div><div>[381]</div></div>											
<div><div>206</div><div>206</div><div>Uuh</div><div>unbihectium</div><div>[382]</div></div>												<div><div>207</div><div>207</div><div>Uus</div><div>unbioctium</div><div>[383]</div></div>											
<div><div>208</div><div>208</div><div>Uuo</div><div>unbiunium</div><div>[384]</div></div>												<div><div>209</div><div>209</div><div>Uuq</div><div>unbibism</div><div>[385]</div></div>											
<div><div>210</div><div>210</div><div>Uuh</div><div>unbihectium</div><div>[386]</div></div>												<div><div>211</div><div>211</div><div>Uus</div><div>unbioctium</div><div>[387]</div></div>											
<div><div>212</div><div>212</div><div>Uuo</div><div>unbiunium</div><div>[388]</div></div>												<div><div>213</div><div>213</div><div>Uuq</div><div>unbibism</div><div>[389]</div></div>											
<div><div>214</div><div>214</div><div>Uuh</div><div>unbihectium</div><div>[390]</div></div>												<div><div>215</div><div>215</div><div>Uus</div><div>unbioctium</div><div>[391]</div></div>											
<div><div>216</div><div>216</div><div>Uuo</div><div>unbiunium</div><div>[392]</div></div>												<div><div>217</div><div>217</div><div>Uuq</div><div>unbibism</div><div>[393]</div></div>											
<div><div>218</div><div>218</div><div>Uuh</div><div>unbihectium</div><div>[394]</div></div>												<div><div>219</div><div>219</div><div>Uus</div><div>unbioctium</div><div>[395]</div></div>											
<div><div>220</div><div>220</div><div>Uuo</div><div>unbiunium</div><div>[396]</div></div>												<div><div>221</div><div>221</div><div>Uuq</div><div>unbibism</div><div>[397]</div></div>											
<div><div>222</div><div>222</div><div>Uuh</div><div>unbihectium</div><div>[398]</div></div>												<div><div>223</div><div>223</div><div>Uus</div><div>unbioctium</div><div>[399]</div></div>											
<div><div>224</div><div>224</div><div>Uuo</div><div>unbiunium</div><div>[399]</div></div>												<div><div>225</div><div>225</div><div>Uuq</div><div>unbibism</div><div>[400]</div></div>											
<div><div>226</div><div>226</div><div>Uuh</div><div>unbihectium</div><div>[400]</div></div>												<div><div>227</div><div>227</div><div>Uus</div><div>unbioctium</div><div>[401]</div></div>											
<div><div>228</div><div>228</div><div>Uuo</div><div>unbiunium</div><div>[401]</div></div>												<div><div>229</div><div>229</div><div>Uuq</div><div>unbibism</div><div>[402]</div></div>											
<div><div>230</div><div>230</div><div>Uuh</div><div>unbihectium</div><div>[402]</div></div>												<div><div>231</div><div>231</div><div>Uus</div><div>unbioctium</div><div>[403]</div></div>											
<div><div>232</div><div>232</div><div>Uuo</div><div>unbiunium</div><div>[403]</div></div>												<div><div>233</div><div>233</div><div>Uuq</div><div>unbibism</div><div>[404]</div></div>											
<div><div>234</div><div>234</div><div>Uuh</div><div>unbihectium</div><div>[404]</div></div>												<div><div>235</div><div>235</div><div>Uus</div><div>unbioctium</div><div>[405]</div></div>											
<div><div>236</div><div>236</div><div>Uuo</div><div>unbiunium</div><div>[405]</div></div>												<div><div>237</div><div>237</div><div>Uuq</div><div>unbibism</div><div>[406]</div></div>											
<div><div>238</div><div>238</div><div>Uuh</div><div>unbihectium</div><div>[406]</div></div>												<div><div>239</div><div>239</div><div>Uus</div><div>unbioctium</div><div>[407]</div></div>											
<div><div>240</div><div>240</div><div>Uuo</div><div>unbiunium</div><div>[407]</div></div>												<div><div>241</div><div>241</div><div>Uuq</div><div>unbibism</div><div>[408]</div></div>											
<div><div>242</div><div>242</div><div>Uuh</div><div>unbihectium</div><div>[408]</div></div>												<div><div>243</div><div>243</div><div>Uus</div><div>unbioctium</div><div>[409]</div></div>											
<div><div>244</div><div>244</div><div>Uuo</div><div>unbiunium</div><div>[409]</div></div>												<div><div>245</div><div>245</div><div>Uuq</div><div>unbibism</div><div>[410]</div></div>											
<div><div>246</div><div>246</div><div>Uuh</div><div>unbihectium</div><div>[410]</div></div>												<div><div>247</div><div>247</div><div>Uus</div><div>unbioctium</div><div>[411]</div></div>											
<div><div>248</div><div>248</div><div>Uuo</div><div>unbiunium</div><div>[411]</div></div>												<div><div>249</div><div>249</div><div>Uuq</div><div>unbibism</div><div>[412]</div></div>											
<div><div>250</div><div>250</div><div>Uuh</div><div>unbihectium</div><div>[412]</div></div>												<div><div>251</div><div>251</div><div>Uus</div><div>unbioctium</div><div>[413]</div></div>											
<div><div>252</div><div>252</div><div>Uuo</div><div>unbiunium</div><div>[413]</div></div>												<div><div>253</div><div>253</div><div>Uuq</div><div>unbibism</div><div>[414]</div></div>											
<div><div>254</div><div>254</div><div>Uuh</div><div>unbihectium</div><div>[414]</div></div>												<div><div>255</div><div>255</div><div>Uus</div><div>unbioctium</div><div>[415]</div></div>											
<div><div>256</div><div>256</div><div>Uuo</div><div>unbiunium</div><div>[415]</div></div>												<div><div>257</div><div>257</div><div>Uuq</div><div>unbibism</div><div>[416]</div></div>											
<div><div>258</div><div>258</div><div>Uuh</div><div>unbihectium</div><div>[416]</div></div>												<div><div>259</div><div>259</div><div>Uus</div><div>unbioctium</div><div>[417]</div></div>											
<div><div>259</div><div>259</div><div>Uuo</div><div>unbiunium</div><div>[417]</div></div>												<div><div>260</div><div>260</div><div>Uuq</div><div>unbibism</div><div>[418]</div></div>											
<div><div>260</div><div>260</div><div>Uuh</div><div>unbihectium</div><div>[418]</div></div>												<div><div>261</div><div>261</div><div>Uus</div><div>unbioctium</div><div>[419]</div></div>											
<div><div>262</div><div>262</div><div>Uuo</div><div>unbiunium</div><div>[419]</div></div>												<div><div>263</div><div>263</div><div>Uuq</div><div>unbibism</div><div>[420]</div></div>											
<div><div>264</div><div>264</div><div>Uuh</div><div>unbihectium</div><div>[420]</div></div>												<div><div>265</div><div>265</div><div>Uus</div><div>unbioctium</div><div>[421]</div></div>											
<div><div>266</div><div>266</div><div>Uuo</div><div>unbiunium</div><div>[421]</div></div>												<div><div>267</div><div>267</div><div>Uuq</div><div>unbibism</div><div>[422]</div></div>											
<div><div>268</div><div>268</div><div>Uuh</div><div>unbihectium</div><div>[422]</div></div>												<div><div>269</div><div>269</div><div>Uus</div><div>unbioctium</div><div>[423]</div></div>											
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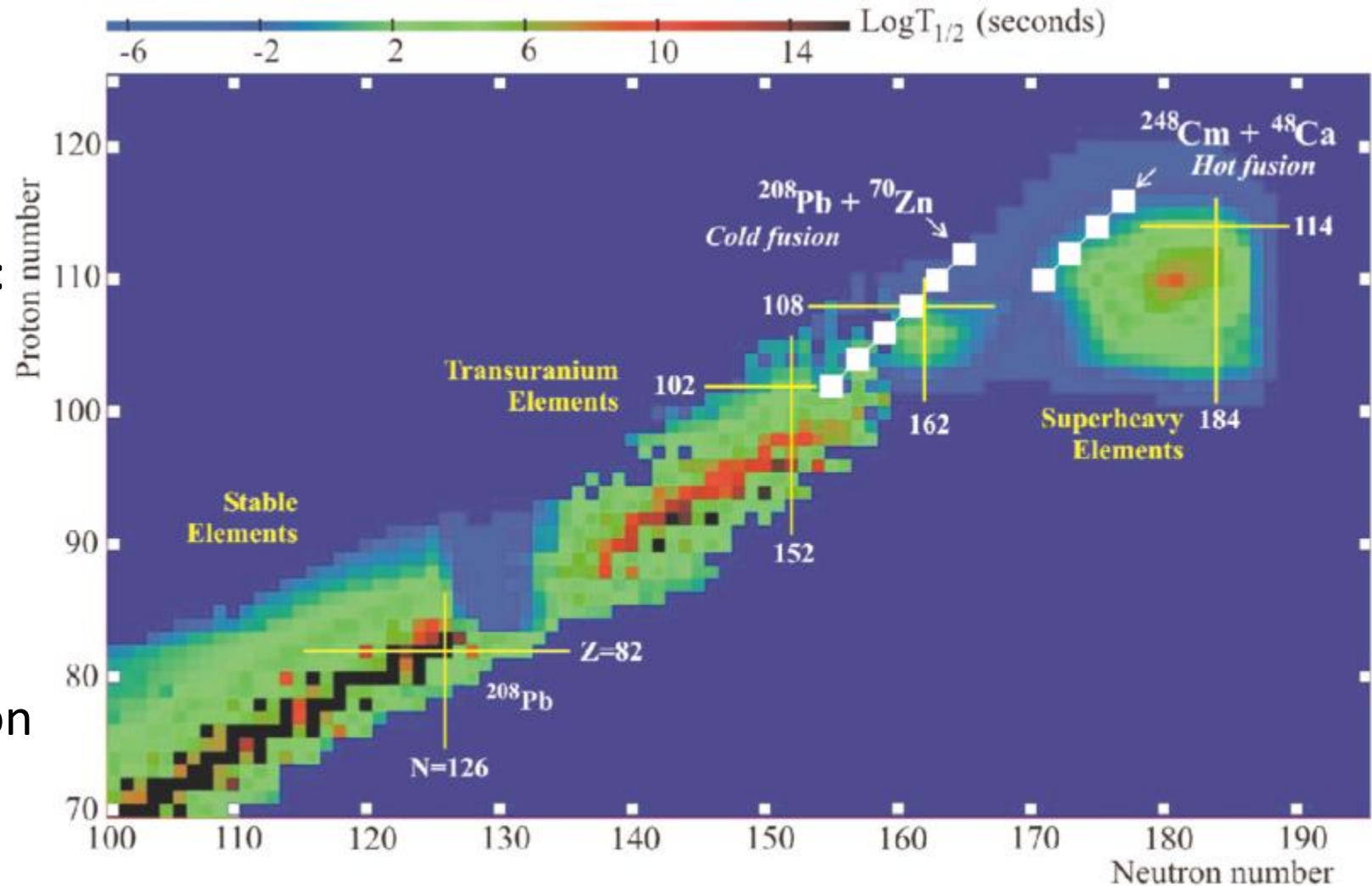
For notes and updates to this table, see [www.iupac.org](http://www.iupac.org). This version is dated 4 May 2022.  
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# Superheavy elements

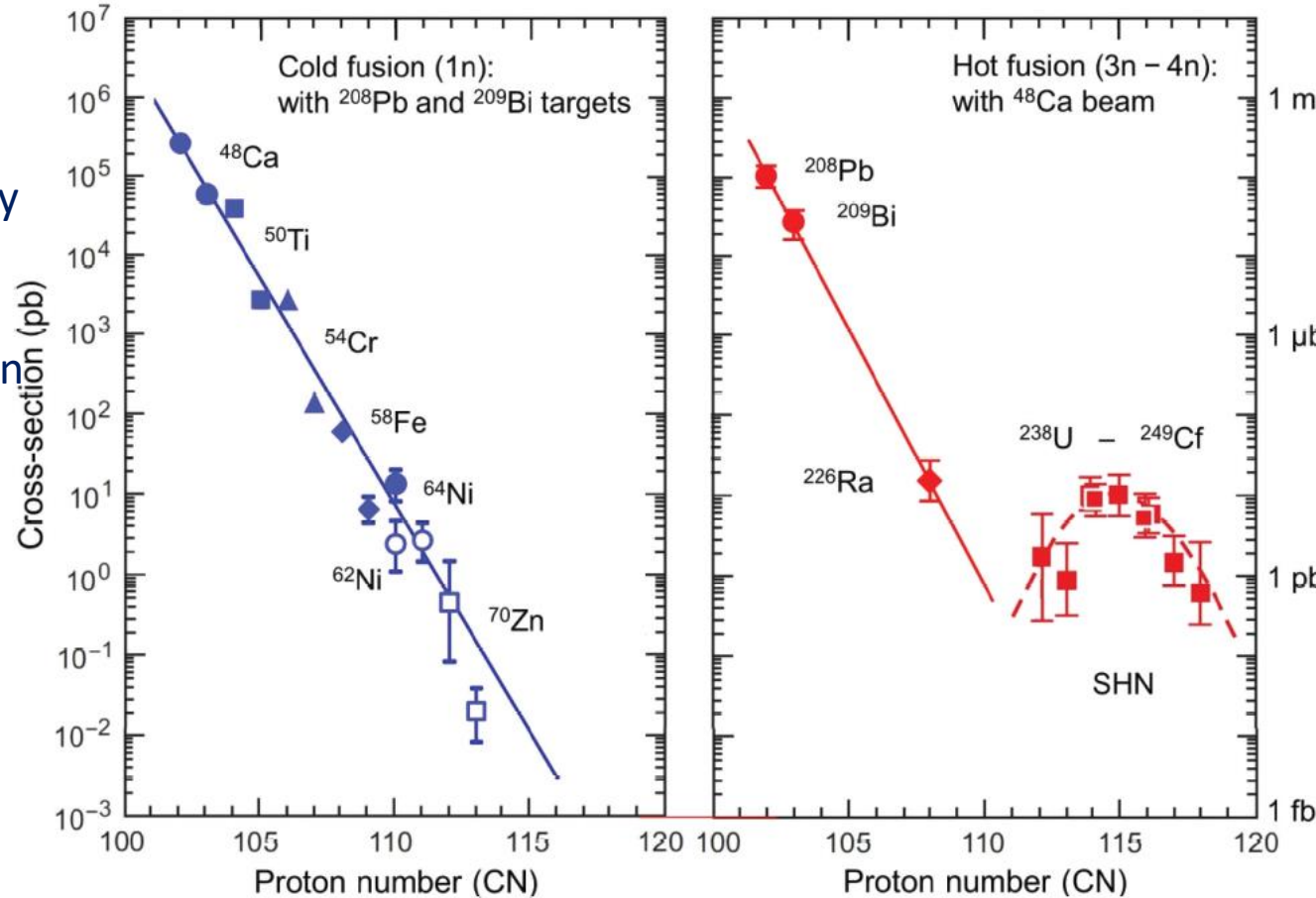
Oganessian, Yu. (2006). Synthesis and decay properties of superheavy elements. Pure and Applied Chemistry - PURE APPL CHEM. 78. 889-904. 10.1351/pac200678050889.

- Only man-made
- $Z > 103$  (transactinides)
- Produced in nuclear reactions:
  - Cold fusion
  - Hot fusion
- Expensive process:
  - Target/Projectile production
  - Length of irradiation



# Cold and hot fusion

- $E^* \approx 10\text{-}20$  MeV
- Compound system is only weakly heated and is cooled down via emission of just one or two neutrons
- Magic nuclei as targets (spherical shapes)
- Projectiles heavier than  $^{40}\text{Ar}$

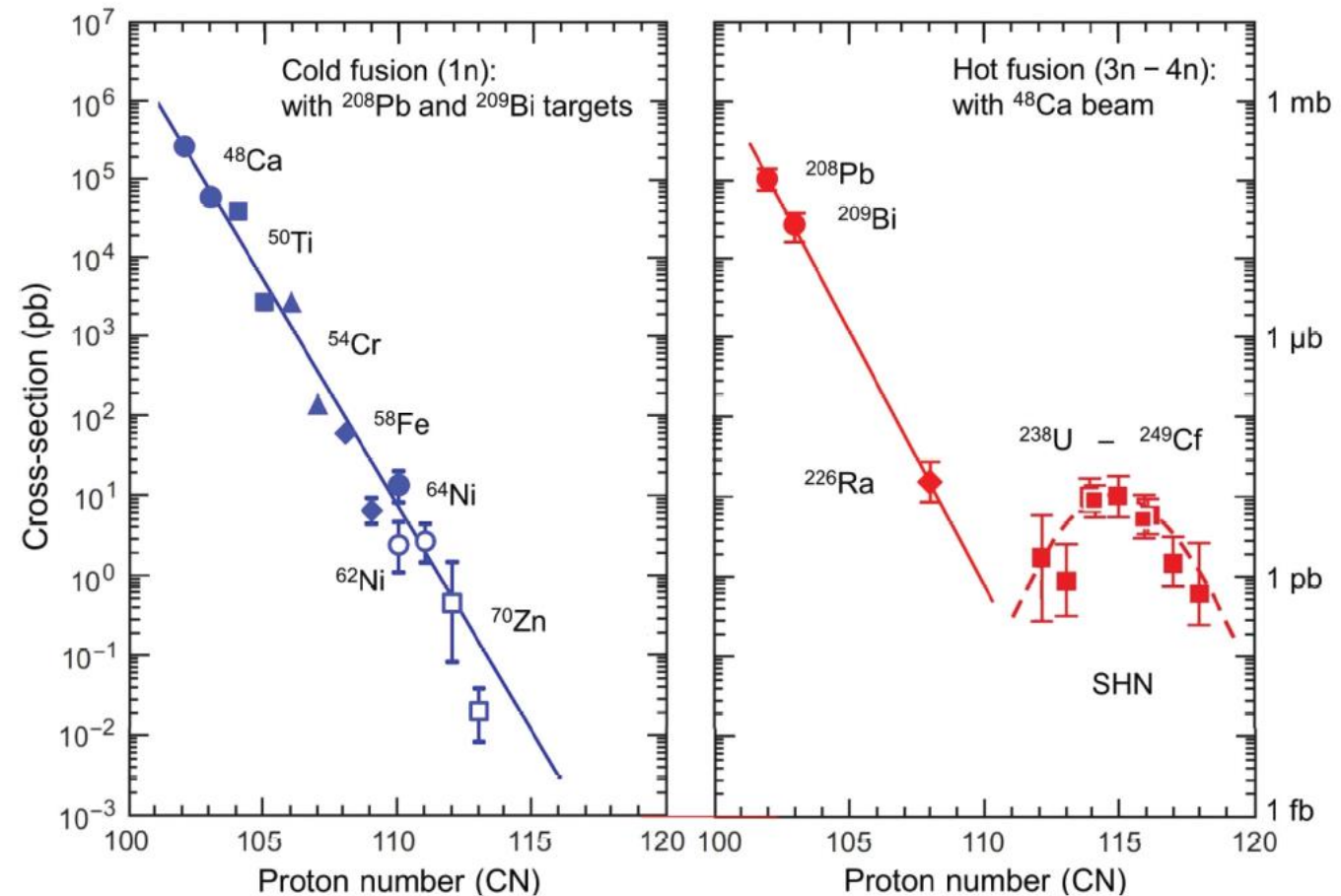


Sigurd Hofmann, Sergey N. Dmitriev, Claes Fahlander, Jacklyn M. Gates, James B. Roberto and Hideyuki Sakai  
Report of the 2017 Joint Working Group of IUPAC and IUPAP, Pure Appl. Chem. 2020; 92(9): 1387–1446

- $E^* = 30\text{-}40$  MeV
- Compound nucleus is quite excited (most often emits 3 neutrons)
- Well-deformed radioactive actinides (Act.) targets
- Doubly magic projectile  $^{48}\text{Ca}$
- Attempts of going beyond the reactions Act. +  $^{48}\text{Ca}$  by using heavier projectiles (like  $^{50}\text{Ti}$ ,  $^{54}\text{Cr}$ ,  $^{58}\text{Fe}$ ,  $^{64}\text{Ni}$ ) gave no results so far.
- Heavier actinides with  $Z > 98$  too short-lived to be used as targets

# Motivation

- Experiments require theory to determine the optimal reactions and bombarding energies
- A way to calculate  $P_{\text{fus}}$  would be very helpful in the search for the new elements 119 and 120
- We wanted to use the micro-macro model with the inclusion of rotational energy and a random walk method on potential energy surfaces (PES) to calculate the probability of fusion, while describing the fusion process
- The model is first tested on cold fusion reactions with near spherical projectiles:  $^{48}\text{Ca}+^{208}\text{Pb}$ ,  $^{50}\text{Ti}+^{208}\text{Pb}$  and  $^{54}\text{Cr}+^{208}\text{Pb}$

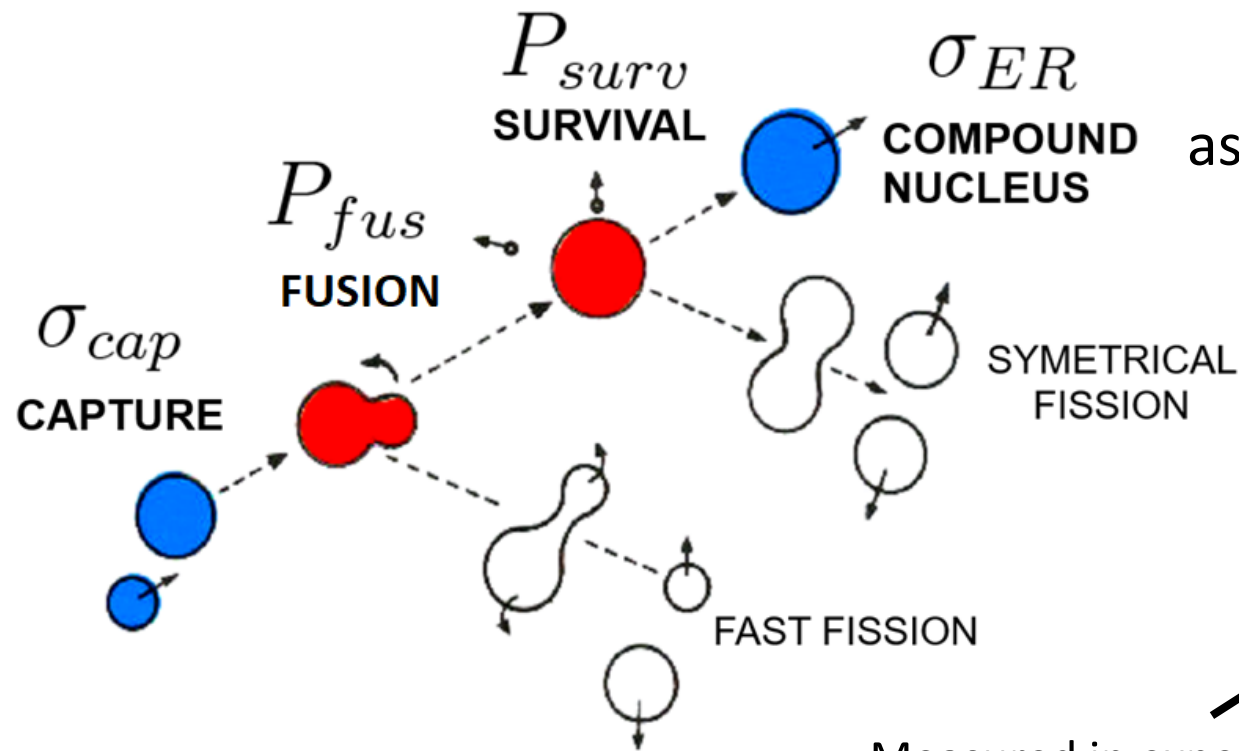


**Sigurd Hofmann, Sergey N. Dmitriev, Claes Fahlander, Jacklyn M. Gates, James B. Roberto and Hideyuki Sakai**  
Report of the 2017 Joint Working Group of IUPAC and IUPAP, Pure Appl. Chem. 2020; 92(9): 1387–1446



# FbD (Fusion-by-Diffusion) model

Synthesis of SHN can be described as a **3** step process, due to the different timescales of the particular reaction stages:



$$\sigma_{ER} = \sigma_{cap} P_{fus} P_{surv}$$

Not measured directly,  
difficult to calculate

Measured in experiments, can be  
calculated using various models

Well established theory  
and formulas  
Monte Carlo Statistical model

$$P_{surv} \ll 1$$

**Diffused barrier formula**  
(Entrance channel barrier is given  
by a Gaussian distribution)

**Smoluchowski**  
**Diffusion Equation,**  
**Random Walk**

**masses, fission barriers,**  
**deformations from Warsaw**  
**Micro-Macro model**

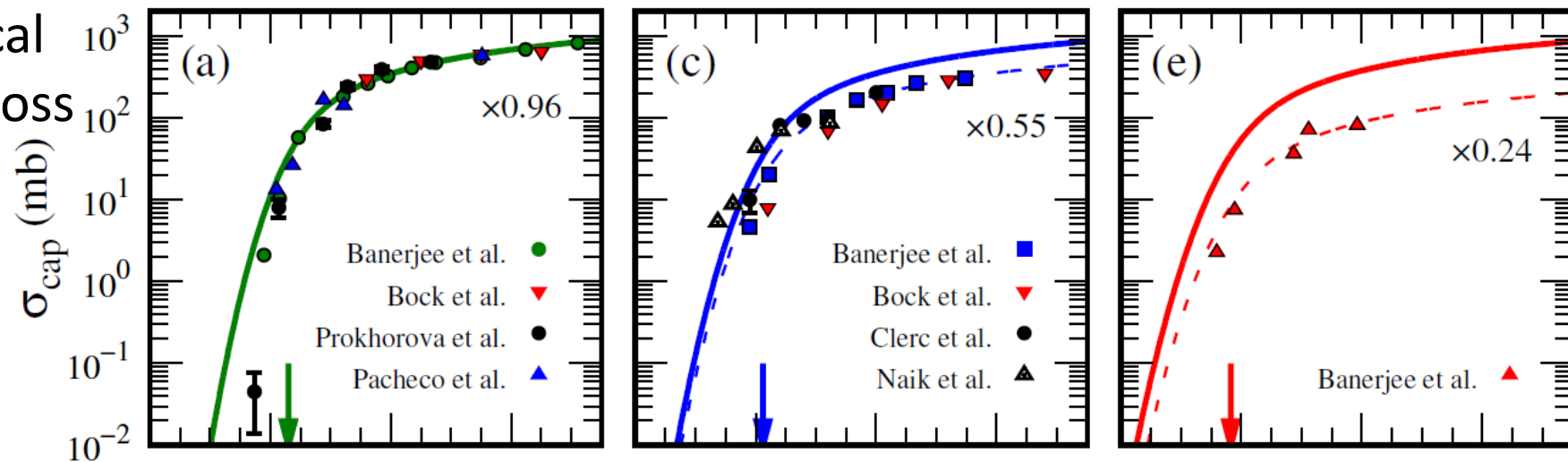
W. J. Świątecki, K. Siwek-Wilczyńska,  
J. Wilczyński, **PRC 2005**  
T. Cap et al., **PRC 2011**  
K. Siwek-Wilczyńska et al. **PRC 2012**  
T. Cap et al., **PRC 2013**  
K. Siwek-Wilczyńska et al. **PRC 2019**

# Capture cross section $\sigma_{cap}$

- The entrance channel barrier is described by a distribution that can be approximated by a Gaussian function
- The formula for the capture cross section is derived by folding the Gaussian barrier distribution with the classical expression for the fusion cross section

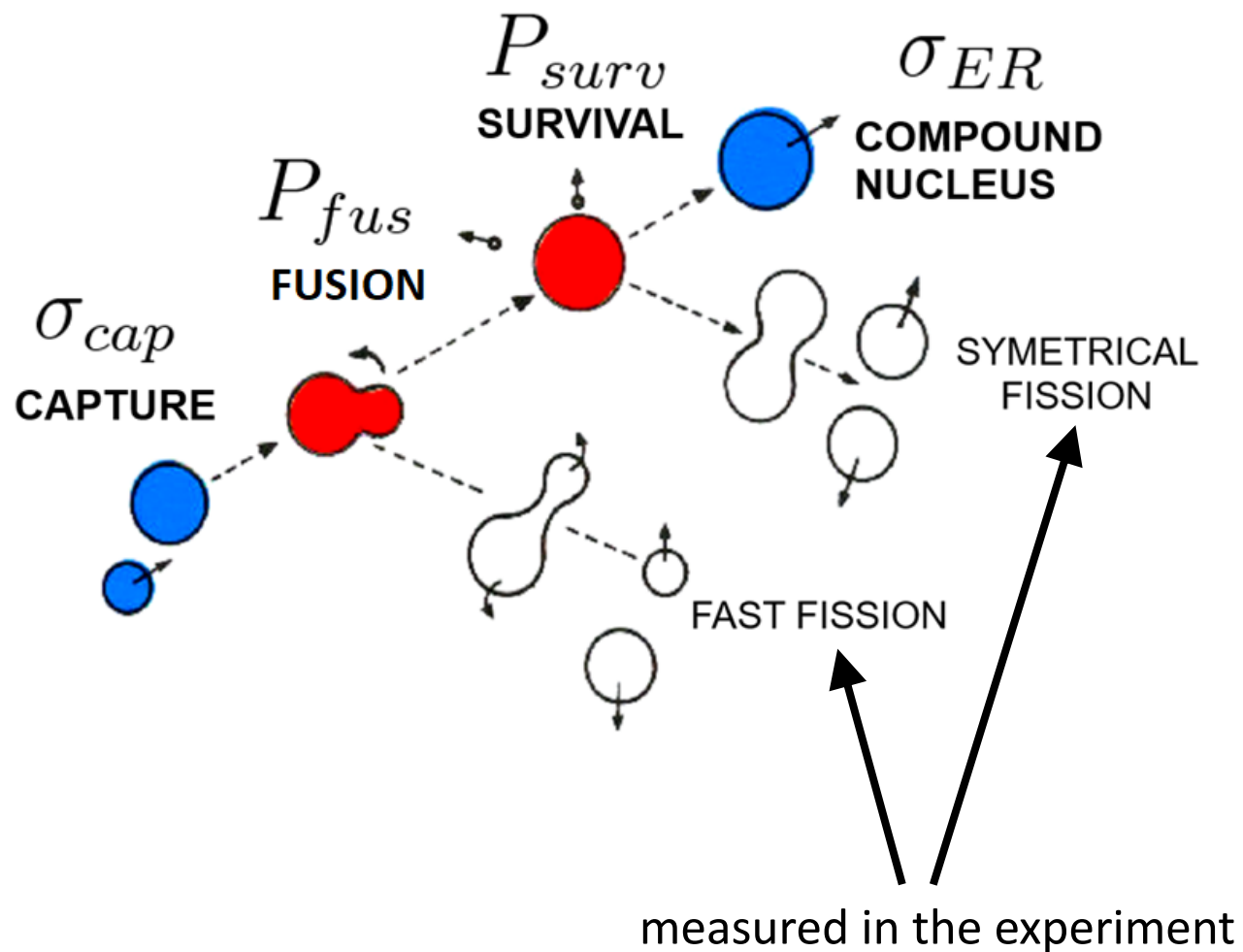
$$\sigma_{cap} = \pi R^2 \frac{\omega}{E_{c.m.} \sqrt{2\pi}} \left[ X \sqrt{\pi} (1 + \text{erf}(X)) + \exp(-X^2) \right] =$$

$$= \pi \lambda^2 (2l_{max} + 1)^2, \quad \text{where } X = \frac{E_{c.m.} - B_0}{\omega \sqrt{2}}$$



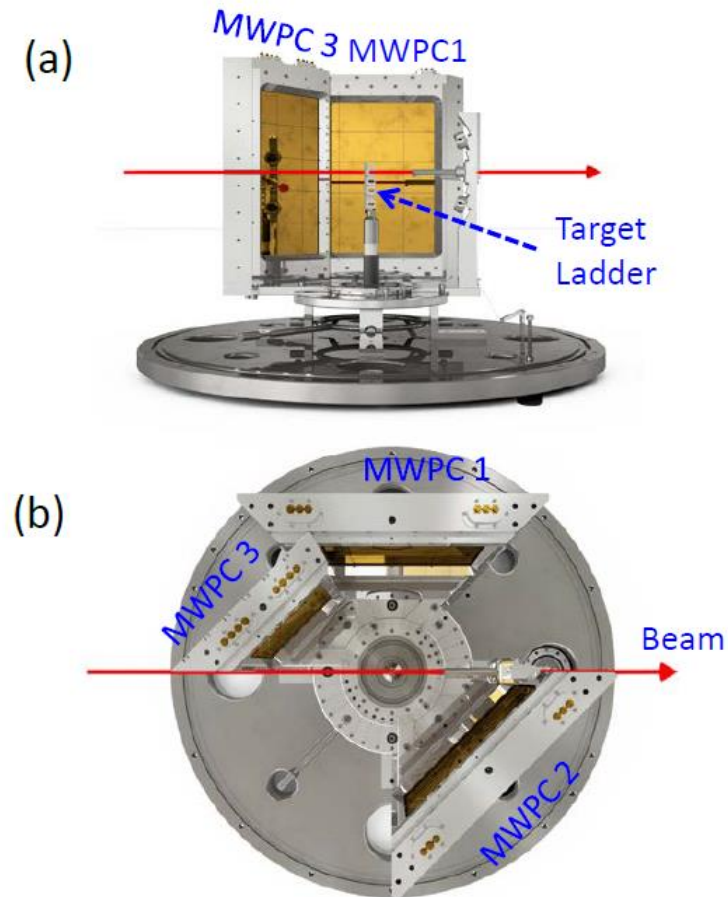
T. Cap, M. Kowal, and K. Siwek-Wilczyńska, Phys. Rev. C **105**, L051601 (2022)

# $P_{fus}$ in experiment



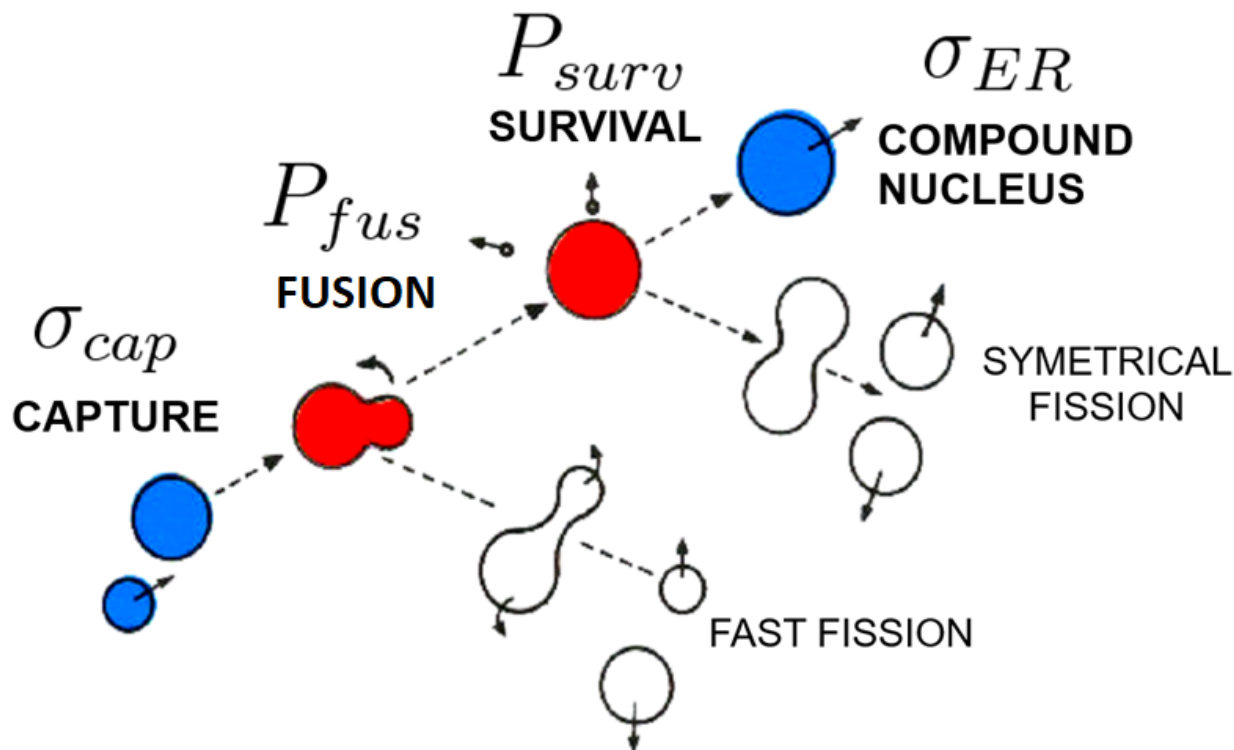
Mechanisms Suppressing Superheavy Element Yields in Cold Fusion Reactions

Banerjee *et al.*, PRL 122, 232503 (2019)





# $P_{fus}$ in experiment

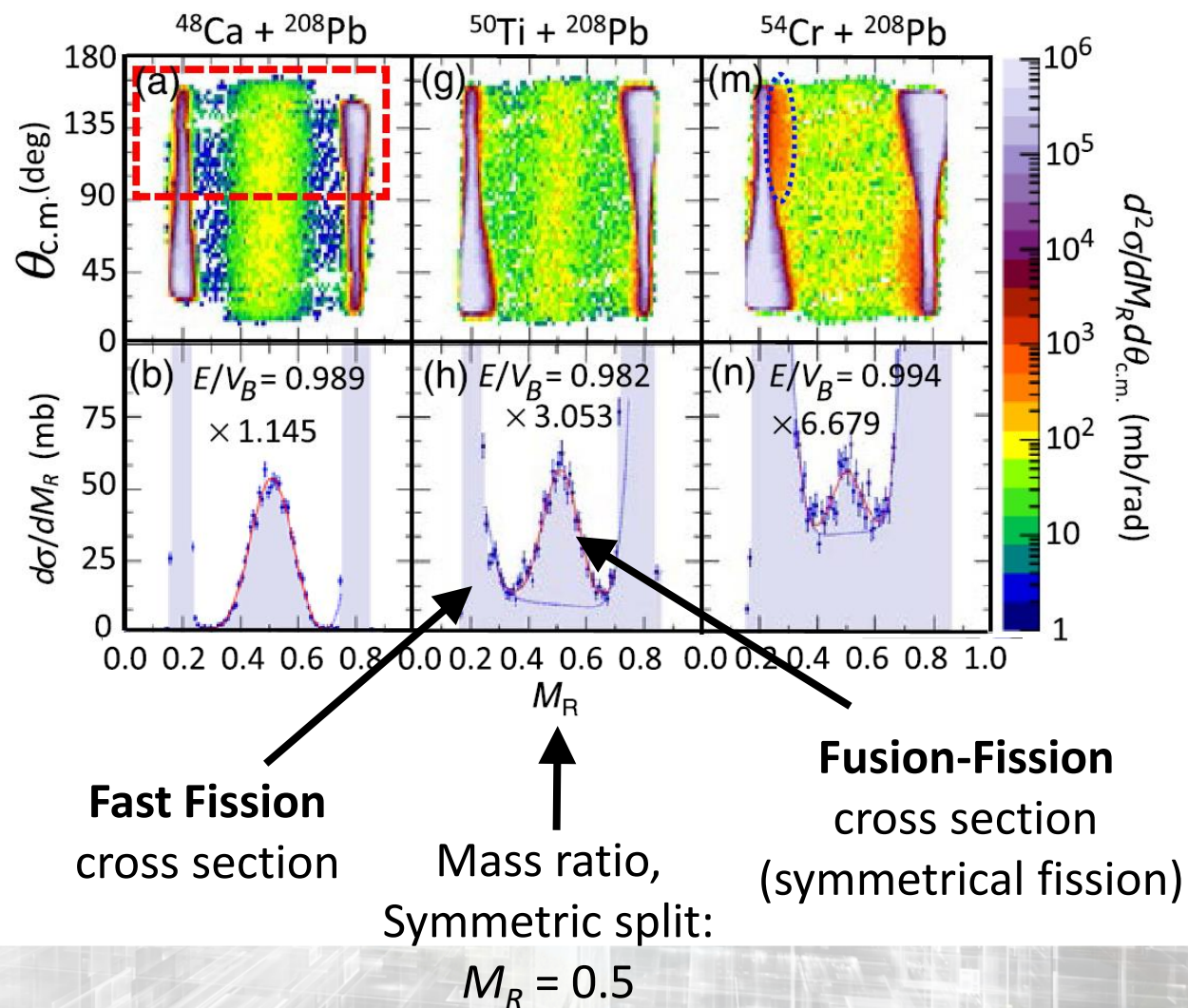


$P_{fus}$  can be experimentally estimated:

$$P_{sym} = \frac{\text{Fusion-Fission cross section}}{\text{Capture cross section}}$$

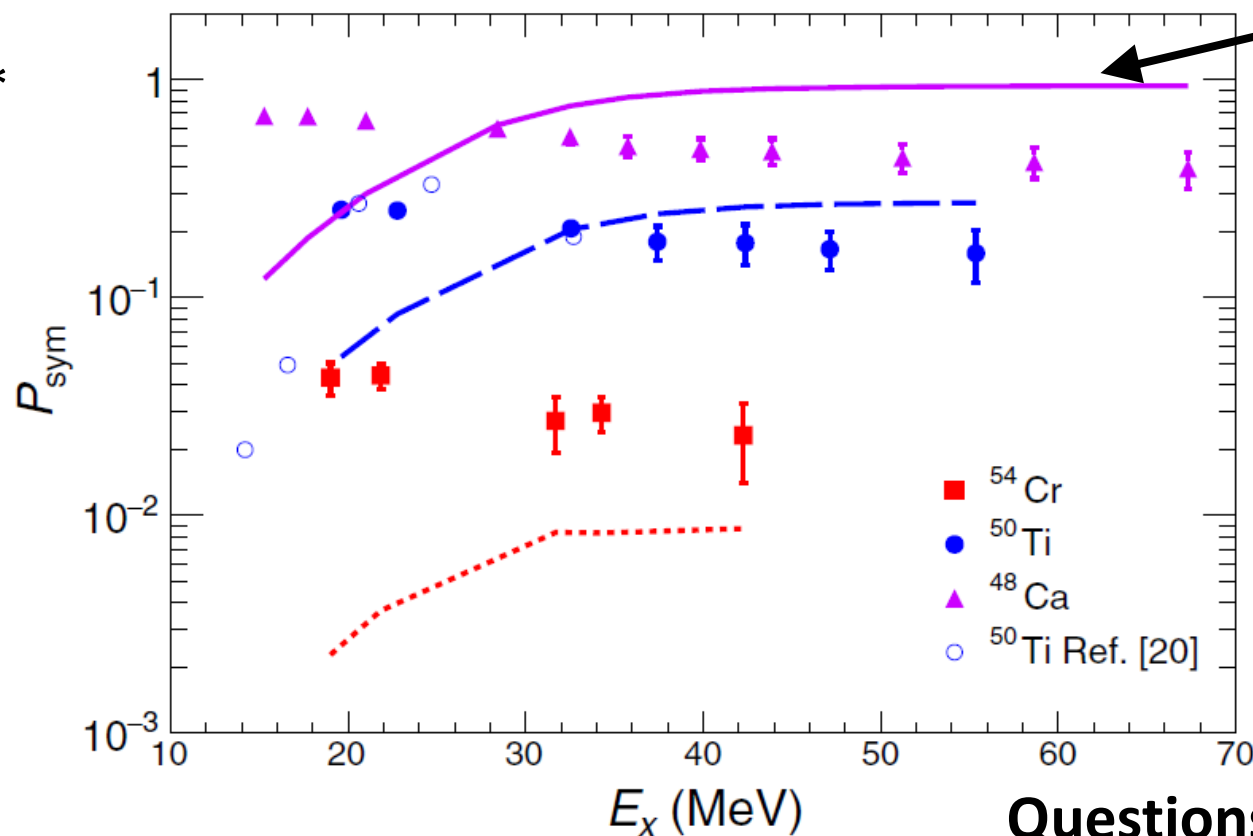
Mechanisms Suppressing Superheavy Element Yields in Cold Fusion Reactions

Banerjee *et al.*, PRL 122, 232503 (2019)



Banerjee et al., PRL 122, 232503 (2019)

Reactions:



Diffusion model calculations by V. Zagrebaev and W. Greiner PRC 78, 034610 (2008).

The experimental trends are different than the model predictions for all 3 reactions.

The conclusion was that diffusion is not the main mechanism responsible for the synthesis of SHN.

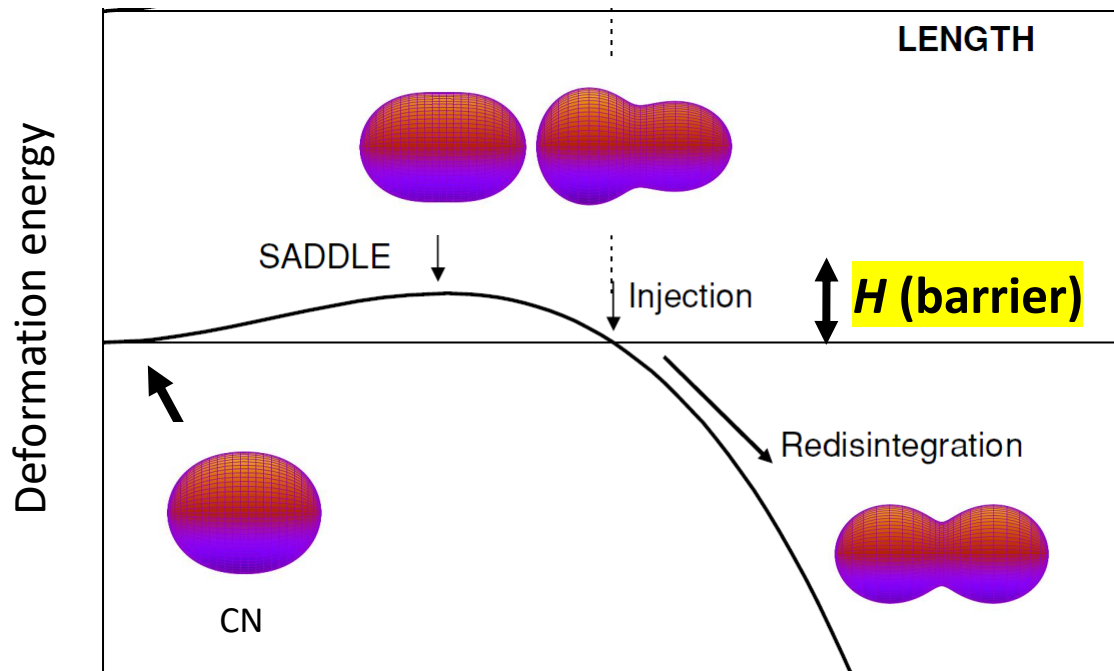
**Questions:**

**Can the diffusion approach (FbD) describe the experimental results?**  
**What is the fusion mechanism?**

# $P_{fus}$ in Fusion by Diffusion

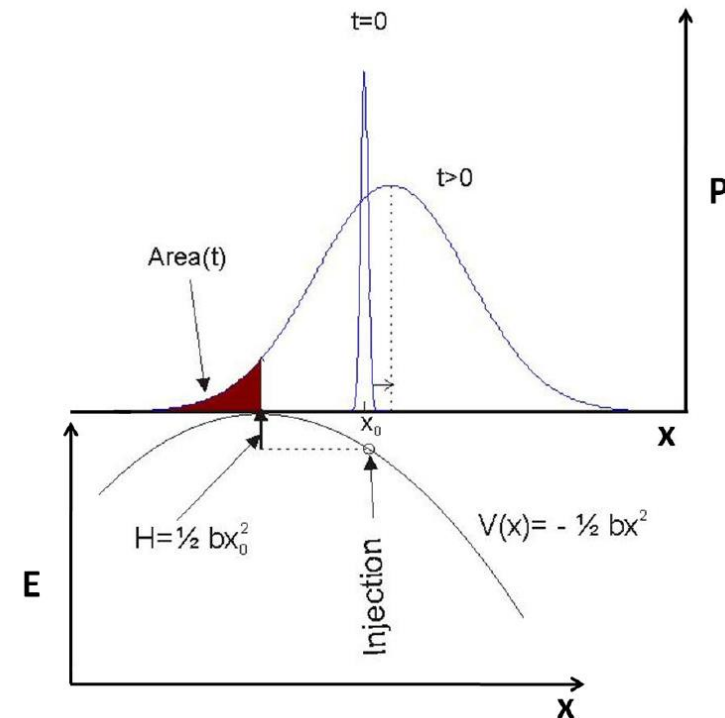
1D motion approximation

The system must overcome an internal barrier  $H$  to fuse.



$L$  is the effective elongation (along the fusion path)

$P_{fus}$  is calculated by solving  
1D Smoluchowski Diffusion Equation



$$P_{fus}(l) = \frac{1}{2} \left( 1 - \operatorname{erf} \left( \sqrt{\frac{H(l)}{T}} \right) \right) \text{ when } L_{inj} \geq L_{saddle}$$

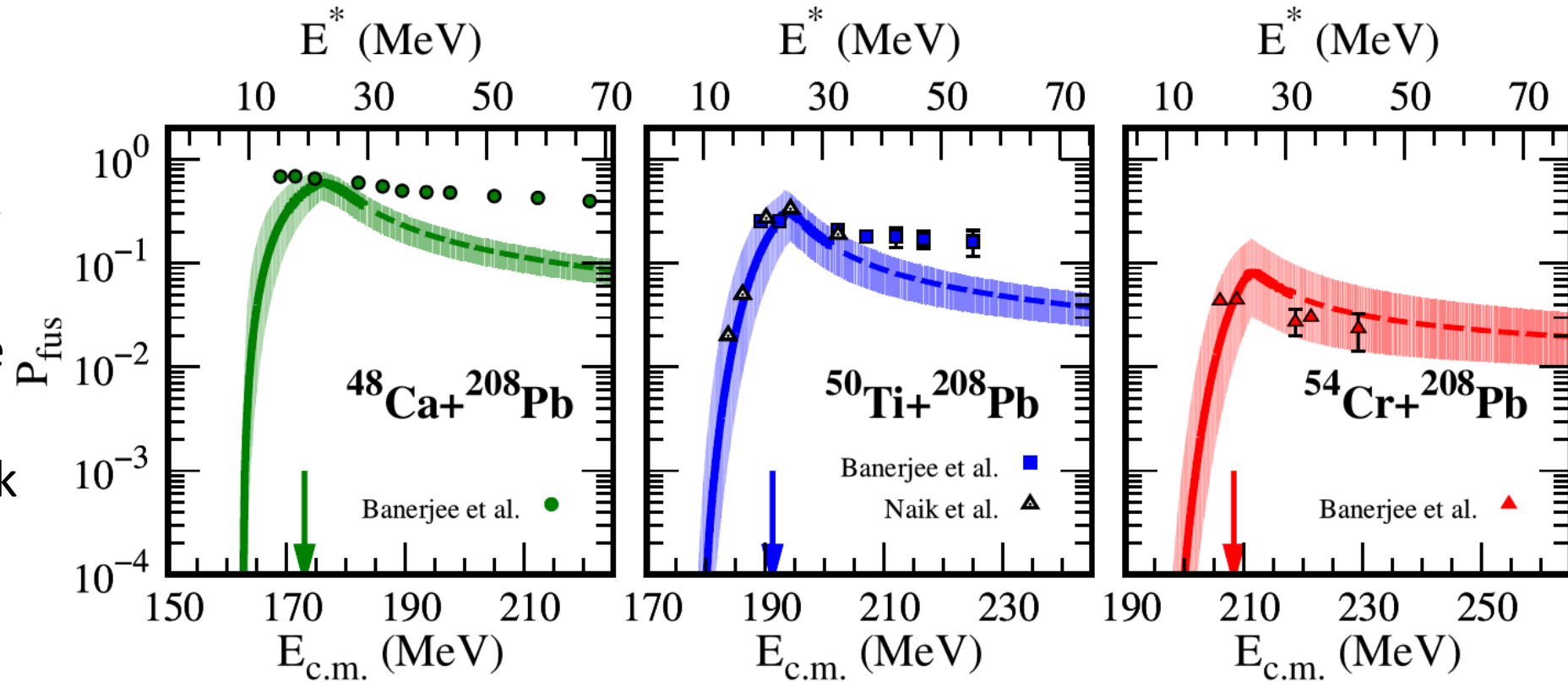
$H(l)$  – the function of angular momentum  
and bombarding energy

$T$  – the temperature depends on available energy



# Fusion probability from FbD model

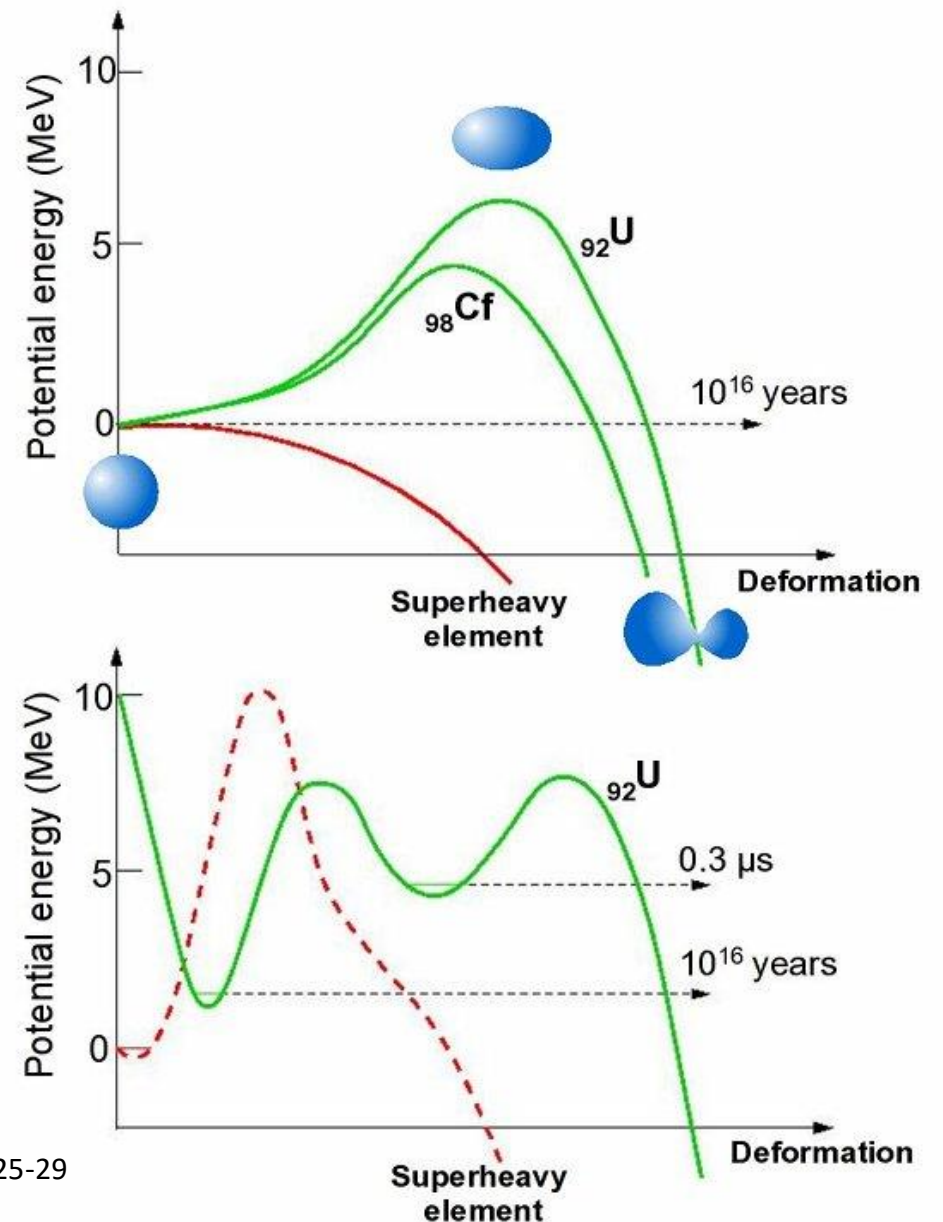
- Only takes into account the macroscopic binding energy
- Doesn't describe the fusion process
- Can the random walk method be better?



T. Cap, M. Kowal, and K. Siwek-Wilczyńska, Phys. Rev. C **105**, L051601 (2022)

# Binding/Potential energy in SHE

- Macroscopic (liquid drop) and microscopic (shell effects) energy
- Shell effects responsible for superdeformed minimum in actinides
- SHE exist thanks to the shell effects creating the ground state (often deformed)
- The model needs to account for both energies



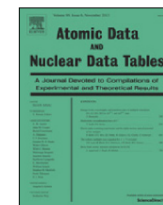
Oganessian, Yu. (2004). Superheavy elements. Physics World, 17(7), 25-29



Contents lists available at ScienceDirect

## Atomic Data and Nuclear Data Tables

journal homepage: [www.elsevier.com/locate/adt](http://www.elsevier.com/locate/adt)



### Properties of heaviest nuclei with $98 \leq Z \leq 126$ and $134 \leq N \leq 192$

P. Jachimowicz<sup>a</sup>, M. Kowal<sup>b,\*</sup>, J. Skalski<sup>b</sup>

<sup>a</sup> Institute of Physics, University of Zielona Góra, Szafrana 4a, 65-516 Zielona Góra, Poland

<sup>b</sup> National Centre for Nuclear Research, Pasteura 7, 02-093 Warsaw, Poland



#### Ground-state and saddle-point shapes and masses for 1305 heavy and superheavy nuclei

including odd-A and odd-odd systems. Static fission barrier heights, one- and two-nucleon separation energies, and  $Q_\alpha$  values.

**Microscopic-macroscopic method** with the deformed Woods-Saxon single-particle potential and the Yukawa-plus-exponential macroscopic energy taken as the smooth part.

Ground-state shapes and energies are found by the minimization over **seven axially-symmetric deformations**.

A search for saddle-points was performed by using the "imaginary water flow" method in three consecutive stages, using five- (for nonaxial shapes) and seven-dimensional (for reflection-asymmetric shapes) deformation spaces.

**Good agreement with the experimental data for actinides.**



# Warsaw macro-micro model with rotational energy

liquid drop with a Yukawa-plus-exponential model

Strutinsky shell correction + Woods-Saxson potential + BCS

rigid body approximation

$$E_{tot}(Z, N, \beta) = E_{mac}(Z, N, \beta) + E_{mic}(Z, N, \beta) + E_{rot}(\beta, l)$$

- Allows to obtain the binding energy for a given nuclear shape  $\beta$  and angular momentum  $l$ .

# Macroscopic energy $E_{mac}$

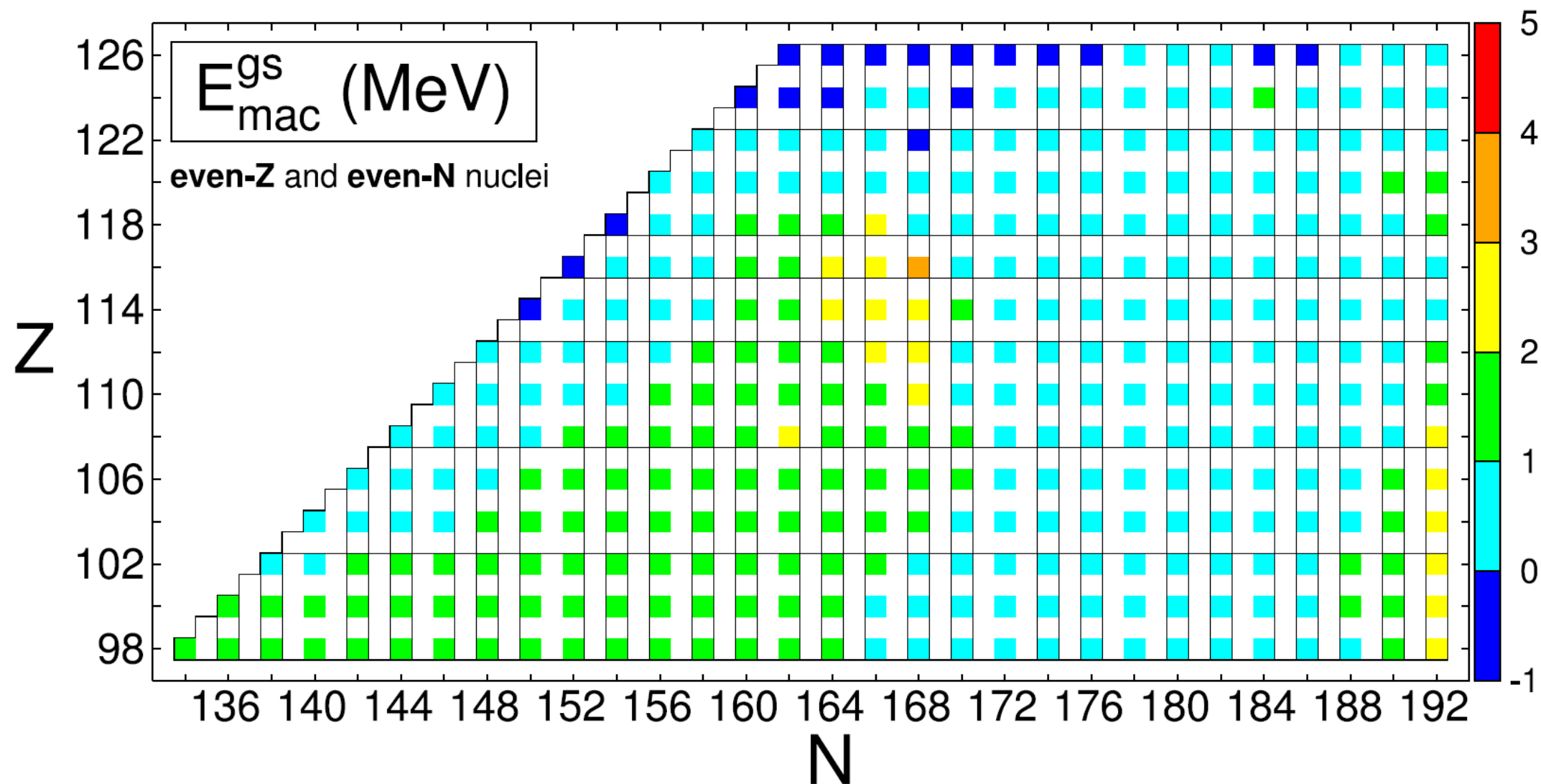
- Liquid drop model
- Responsible for the majority of energy/mass
- Dependence on shape in the surface and Coulomb term
- Most often normalized with respect to the sphere

$$E_{mac}(Z, N, \beta) = -a_v(1 - \kappa_v I^2)A + a_s(1 - \kappa_s I^2)A^{2/3}B_S(\beta) + a_0 A^0 + c_1 Z^2 A^{-1/3} B_C(\beta) - c_4 Z^{4/3} A^{-1/3} - f(k_F r_p) Z^2 A^{-1} + \bar{\Delta}_{mac}$$

$$B_S = \frac{A^{-2/3}}{8\pi^2 r_0^2 a^4} \int \int_V \left(2 - \frac{r_{12}}{a}\right) \frac{e^{-r_{12}/a}}{r_{12}/a} d^3 r_1 d^3 r_2,$$

$$E_{mac}^{gs} = E_{mac}^{gs}(deformation) - E_{mac}^{gs}(sphere)$$

$$B_C = \frac{15}{32\pi^2} \frac{A^{-5/3}}{r_0^5} \int \int_V \frac{1}{r_{12}} \left[1 - \left(1 + \frac{1}{2} \frac{r_{12}}{a_{den}}\right) e^{-r_{12}/a_{den}}\right] d^3 r_1 d^3 r_2$$



P. Jachimowicz, M. Kowal, J. Skalski, Properties of heaviest nuclei with  $98 \leq Z \leq 126$  and  $134 \leq N \leq 192$ , Atomic Data and Nuclear Data Tables, Volume 138, 2021, 101393

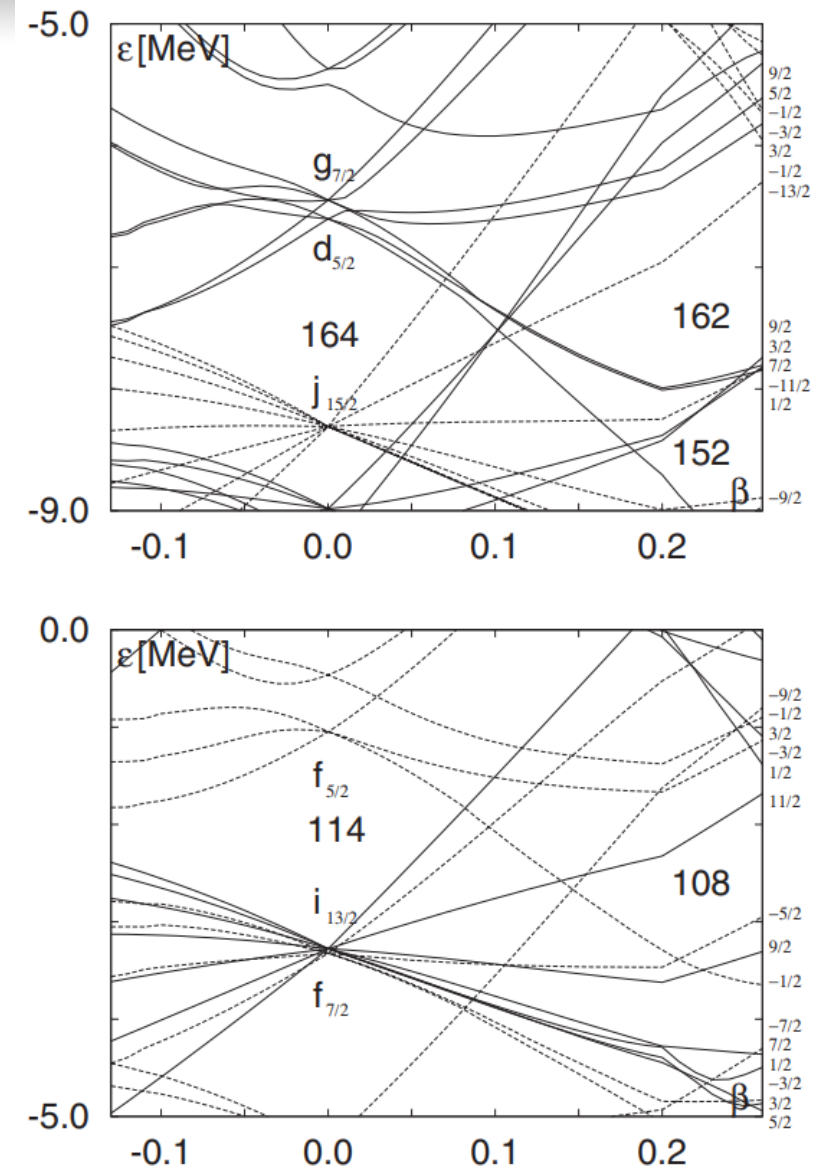


# Microscopic energy $E_{mic}$

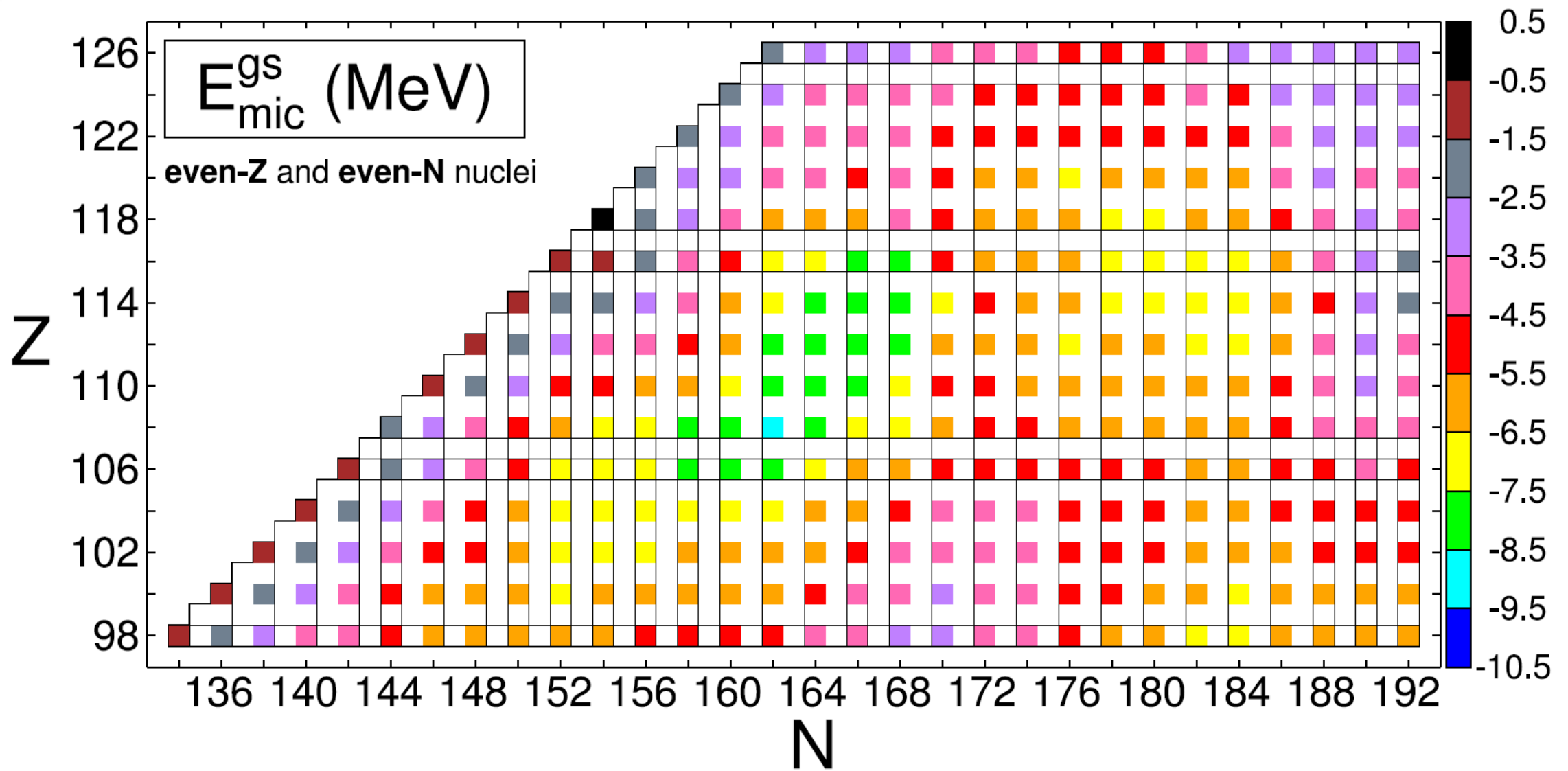
$$E_{mic}(Z, N, \beta) = E_{corr}^{sh}(Z, N, \beta) + E_{corr}^{pair}(Z, N, \beta)$$

- Strutinsky shell correction based on the deformed Woods–Saxon single-particle potential
- The single-particle potential is diagonalized in the deformed harmonic-oscillator basis
- Pairing energy, pair correlation from Bardeen–Cooper–Schrieffer (BCS) theory

$$V_{WS}(\vec{r}) = -\frac{V}{1 + e^{d(\vec{r}, \beta)/a_{ws}}}$$



Jachimowicz, P. & Kowal, M. & Skalski, J.. (2014). Q  $\alpha$  values in superheavy nuclei from the deformed Woods-Saxon model. Physical Review C. 89. 10.1103/PhysRevC.89.024304.



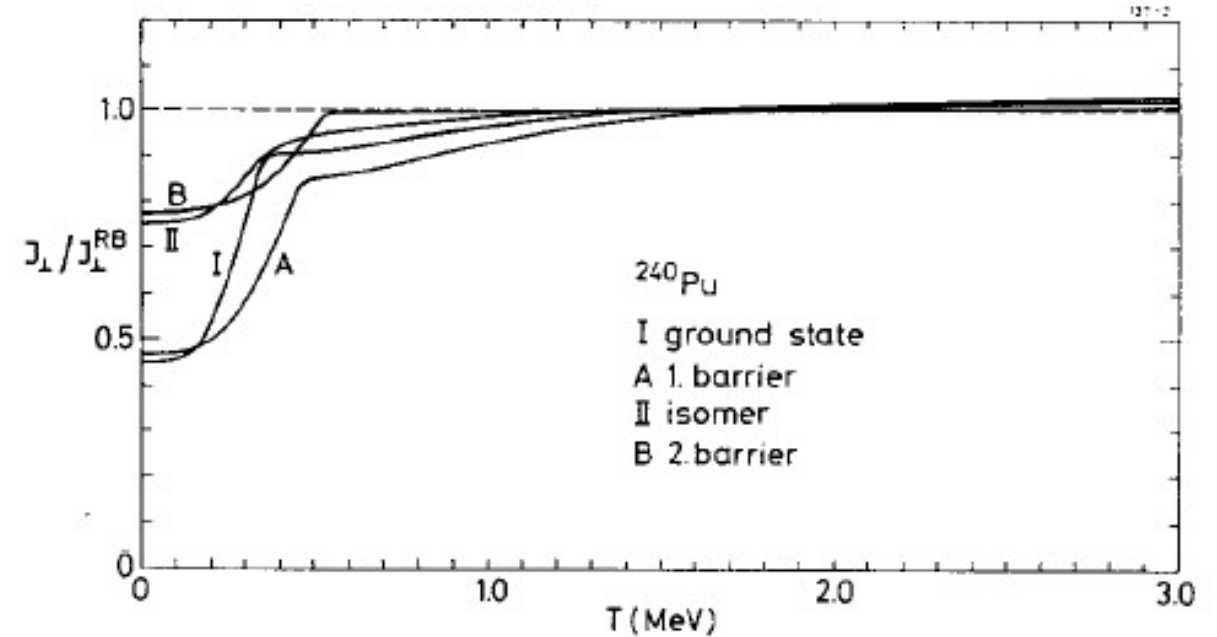
P. Jachimowicz, M. Kowal, J. Skalski, Properties of heaviest nuclei with  $98 \leq Z \leq 126$  and  $134 \leq N \leq 192$ , Atomic Data and Nuclear Data Tables, Volume 138, 2021, 101393

# Rotational energy $E_{rot}$

- Rigid body approximation
- Moment of inertia calculated analytically

$$E_{rot} = l(l+1) \frac{(\hbar c)^2}{2I(\beta)} \quad \mathbf{I} = \begin{pmatrix} I_{\perp} & & \\ & I_{\perp} & \\ & & I_{\parallel} \end{pmatrix}$$

$$I_{\perp} = \frac{1}{5} \rho R_0^5 \int \sin(\theta) (\pi \sin^2(\theta) + 2\pi \cos^2(\theta)) \left( 1 + \frac{1}{2} \sqrt{\frac{3}{\pi}} \beta_{10} \cos(\theta) + \frac{1}{4} \sqrt{\frac{5}{\pi}} \beta_{20} (3 \cos^2(\theta) - 1) \right. \\ \left. + \frac{1}{4} \sqrt{\frac{7}{\pi}} \beta_{30} (5 \cos^3(\theta) - 3 \cos(\theta)) + \frac{1}{16} \sqrt{\frac{9}{\pi}} \beta_{40} (35 \cos^4(\theta) - 30 \cos^2(\theta) + 3) \right)^5 d\theta$$



M. Brack, T. Ledergerber, H. Pauli, A. Jensen, Nuclear Physics A **234**, 185–215 (1974)

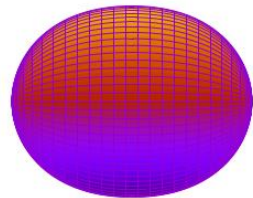
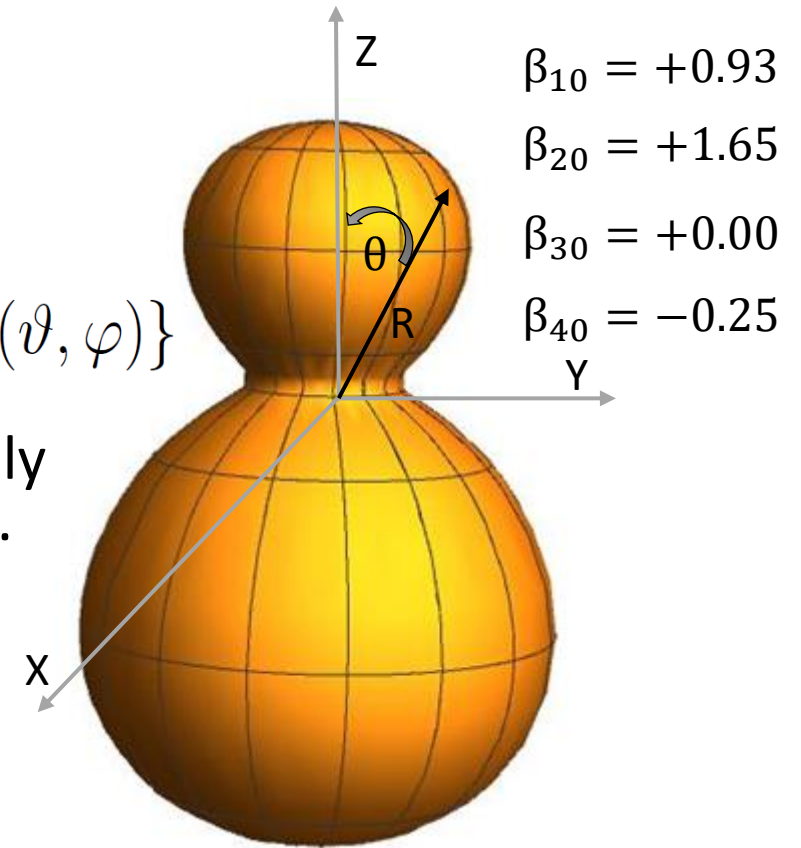


# Shape parametrization

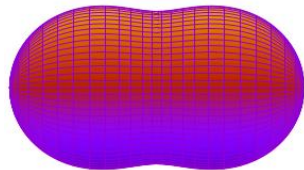
- An expansion of the nuclear radius  $R(\theta, \phi)$  onto spherical harmonics  $Y_{\lambda\mu}(\theta, \phi)$  is used:

$$R(\vartheta, \varphi) = cR_0 \left\{ 1 + \sum_{\lambda=1}^{\infty} \beta_{\lambda 0} Y_{\lambda 0}(\vartheta, \varphi) \right\}$$

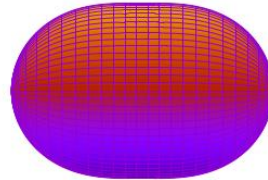
- For now, shapes in random walk method are limited to axially symmetrical ( $\mu = 0$ ) and depend only on  $\beta_{10}$ ,  $\beta_{20}$ ,  $\beta_{30}$  and  $\beta_{40}$ .



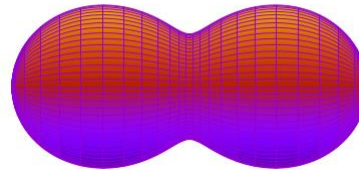
**Compound nucleus**



**2nd minimum**



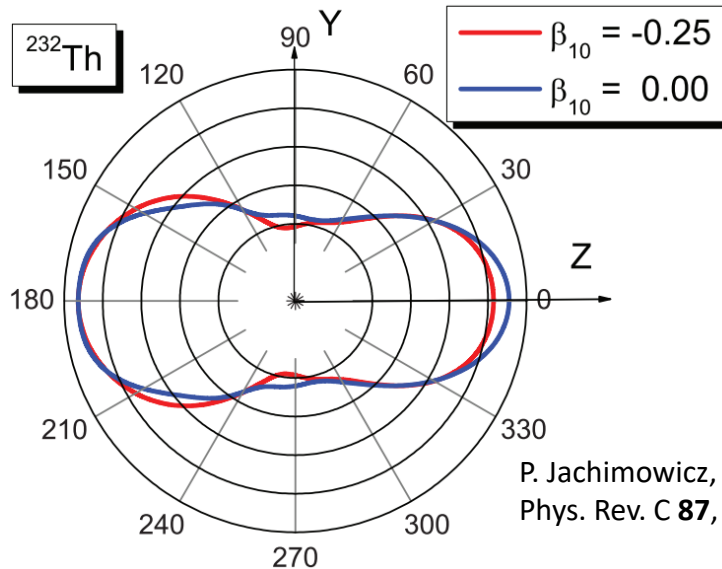
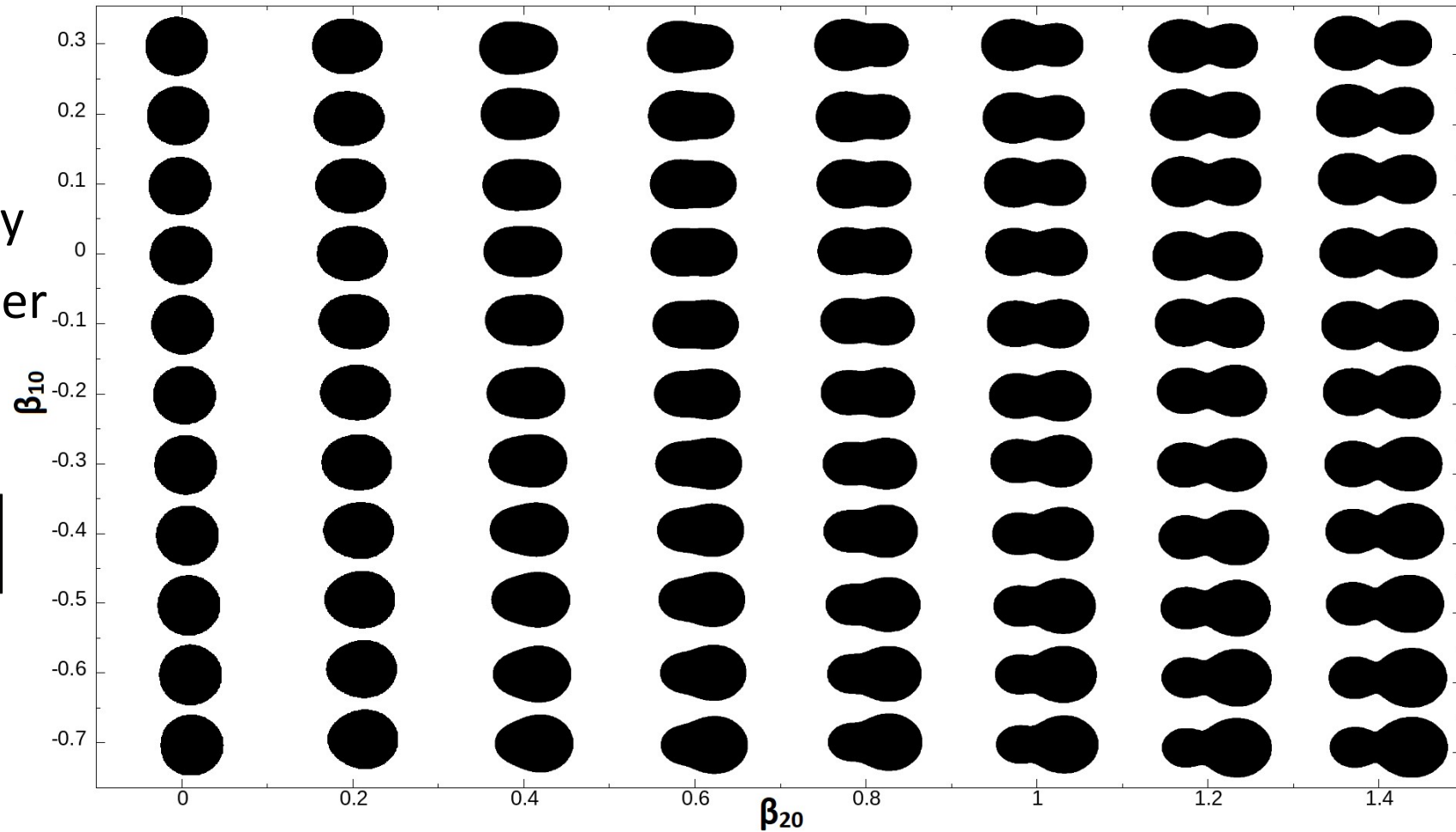
**Fission saddle point**



**Scission point  
symmetrical fission**

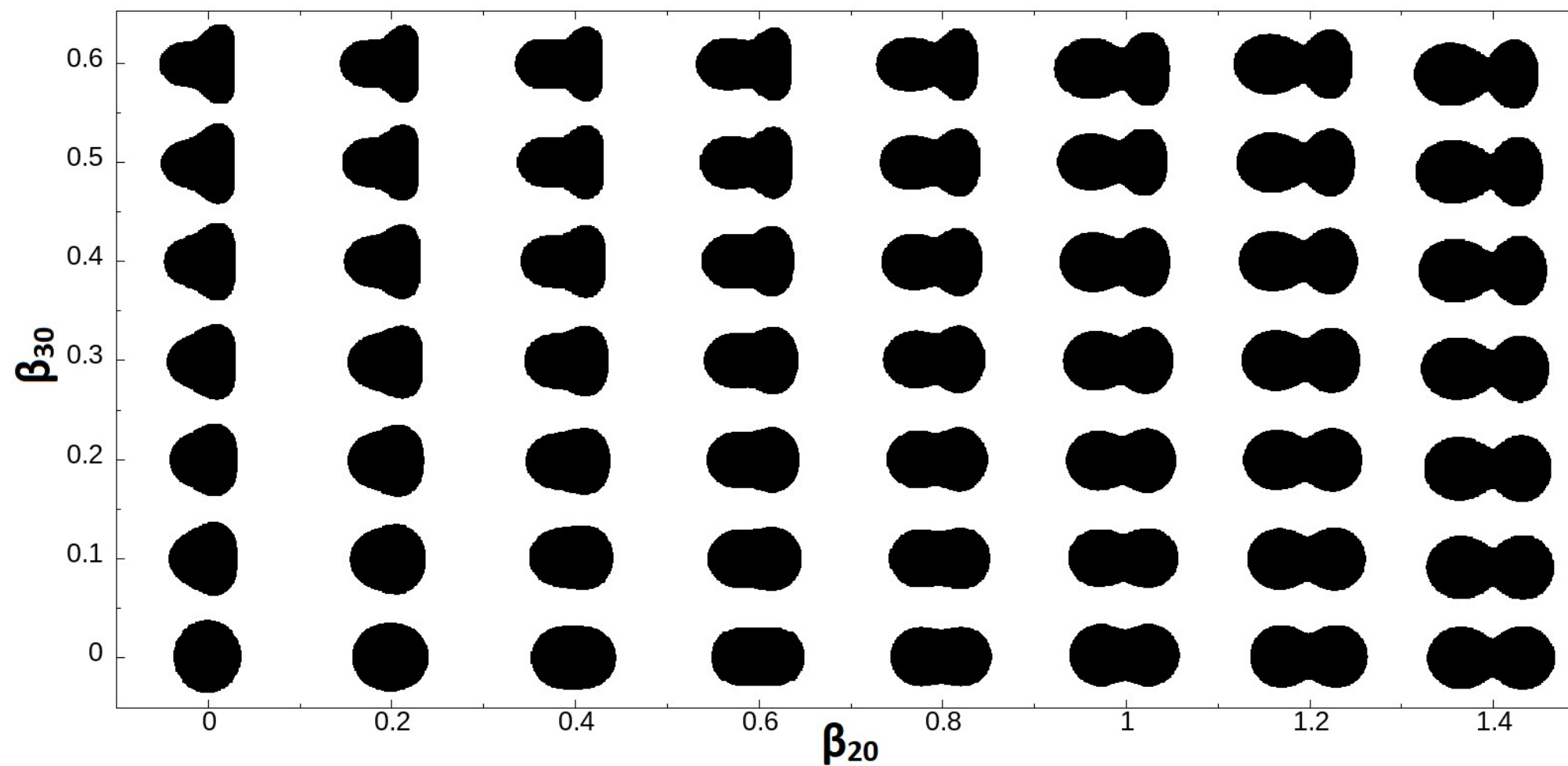
# Shape parametrization

- $\beta_{10}$  – dipole
- $\beta_{20}$  – quadrupole/elongation
- $\beta_{30}$  – hexadecople/asymmetry
- $\beta_{40}$  – octupole/neck parameter
- $\beta_{10}$  used as an actual shape parameter



P. Jachimowicz, M. Kowal, and J. Skalski,  
Phys. Rev. C **87**, 044308 (2013)

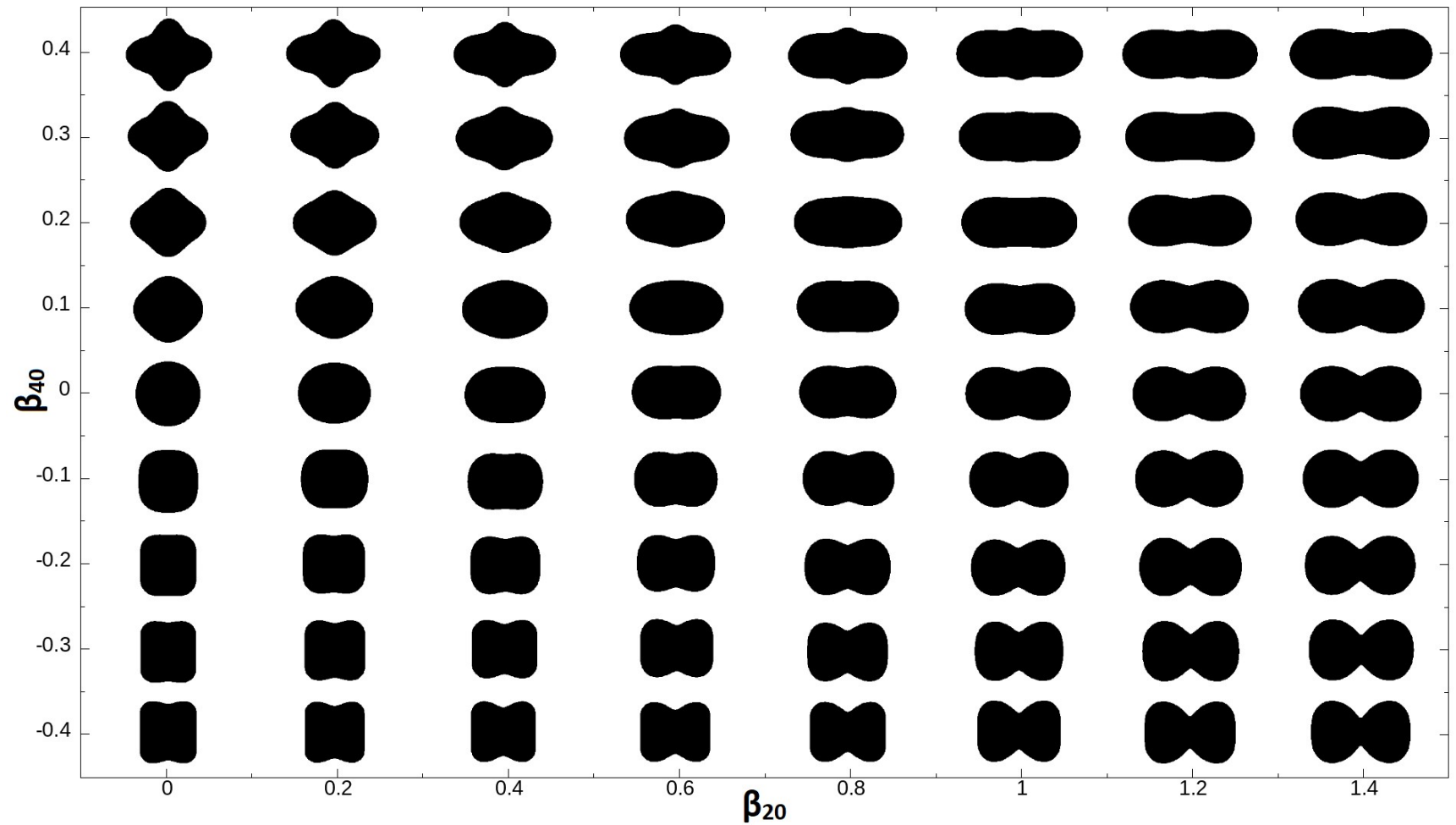
# Shape parametrization





# Shape parametrization

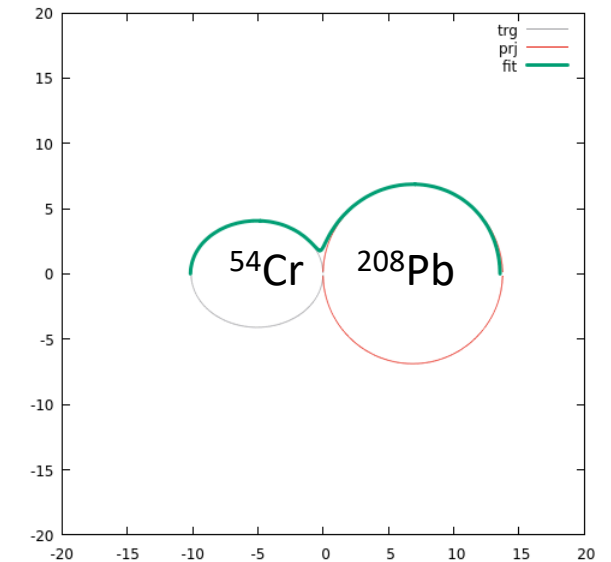
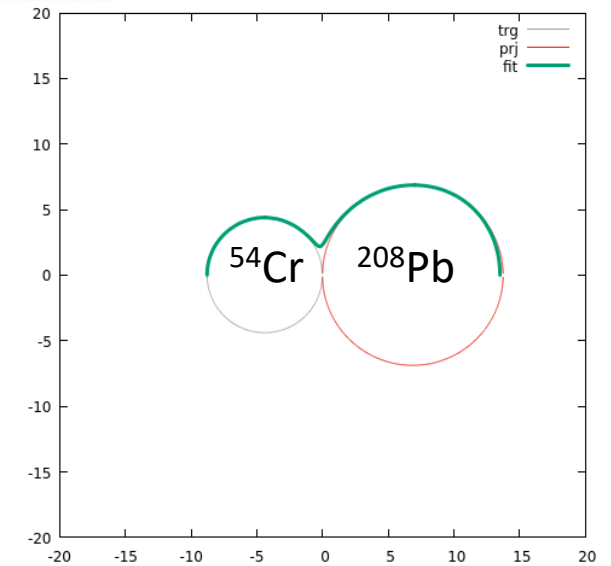
- $\beta_{40}$  is crucial in the beginning of the fusion process and during scission



# Starting point parametrization

- After overcoming the entrance channel barrier, the projectile and the target are assumed to be in a touching configuration.
- The spherical harmonic parametrization is fitted, with the origin situated in the neck, giving the  $\beta$  parameters for the starting point configuration.
- The shapes are asymmetrical, but  $\beta_{30}$  is near to 0, thanks to the inclusion of  $\beta_{10}$ .
- Calculations were done for  $^{54}\text{Cr}$  spherical and deformed (least optimal for fusion).

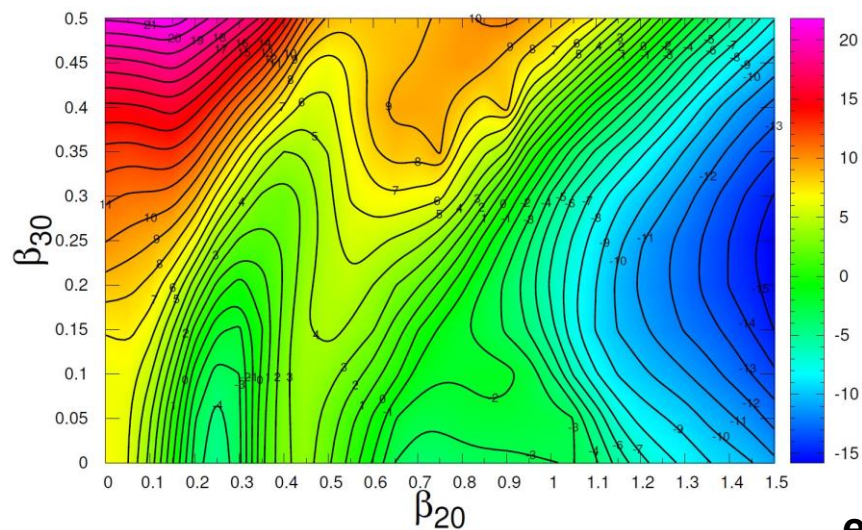
System	$\beta_{10}$	$\beta_{20}$	$\beta_{30}$	$\beta_{40}$
$^{48}\text{Ca}+^{208}\text{Pb}$	0.93	1.65	0.0	-0.24
$^{50}\text{Ti}+^{208}\text{Pb}$	0.92	1.75	0.01	-0.30
$^{54}\text{Cr}(\text{spherical})+^{208}\text{Pb}$	-0.87	1.75	-0.01	-0.30
$^{54}\text{Cr}(\text{deformed})+^{208}\text{Pb}$	-0.94	1.83	0.18	-0.16



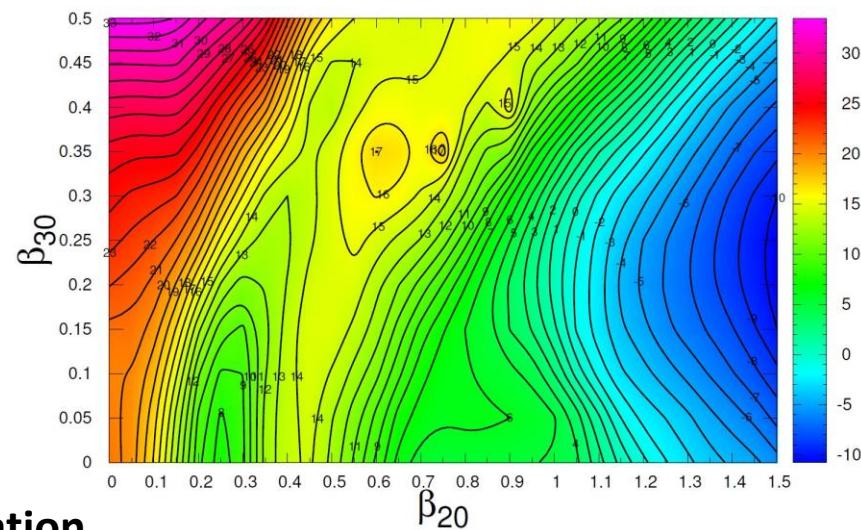


# Potential energy surfaces

asymmetry

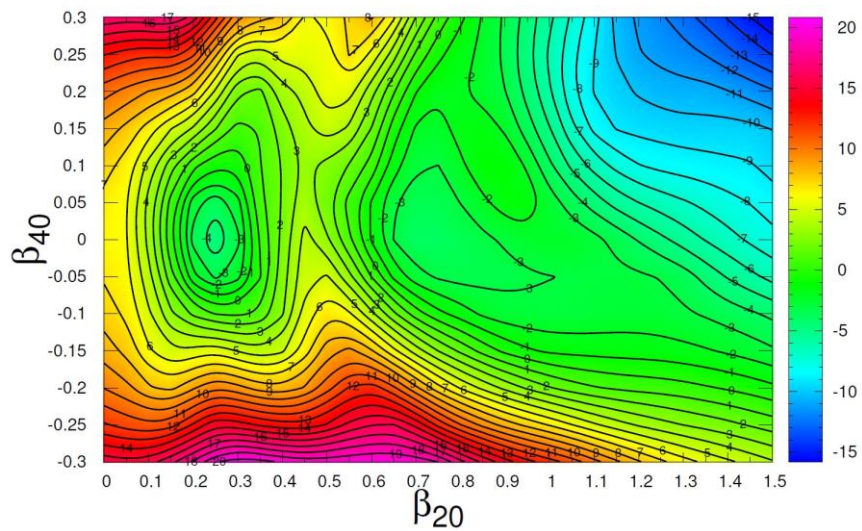


$^{48}\text{Ca} + ^{208}\text{Pb}$   
 $l = 0$

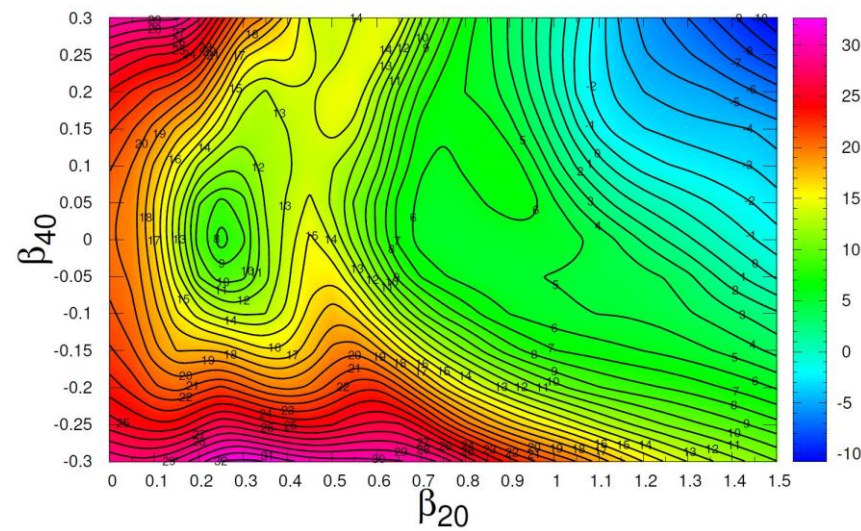


$^{48}\text{Ca} + ^{208}\text{Pb}$   
 $l = 60$

elongation



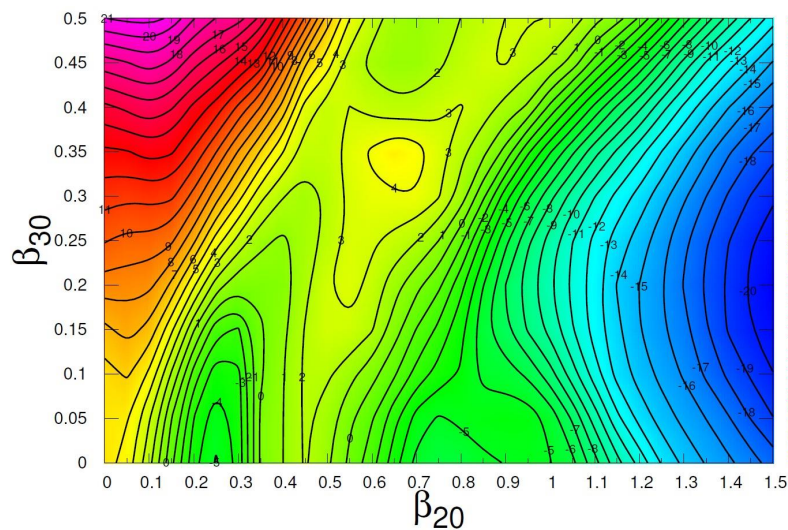
neck parameter



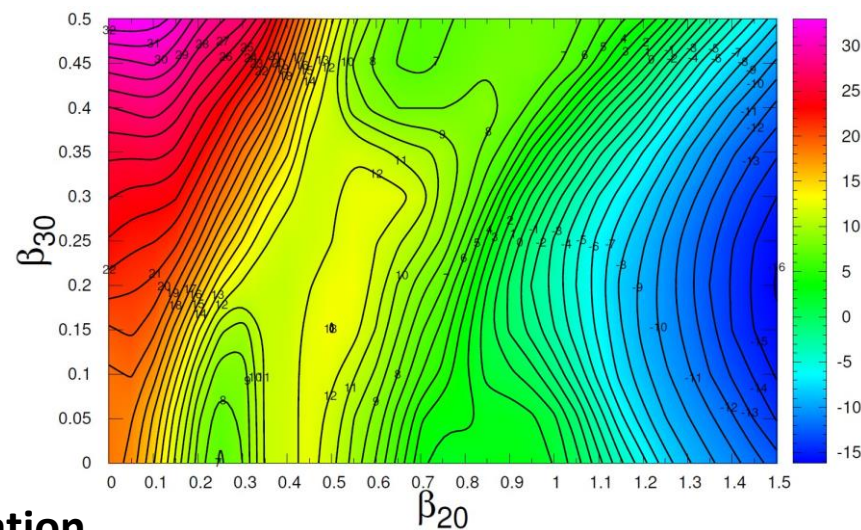


# Potential energy surfaces

asymmetry

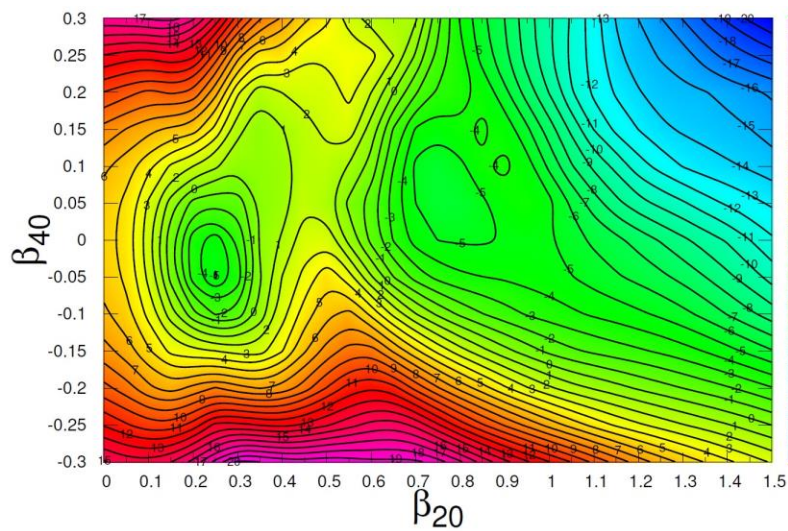


$^{54}\text{Cr} + ^{208}\text{Pb}$   
 $l = 0$

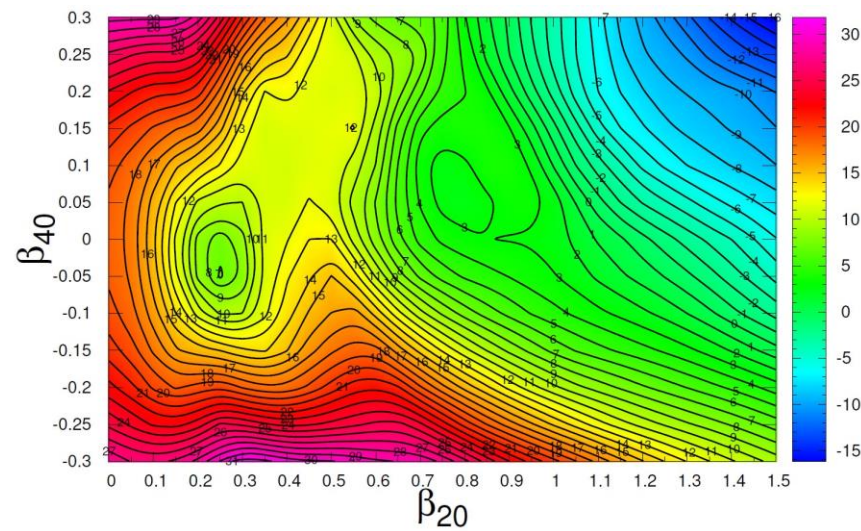


$^{54}\text{Cr} + ^{208}\text{Pb}$   
 $l = 60$

elongation



neck parameter





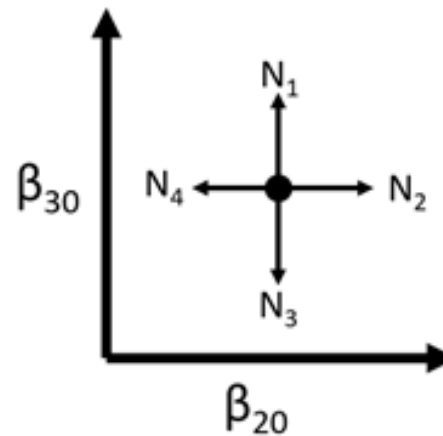
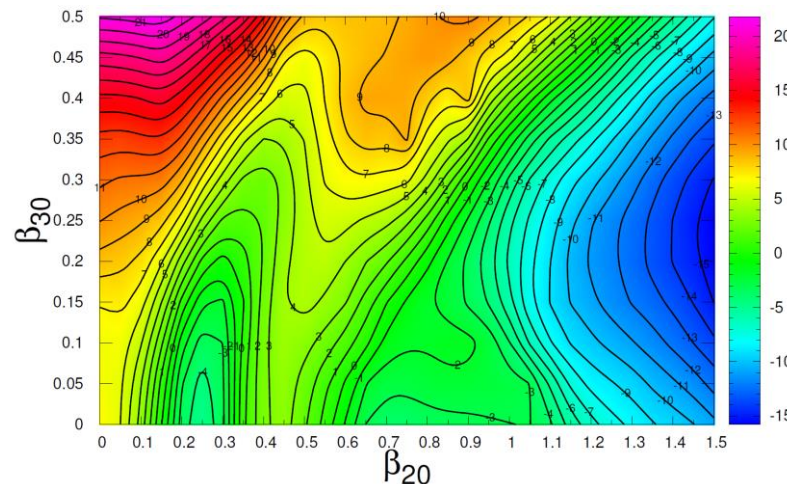
# Random walk method

- The probability of transitioning from one shape to another is determined by the number of available energy levels for a given shape  $\beta$ .

$$N_i(\beta_i) \propto \exp\left(2\sqrt{a(E^*(\beta_i) - E_{rot}(\beta_i))}\right) \quad a - \text{constant density parameter}$$

- Only one  $\beta$  parameter changes at a time, by a step of 0.05, giving 8 possible directions of movement.

$^{48}\text{Ca} + ^{208}\text{Pb}$   
 $l = 0$



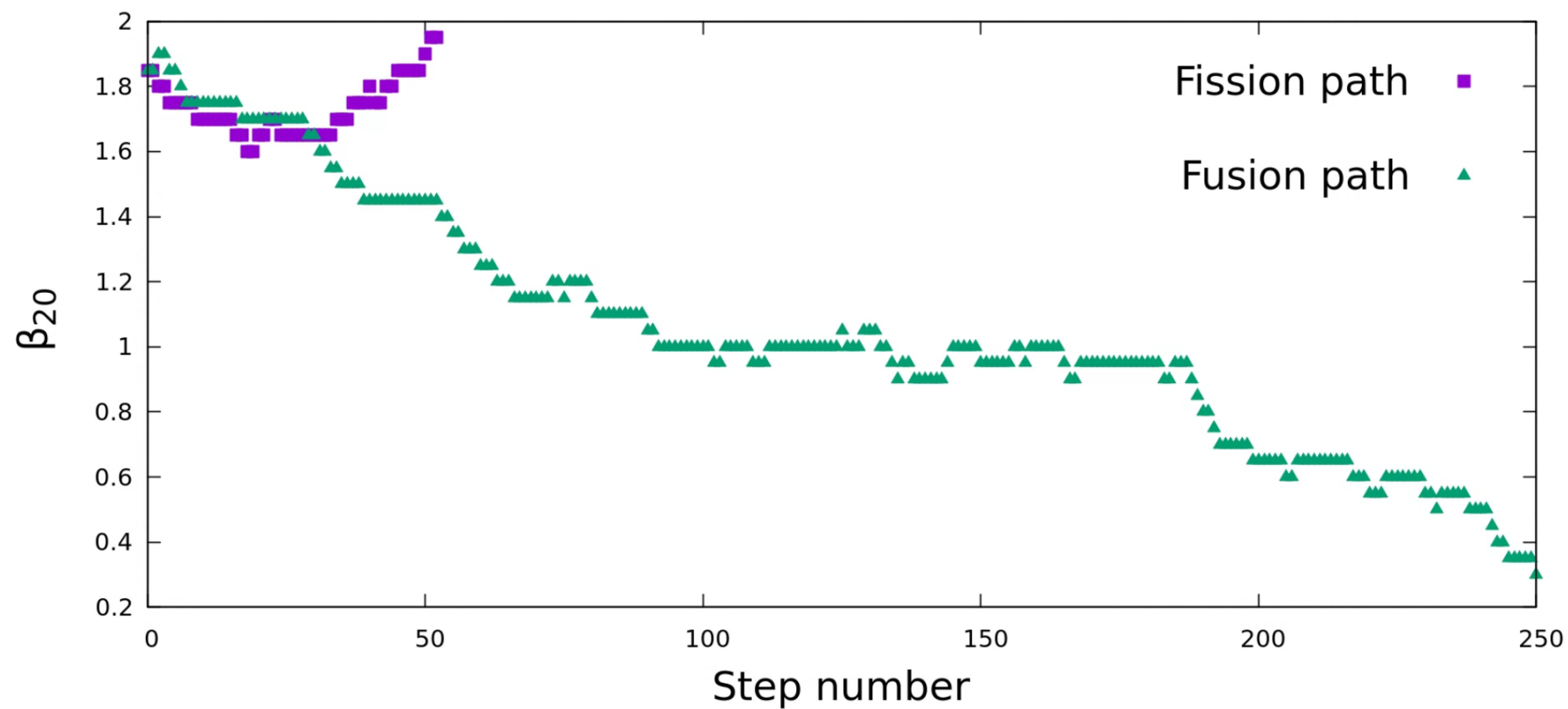
$$P_i = \frac{N_i(\beta_i)}{\sum_j N_j(\beta_j)}$$

- Fusion:  $\beta_{20} \leq 0.3$ ,  $\beta_{30} \leq 0.2$ ,  $\beta_{40} \leq 0.2 \rightarrow$  compound nucleus.
- Fission: when the thickness of the neck connecting the fission fragments is less than 4.0 fm.

# Example of a paths

$^{54}\text{Cr} + ^{208}\text{Pb}$

$E^* = 50 \text{ MeV}, l = 40$

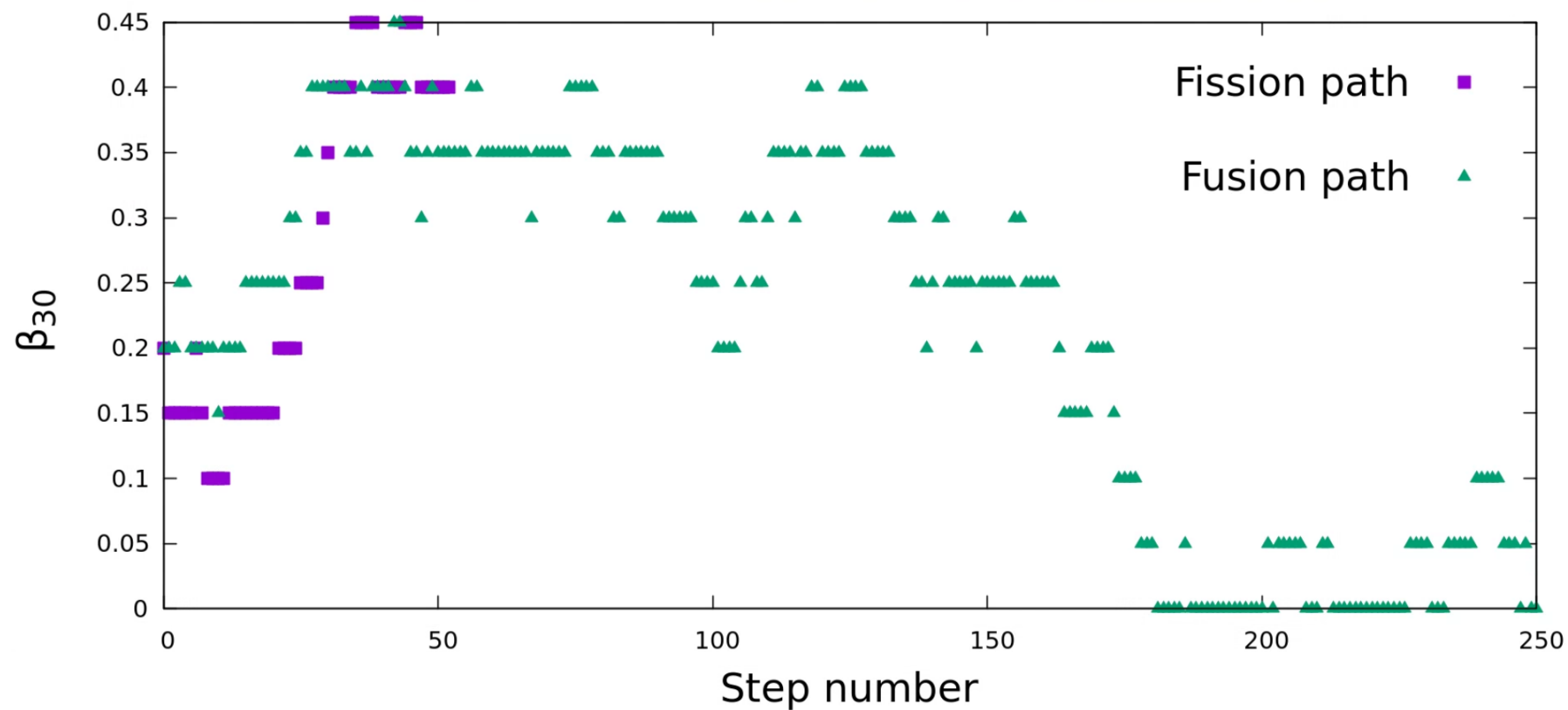




# Example of a paths

$^{54}\text{Cr} + ^{208}\text{Pb}$

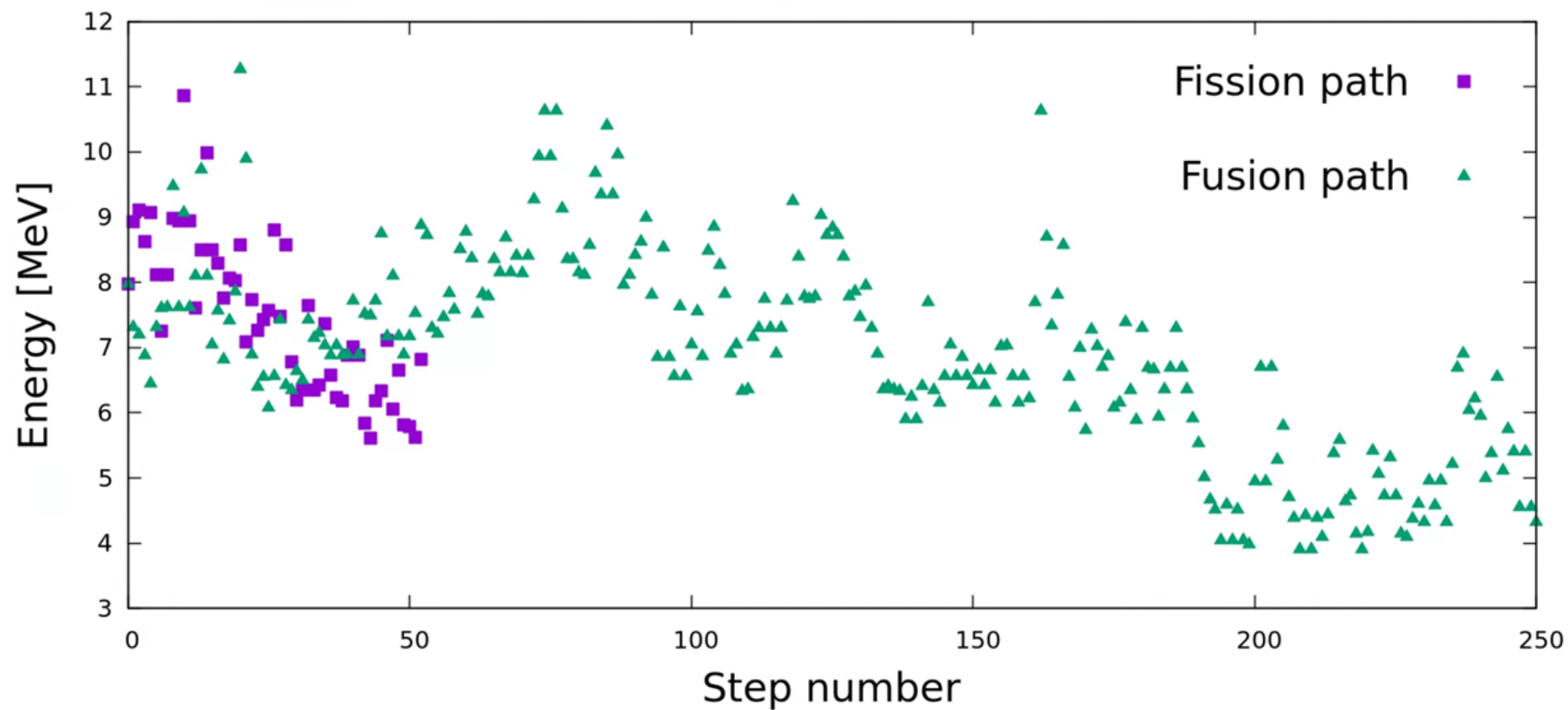
$E^* = 50 \text{ MeV}, l = 40$



# Example of a paths

$^{54}\text{Cr} + ^{208}\text{Pb}$

$E^* = 50 \text{ MeV}, l = 40$



# Random walk method

- Calculations were done for excitation energies from 20 to 70 MeV with 1 MeV step. 10000 paths were calculated for a given energy and  $l$ -value from 0 to  $l_{\max}$ .  $P_{\text{fus}}(E_{\text{cm}}, l)$  is given as a ratio of the number of paths that lead to fusion to the total number of paths

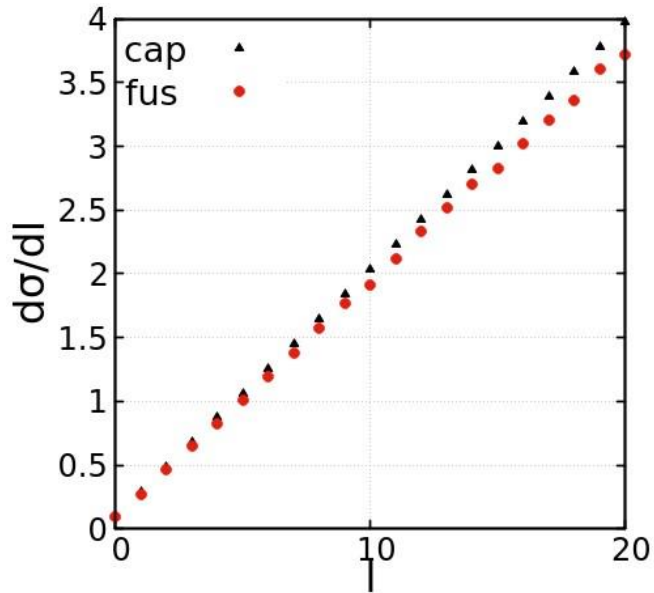
$$P_{\text{fus}}(E_{\text{cm}}, l) = \frac{\text{paths which ended in fusion}}{10000}$$

- $\sim 3600 E^*$  and  $l$  combinations  $\rightarrow \sim 36$  million paths per reaction
- Average over  $l$  to get  $P_{\text{fus}}$  dependant on  $E_{\text{cm}}$ :

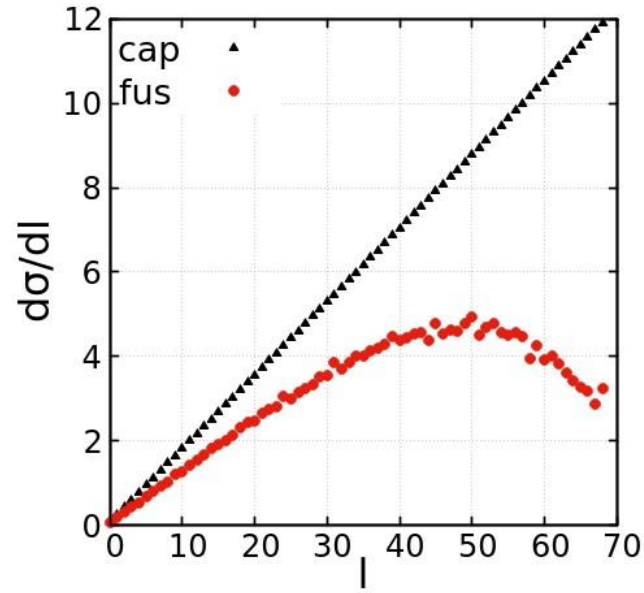
$$P_{\text{fus}}(E_{\text{cm}}) = \frac{\sum_{l=0}^{l_{\max}} (2l+1) P_{\text{fus}}(l)}{(2l_{\max}+1)^2} \quad \text{fusion probability averaged over } l$$

# Capture and fusion cross section

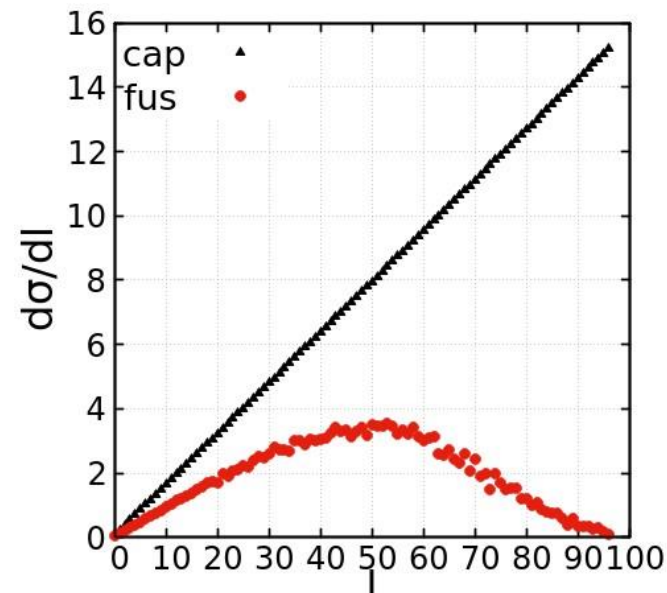
- Capture cross section calculated from FbD model
- Fusion cross section from the random walk method  $\sigma_{fus} = \pi\lambda^2 \sum_{l=0}^{l_{max}} (2l+1)T(l)P_{fus}(l) = \sigma_{cap} \times P_{fus}$
- Distributions of  $\frac{d\sigma_{cap}}{dl}$  (black) and  $\frac{d\sigma_{fus}}{dl}$  (red) for  $^{48}\text{Ca} + ^{208}\text{Pb}$



$E^* = 20$  MeV



$E^* = 40$  MeV



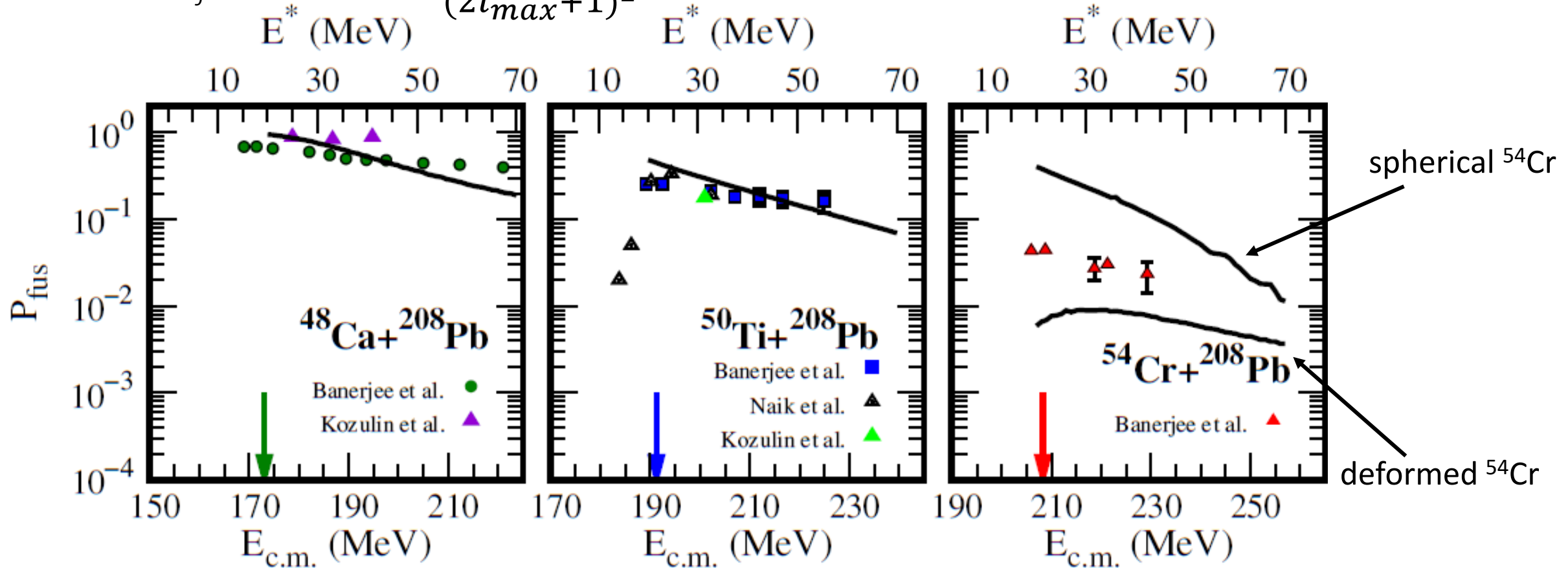
$E^* = 60$  MeV



# Fusion probability from the random walk

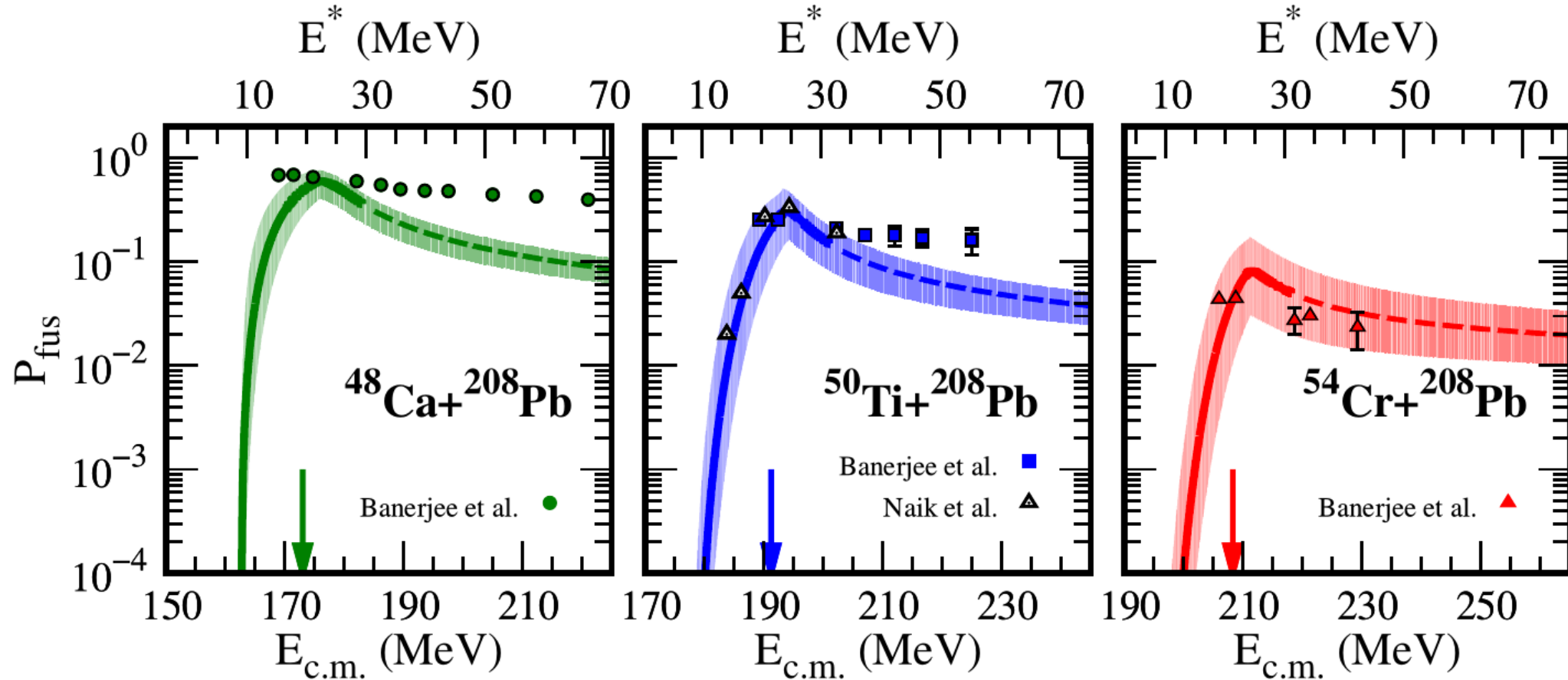
$$P_{fus}(E_{cm}) = \frac{\sum_{l=0}^{l_{max}} (2l+1) P_{fus}(l)}{(2l_{max}+1)^2}$$

fusion probability averaged over  $l$



The averaged fusion probability, shown as solid, black lines, calculated with the random walk method, for the reactions  $^{48}\text{Ca} + ^{208}\text{Pb}$ ,  $^{50}\text{Ti} + ^{208}\text{Pb}$  and  $^{54}\text{Cr} + ^{208}\text{Pb}$ . For comparison, experimental results obtained in [K. Banerjee et al., PRL 122, 232503 (2019)] and [E. M. Kozulin et al., NPA 802, 45 (2008)] are also shown. The arrows indicate the value of the mean entrance channel barrier for each reaction

# Fusion probability from FbD model



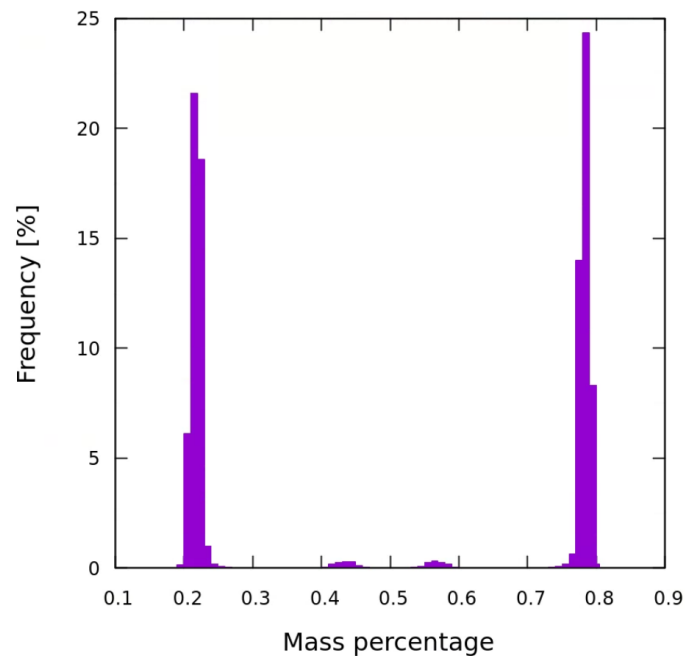
T. Cap, M. Kowal, and K. Siwek-Wilczyńska, Phys. Rev. C **105**, L051601 (2022)

# Mass distribution of fission fragments

- The final fission shapes can be divided, and their volumes compared, giving the mass distribution of fission fragments, for each  $E^*$  and  $l$ .

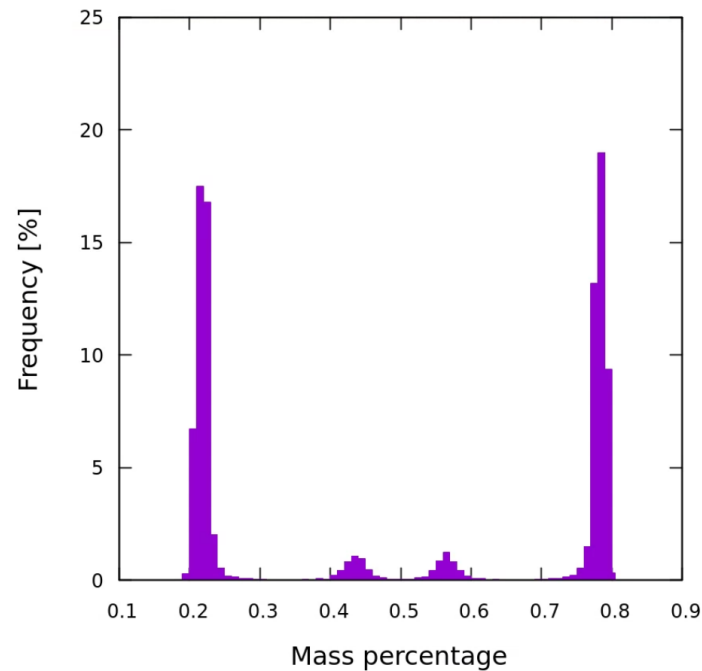
$^{54}\text{Cr} + ^{208}\text{Pb}$

$E^* = 30 \text{ MeV}, l = 20$



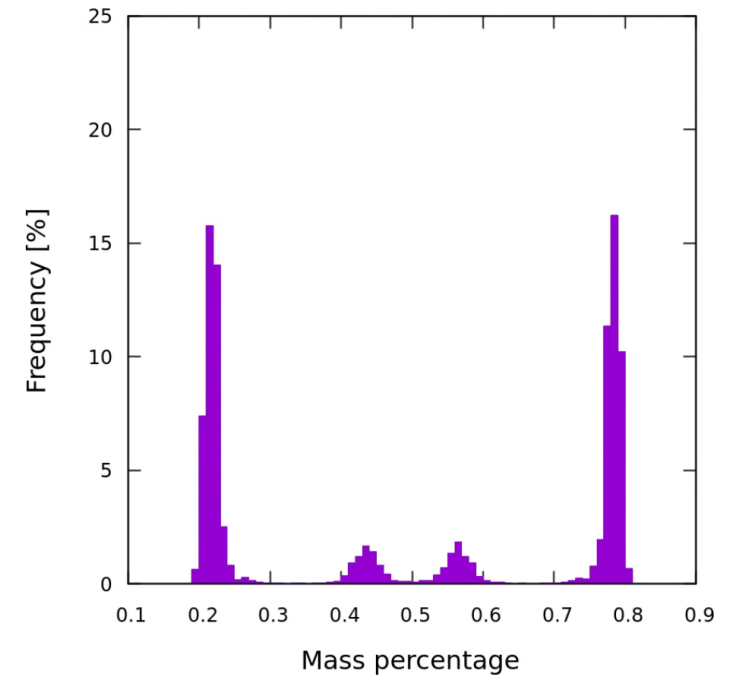
$^{54}\text{Cr} + ^{208}\text{Pb}$

$E^* = 50 \text{ MeV}, l = 40$



$^{54}\text{Cr} + ^{208}\text{Pb}$

$E^* = 70 \text{ MeV}, l = 70$





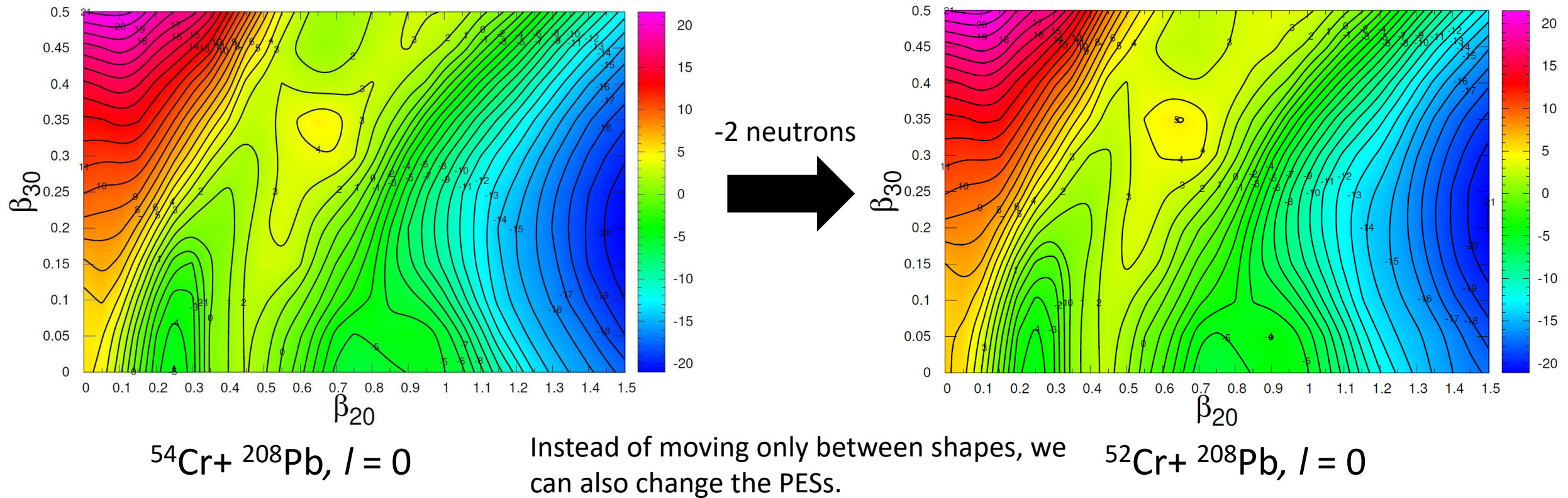
# Summary

- The random walk method reproduces experimental results for spherical pairs of targets and projectiles. For deformed systems, limited to only axially symmetric shapes, the model gives a lower limit of  $P_{fus}$  which is an order of magnitude smaller than the data. To properly describe such systems, the method would have to be expanded to non-axially symmetric shapes and would have to incorporate multiple possible starting points depending on the orientation of the target and the projectile.
- The random walk method looks to be a promising direction of study to better understand the fusion probability in reactions leading to the synthesis of superheavy nuclei.

# Next steps

- Expand to 8  $\beta_{\lambda 0}$  dimensions
- Determine optimal step size for each  $\beta$  parameter
- Expand to non-axially symmetric shapes ( $\beta_{\lambda \mu}$ ) and incorporate multiple possible starting points depending on the orientation of the target and the projectile
- Introduce a density parameter beyond Fermi gas model
- Incorporate shell-correction damping
- Allow for the emission of neutrons, protons and alfa particles during the random walk
- Calculate  $P_{\text{fus}}$  for other cold fusion reactions
- Calculate  $P_{\text{fus}}$  for hot fusion reactions, both already performed and planned experiments

# Emission of neutrons, protons and alfa particles during the random walk





# Thank you for your attention!



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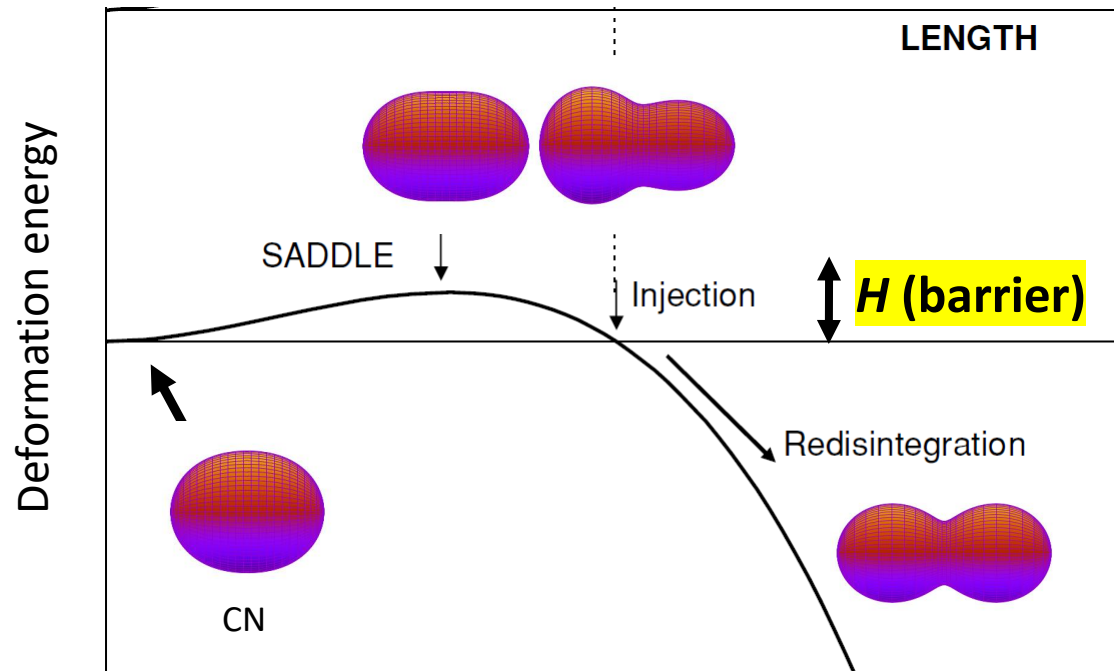
[www.ncbj.gov.pl](http://www.ncbj.gov.pl)



# BONUS SLIDES

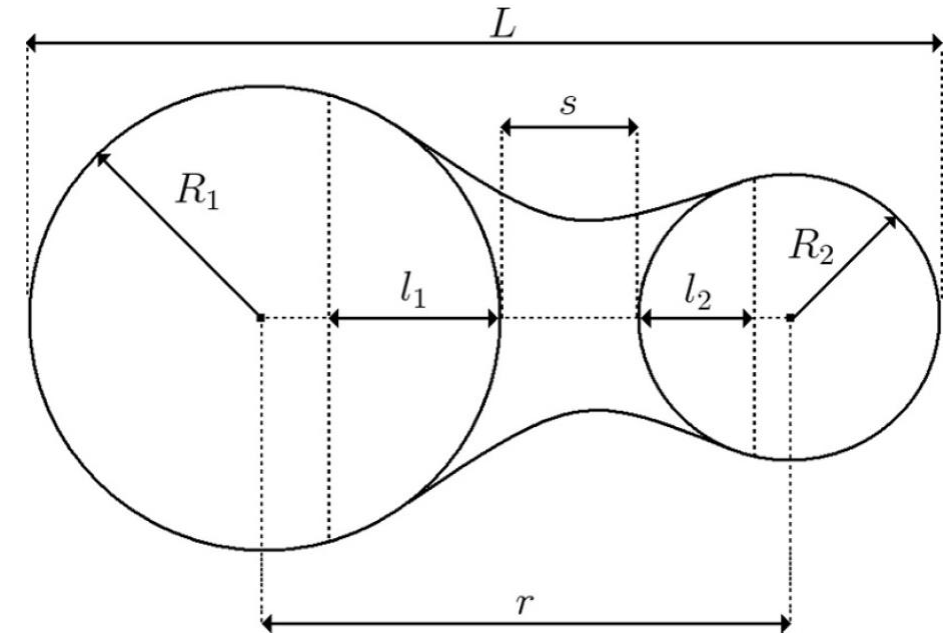
In the **FBD** model, we use  
1D motion approximation

The system must overcome an internal  
barrier  **$H$**  to fuse.



$L$  is the effective elongation (along the fusion path)

Macroscopic deformation energies are calculated using the parameterization of the nuclear shapes by two spheres joined smoothly by a third quadratic surface of revolution.

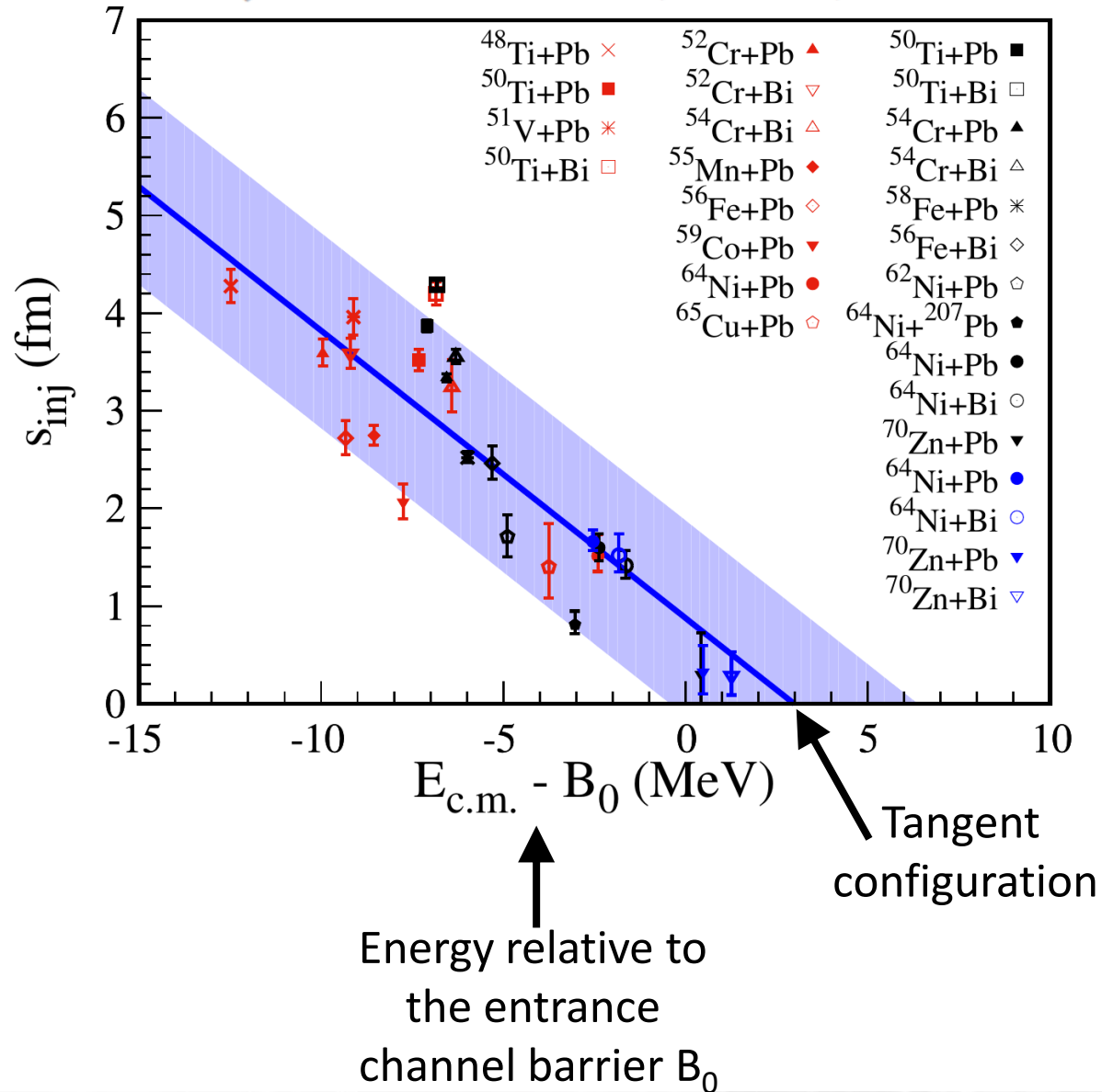


The distance between the nuclear surfaces of two colliding nuclei at the **injection point**  $s_{inj}$  is the only adjustable parameter of the model.

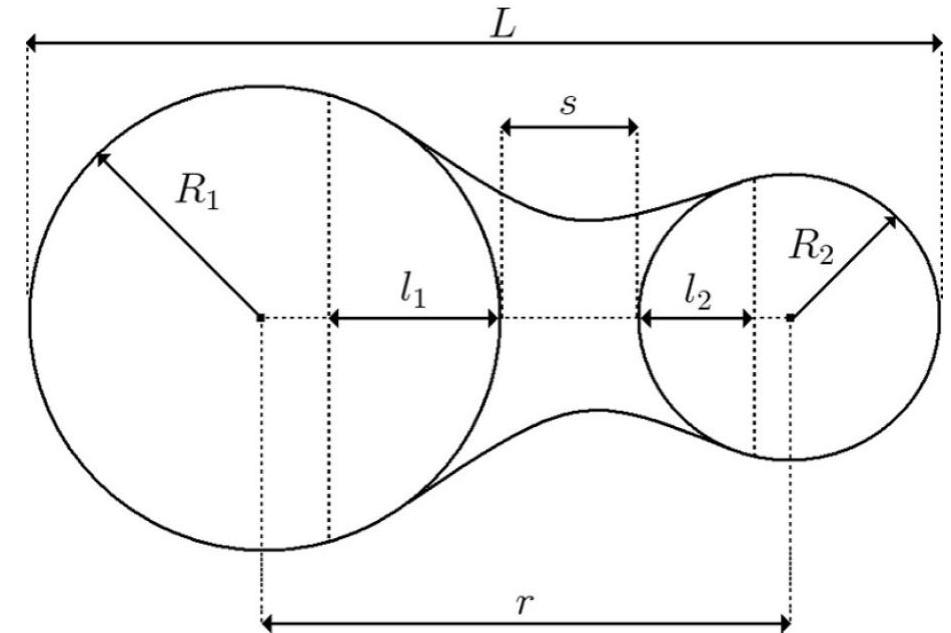
$s_{inj}$  distance was parametrized by analyzing 27 cold fusion reactions.



$$s_{inj} = 0.878 \text{ fm} - 0.294 \times (E_{c.m.} - B_0) \text{ fm/MeV}$$

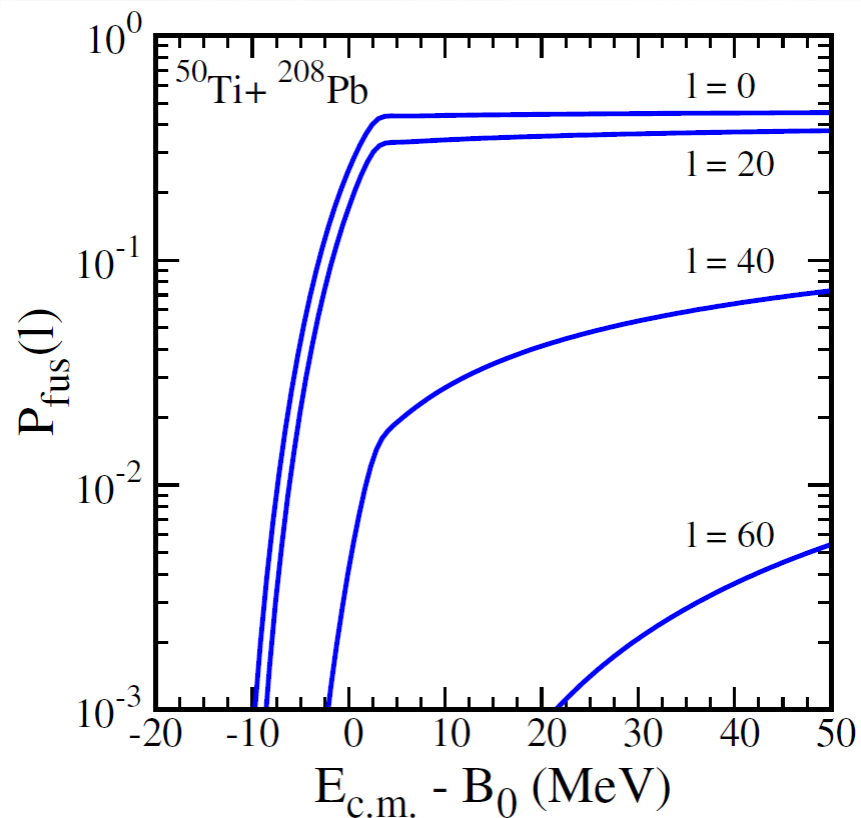


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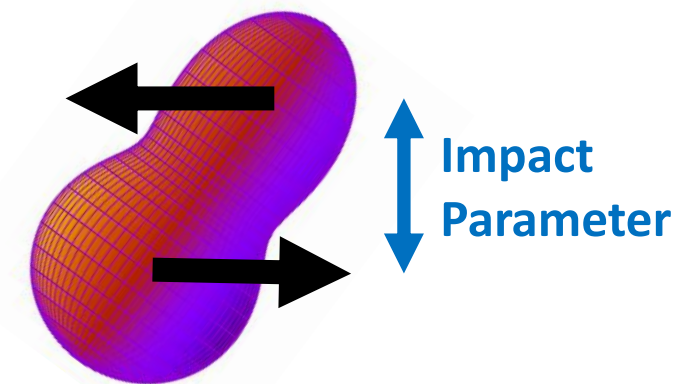
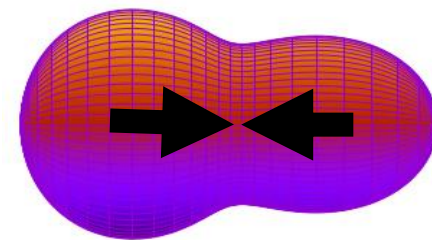
Energy relative to the entrance  
channel barrier  $B_0$

$$B_0 = 191.3 \text{ MeV}$$

$$E^*(E_{\text{c.m.}} = B_0) = 21.7 \text{ MeV}$$

$l = 0$   
Central collision

Peripheral  
collisions

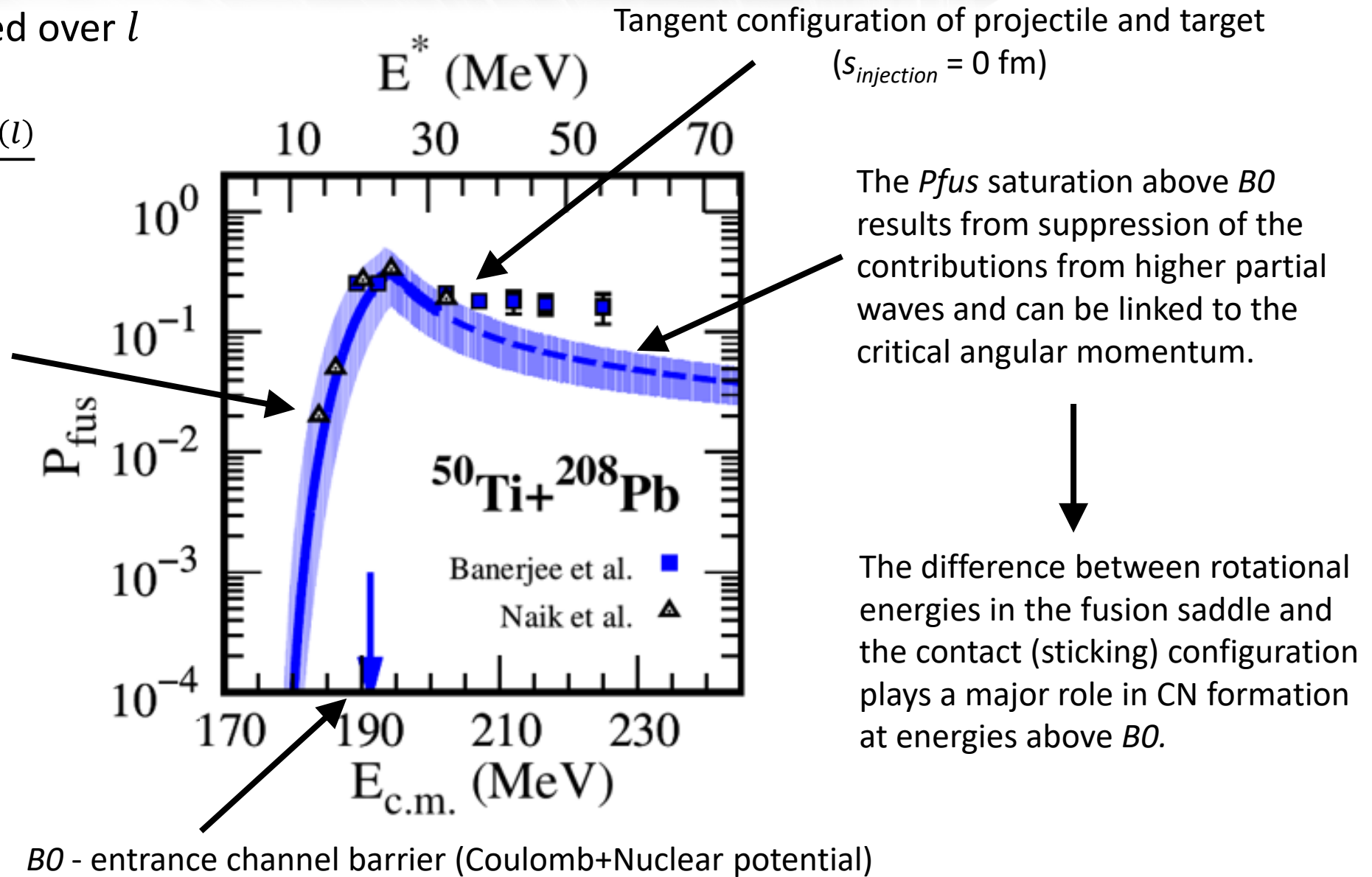
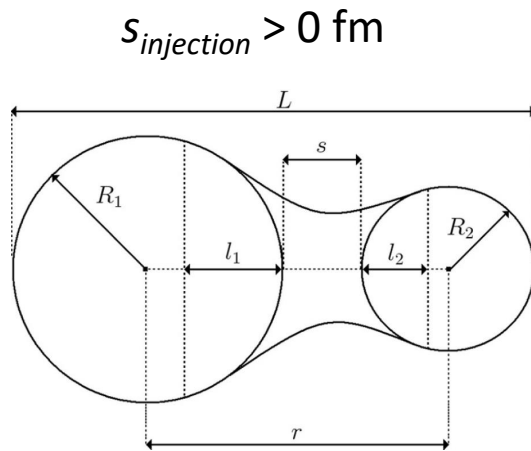


Higher partial waves  $l$   
=  
Higher rotational energy  
=  
Higher barrier  $H(l)$   
=  
Lower  $P_{\text{fus}}(l)$

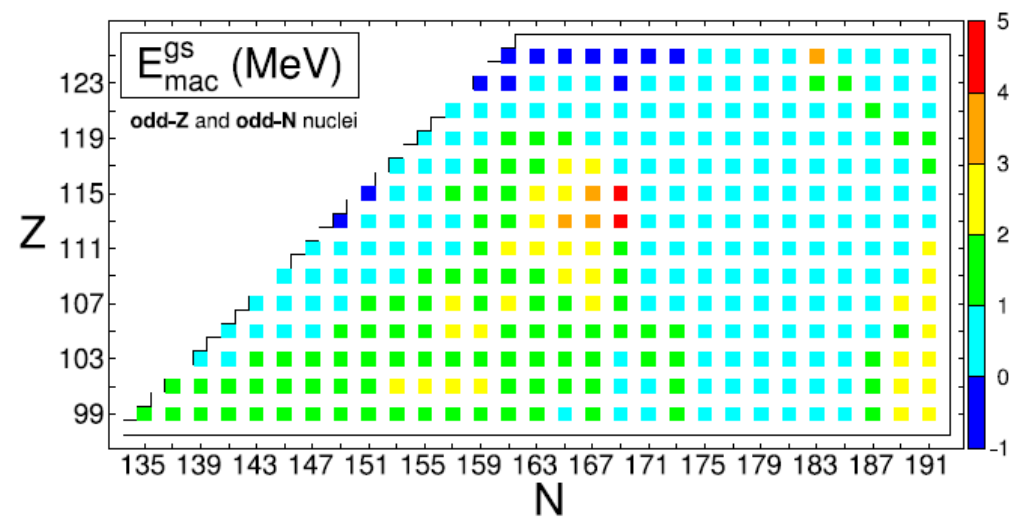
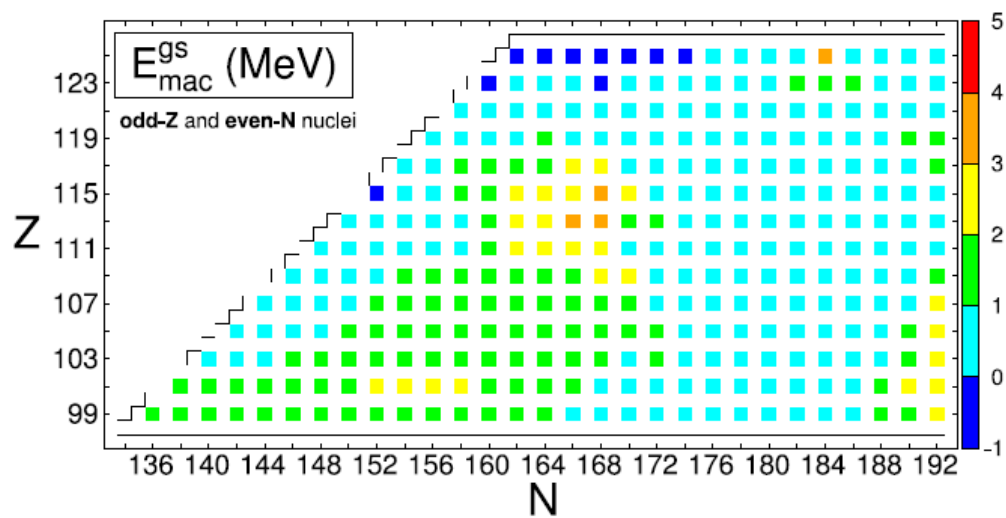
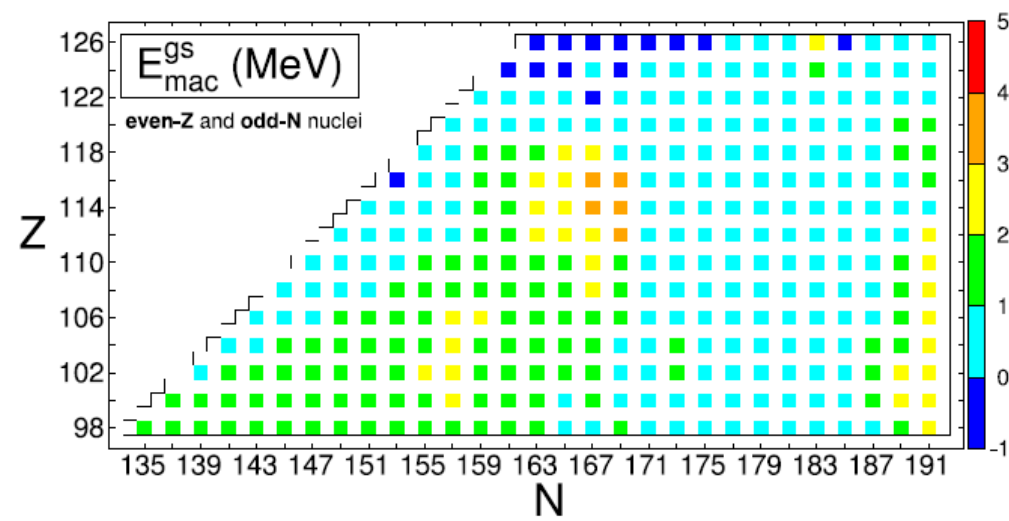
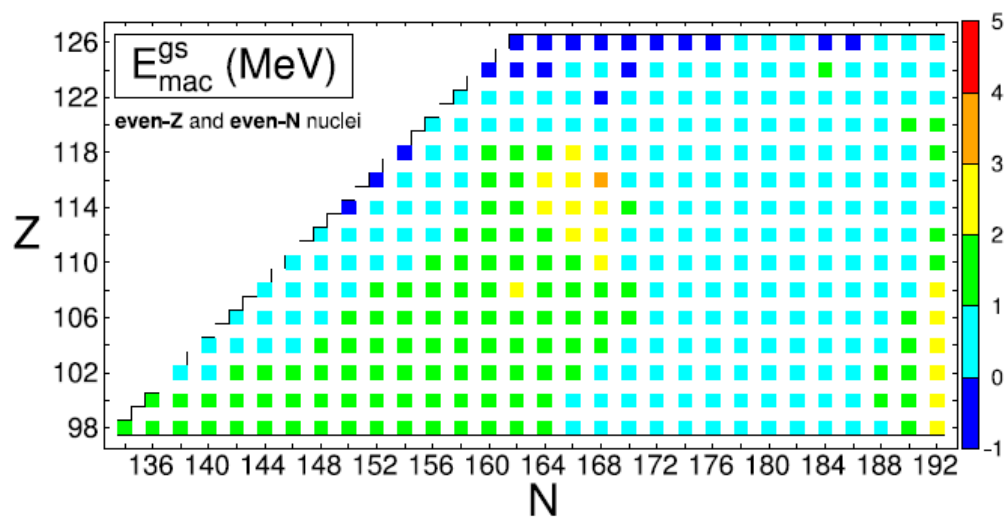
## Fusion probability averaged over $l$

$$P_{fus}(E_{c.m.}) = \frac{\sum_{l=0}^{l_{max}} (2l+1) P_{fus}(l)}{(2l_{max}+1)^2}$$

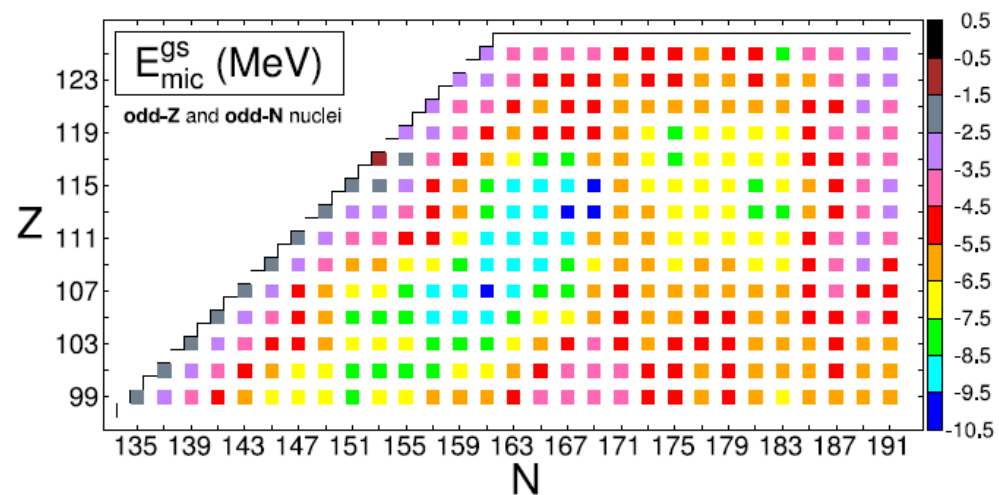
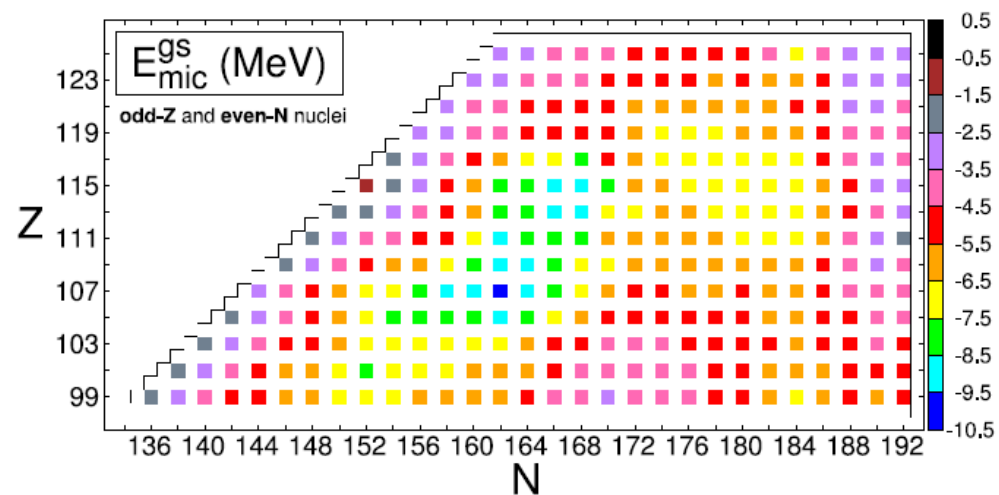
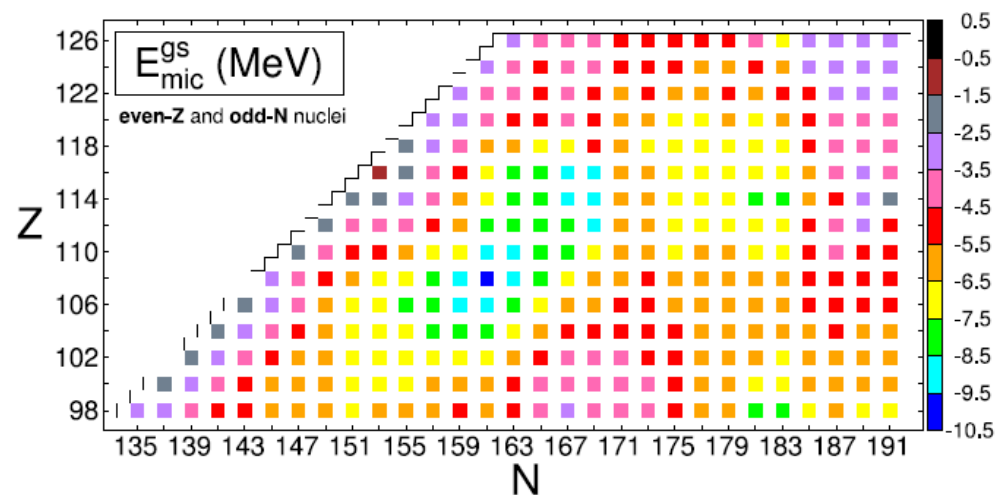
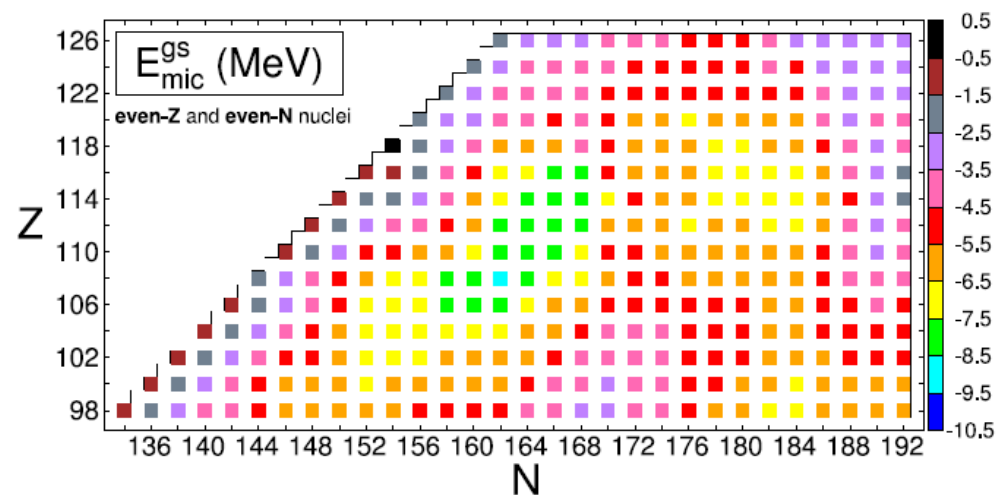
Below  $B0$ , the  $P_{fus}$  growth comes from the reduction in the height of the internal barrier opposing fusion.







P. Jachimowicz, M. Kowal, J. Skalski, Properties of heaviest nuclei with  $98 \leq Z \leq 126$  and  $134 \leq N \leq 192$ , Atomic Data and Nuclear Data Tables, Volume 138, 2021, 101393



**Fig. 2.** Calculated microscopic component  $E_{mic}^{gs}$  of the ground state binding energy in 4 separate groups of nuclei.

P. Jachimowicz, M. Kowal, J. Skalski, Properties of heaviest nuclei with  $98 \leq Z \leq 126$  and  $134 \leq N \leq 192$ , Atomic Data and Nuclear Data Tables, Volume 138, 2021, 101393

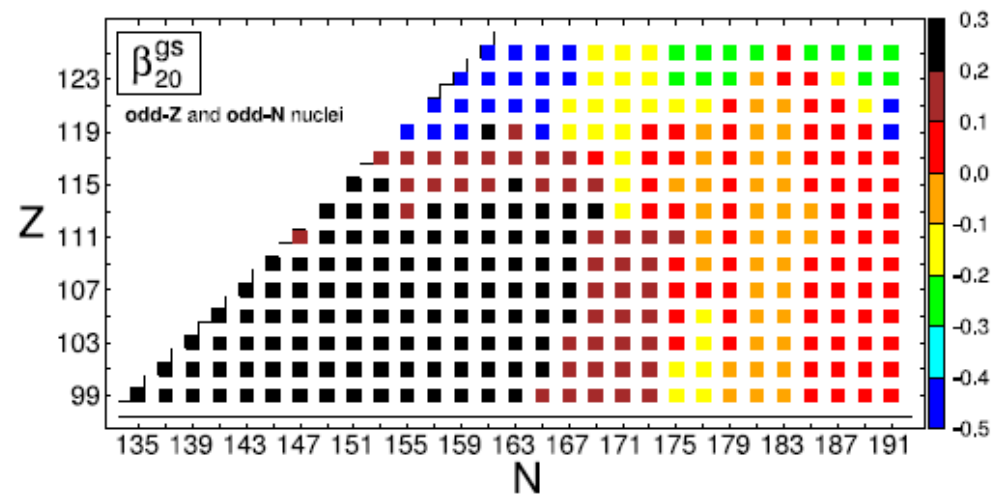
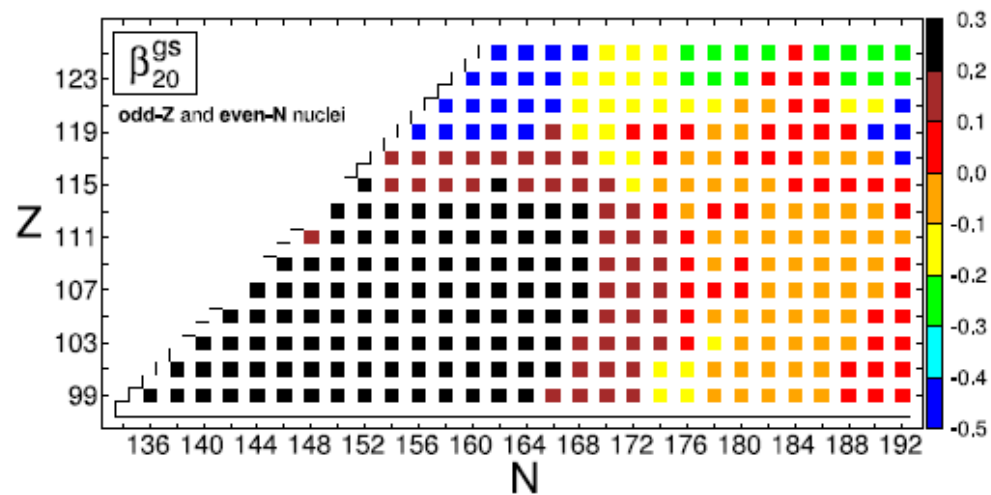
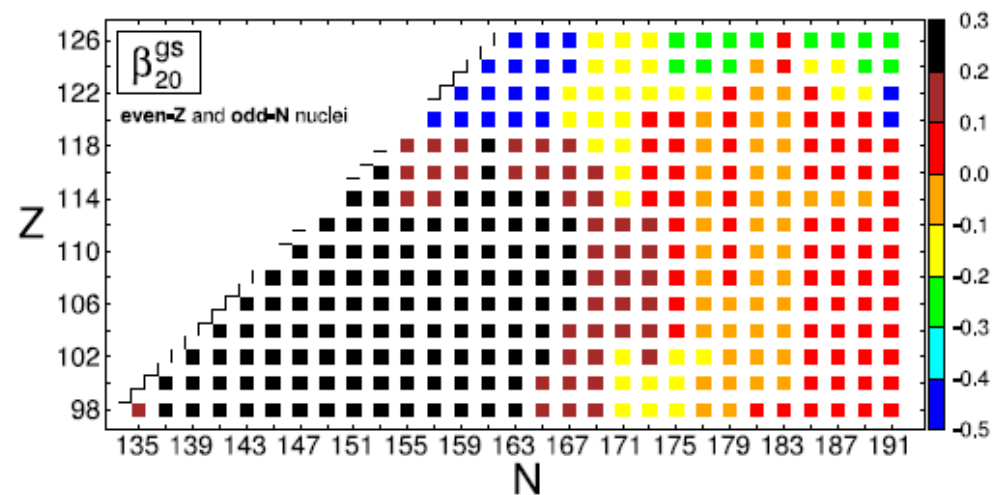
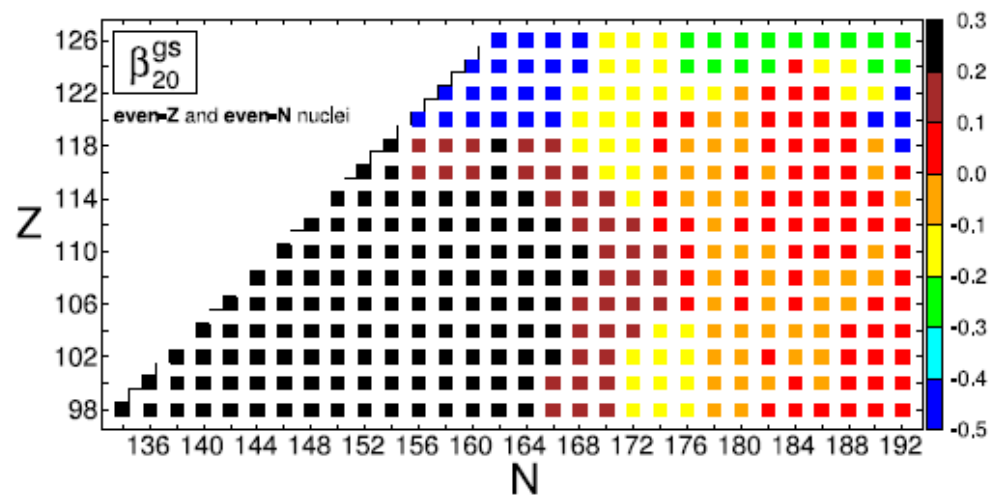


Fig. 4. Calculated ground-state quadrupole deformations  $\beta_{20}^{gs}$  in 4 separate groups of nuclei.

P. Jachimowicz, M. Kowal, J. Skalski, Properties of heaviest nuclei with  $98 \leq Z \leq 126$  and  $134 \leq N \leq 192$ , Atomic Data and Nuclear Data Tables, Volume 138, 2021, 101393



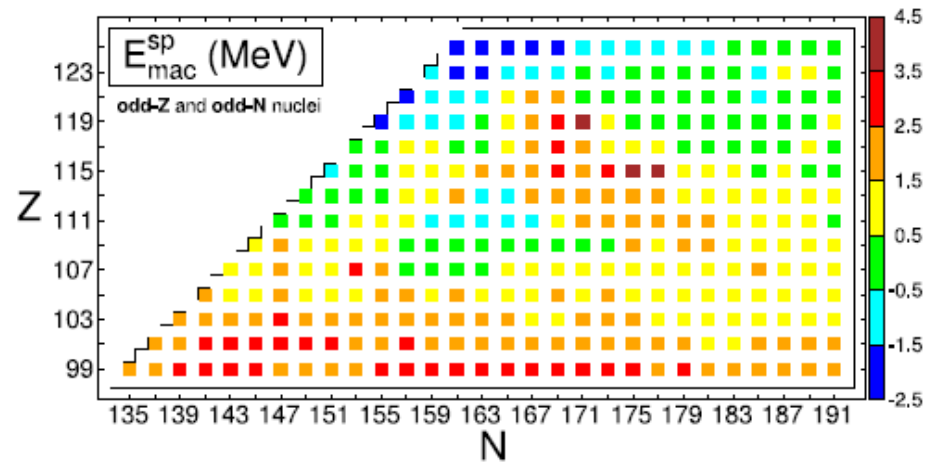
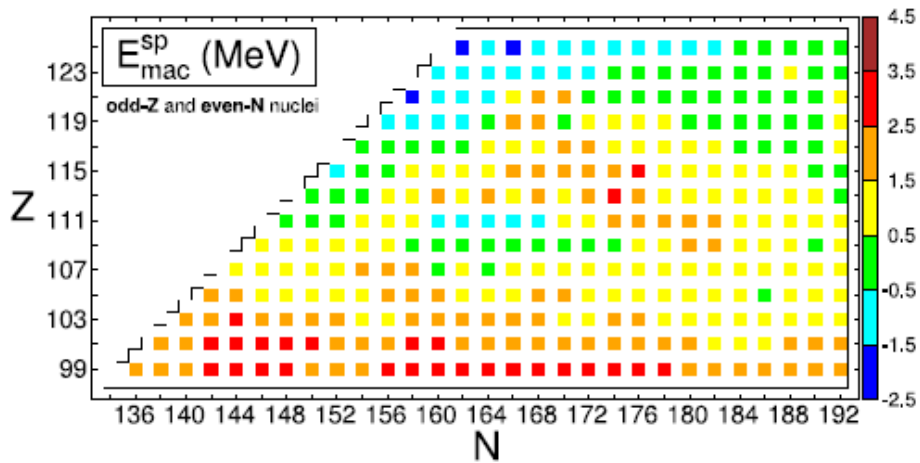
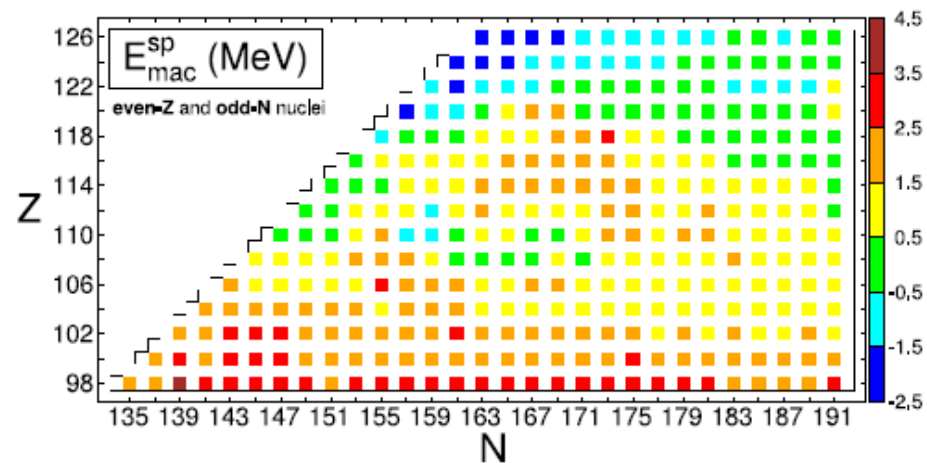
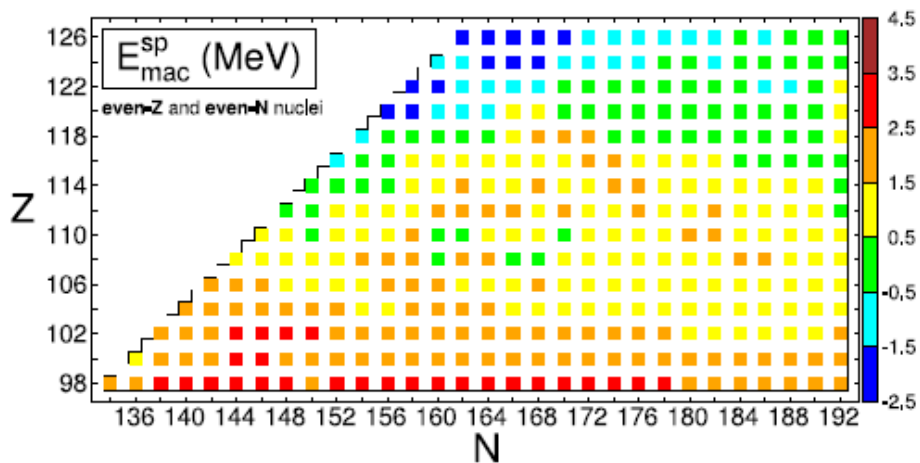


Fig. 12. As in Fig. 1, but for the calculated saddle points.

P. Jachimowicz, M. Kowal, J. Skalski, Properties of heaviest nuclei with  $98 \leq Z \leq 126$  and  $134 \leq N \leq 192$ , Atomic Data and Nuclear Data Tables, Volume 138, 2021, 101393

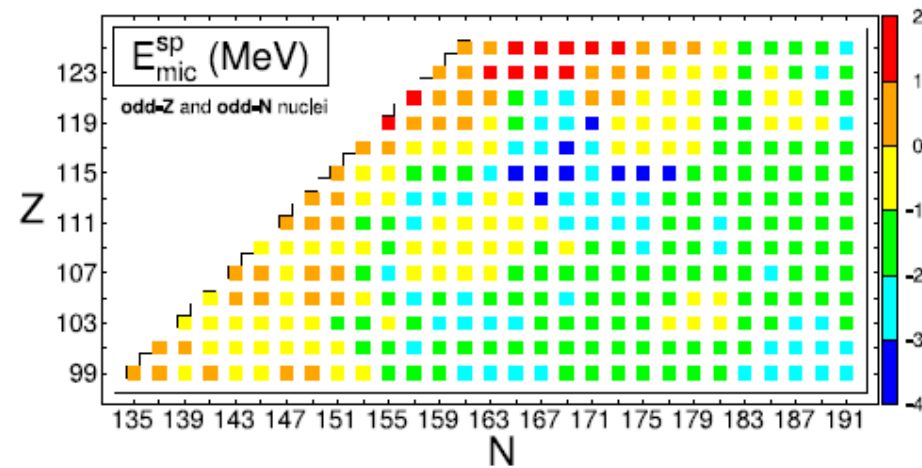
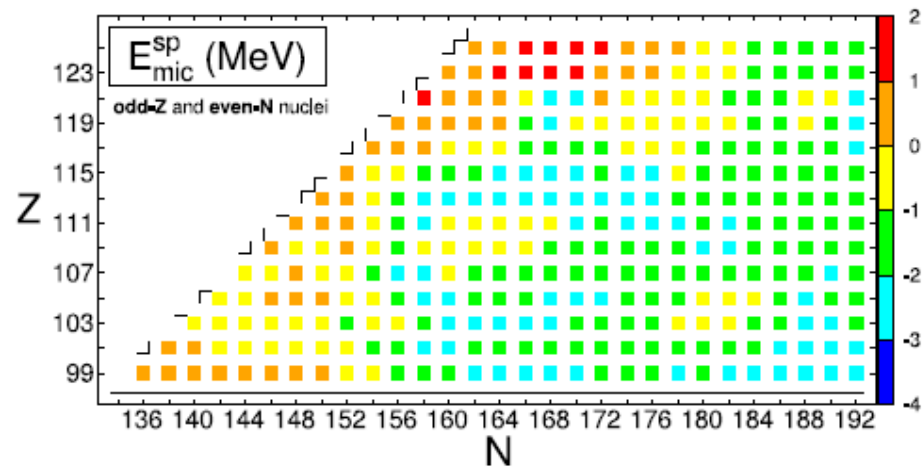
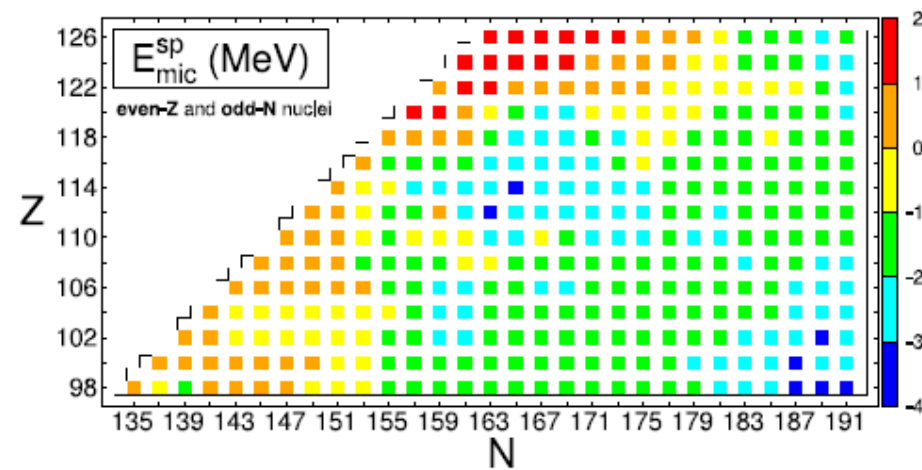
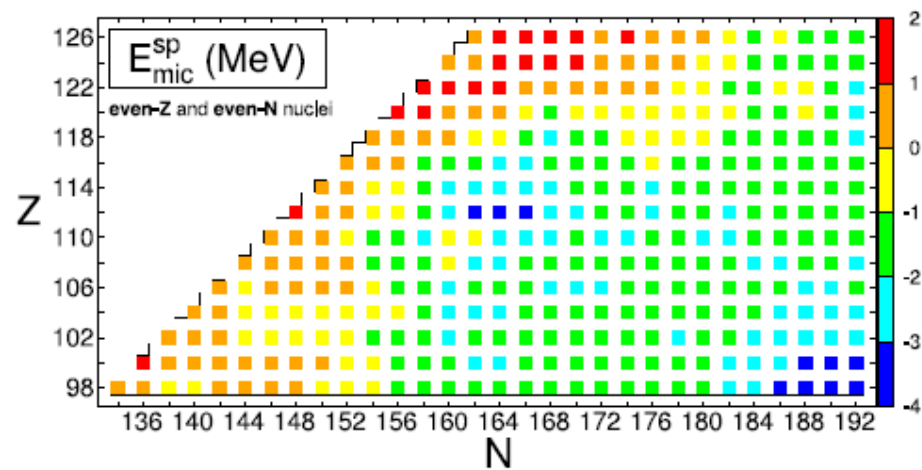


Fig. 13. As in Fig. 2, but for the calculated saddle points.

P. Jachimowicz, M. Kowal, J. Skalski, Properties of heaviest nuclei with  $98 \leq Z \leq 126$  and  $134 \leq N \leq 192$ , Atomic Data and Nuclear Data Tables, Volume 138, 2021, 101393