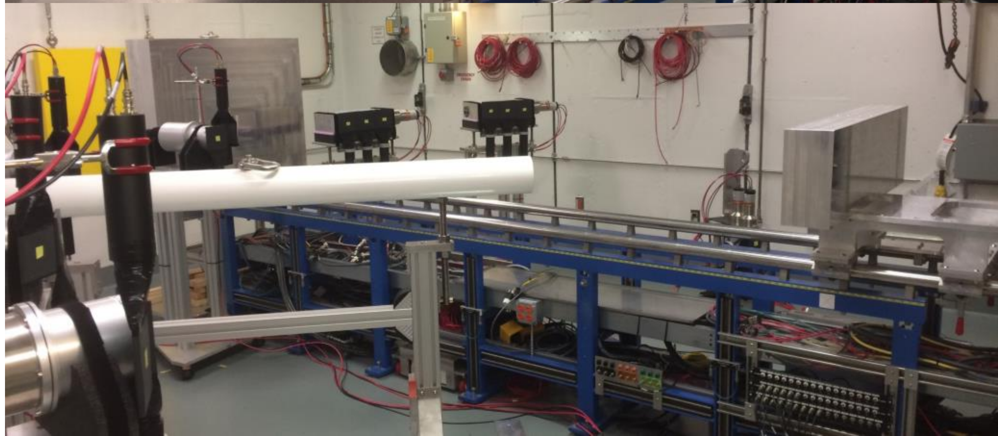
Secondary Neutron Production
in space (and ion therapy)

Where they come from,
Why they are important, and
The current state of the data.

Hunter Ratliff
Department of Computer science, Electrical engineering and Mathematical sciences
2 March 2022

Where do secondary neutrons come from in space?

- 2 radiation sources in deep space
  - Solar energetic particles (mostly p^+, some He)
    - Acute risk - solar particle events
  - Galactic Cosmic Rays (GCRs, all ions)
    - Chronic risk - constant GCR flux
- GCR energies peak around 0.1-1 GeV/n
- Neutrons produced in fragmentation reactions with target material (shielding / tissue)

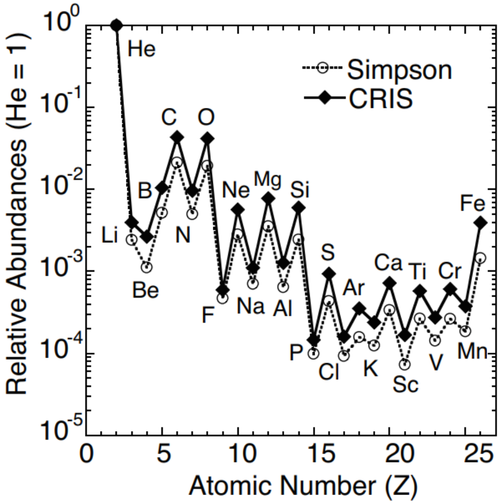


Fig. 3. Comparison of elemental abundance of galactic cosmic rays, based on the data (Simpson, 1983) with the data from ACE/CRIS (Israel *et al*., 2005).

GCR ion relative abundances by element [1]
(~87% H, 12%He, 1% everything else)

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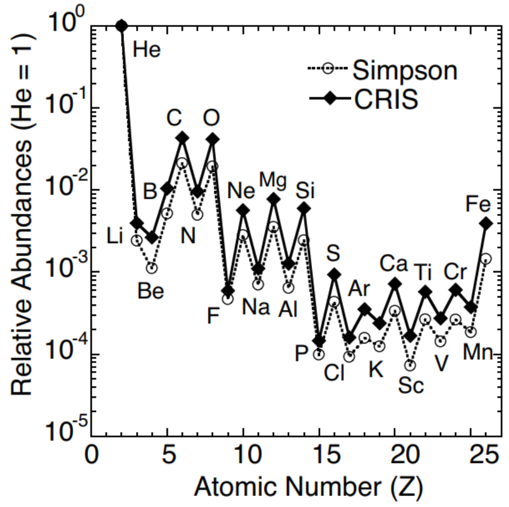
- Secondaries cause heavier GCR components to have similar dosimetric contribution to lighter components, despite decreased abundance.
- Ion therapy sees similar ion species, energies, and target materials of interest.



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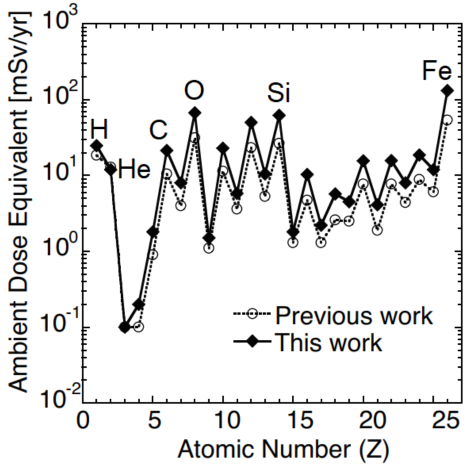

Fig. 5. Annual ambient dose equivalent from each component of GCRs for the solar activity averaged over a solar cycle. The solid line shows the dose estimated from ACE/CRIS abundance data and the dash line from Simpson's abundance data.

Dose equivalent contribution of each GCR component in a lunar surface environment [1]

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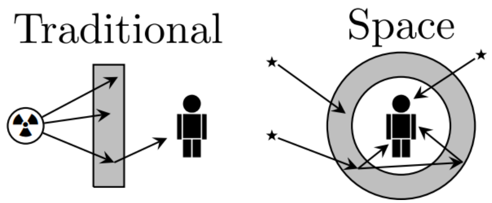
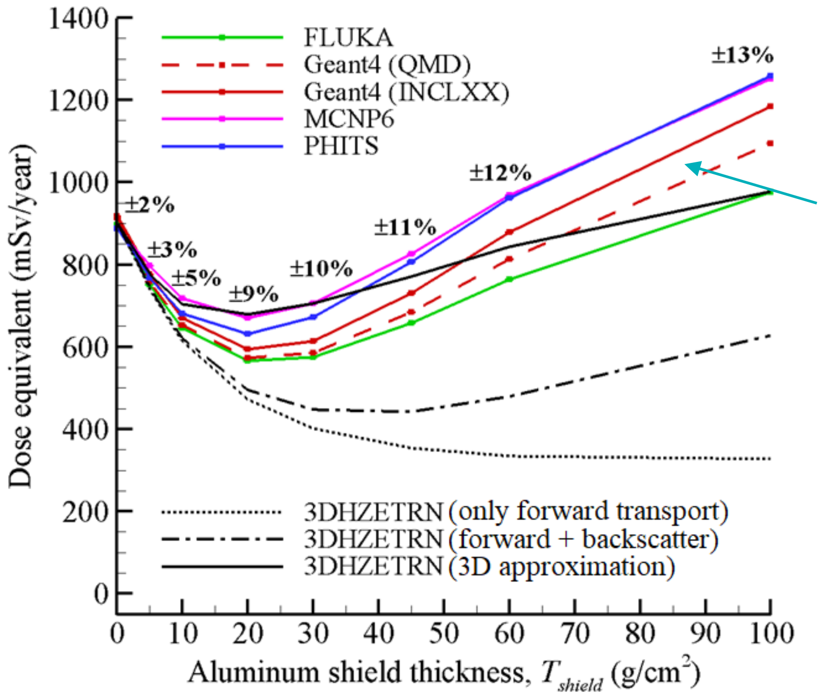
Why is knowledge of these secondary neutrons important?

- With increasing shielding thicknesses, neutrons become increasingly prevalent contributors to astronaut dose.





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Simulated dose equivalent as a function of Al shielding thickness in an enclosed environment [2]

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- MSL-RAD (detector onboard the Curiosity rover) observed dose equivalent rates of:
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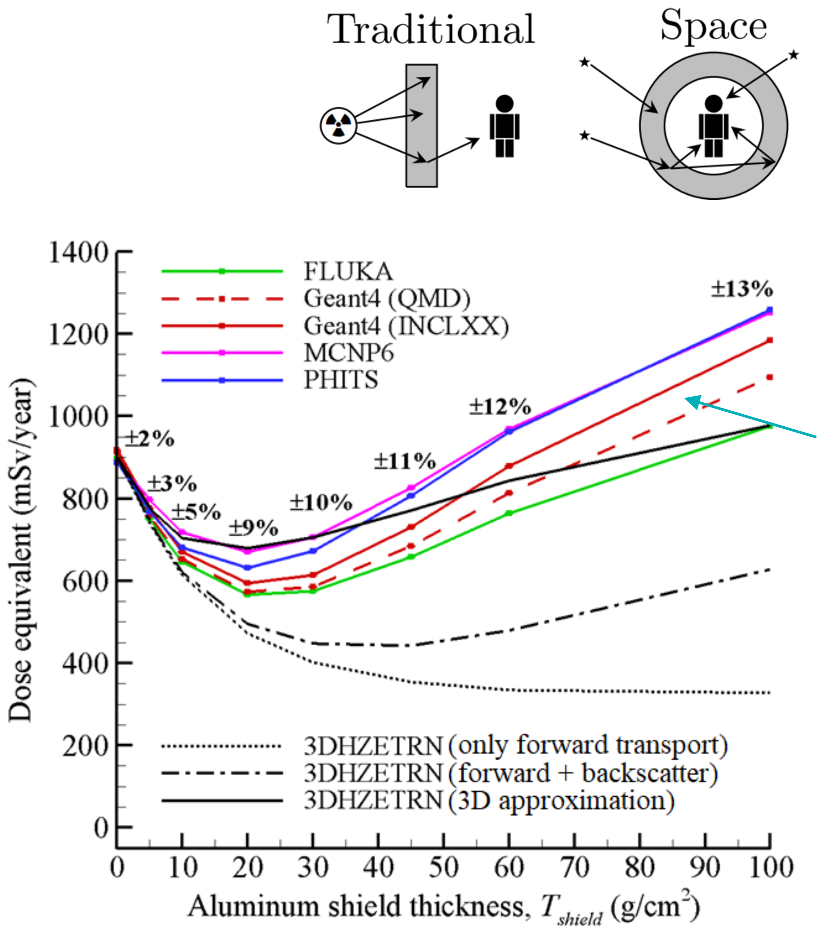

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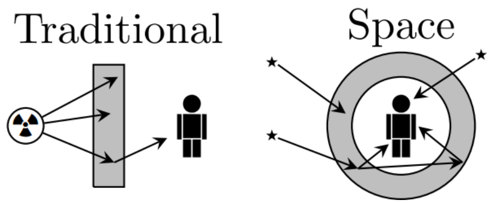

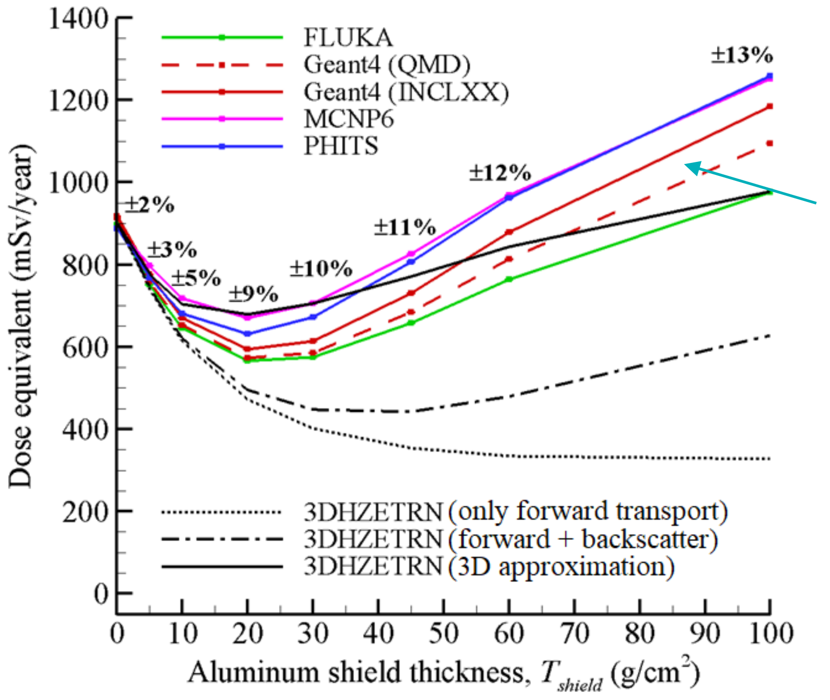

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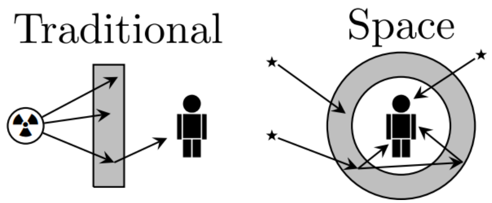
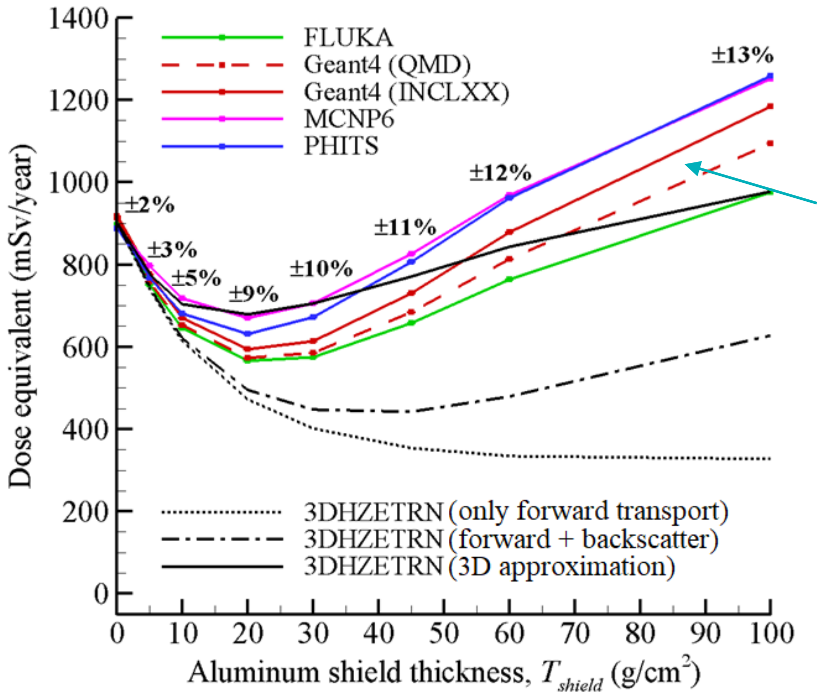
- These neutrons are also important for ion therapy doses and proposed range verification and imaging systems [5].





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What data on secondary neutrons is currently available?

- Both angular & energy dependencies are important since neutrons can scatter at large angles.
- 2 primary categories of interest:

- Double-differential cross sections $\frac{d^2\sigma}{dE d\Omega}$
- Thin target to isolate single interactions
  - Known E_{beam} inducing every reaction

- Double-differential (thick target) yields $\frac{d^2Y}{dE d\Omega}$
- Neutrons produced from a large variety of reactions and energies in thick targets
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- More target → more interactions → more secondaries → better statistics

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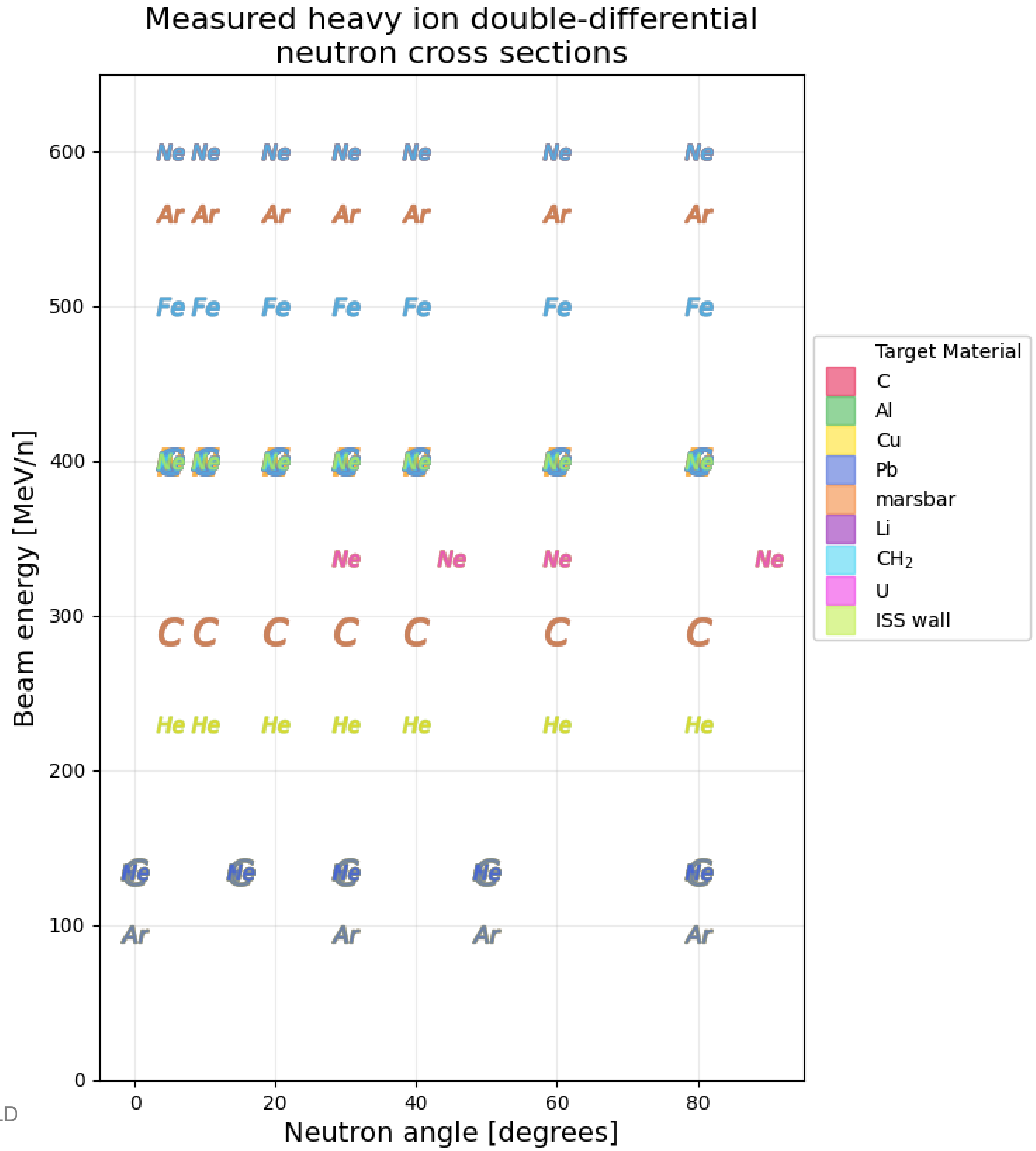

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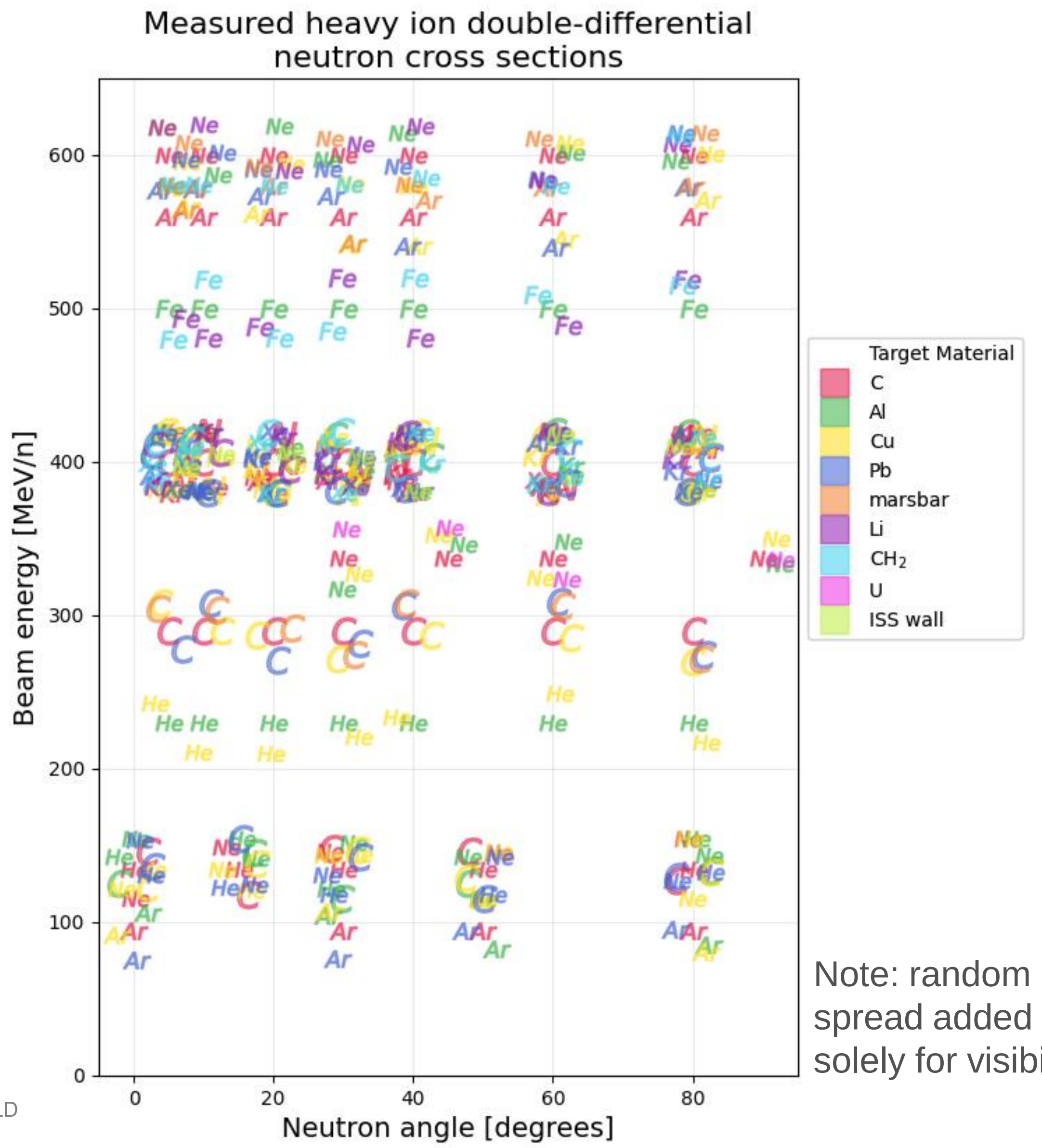

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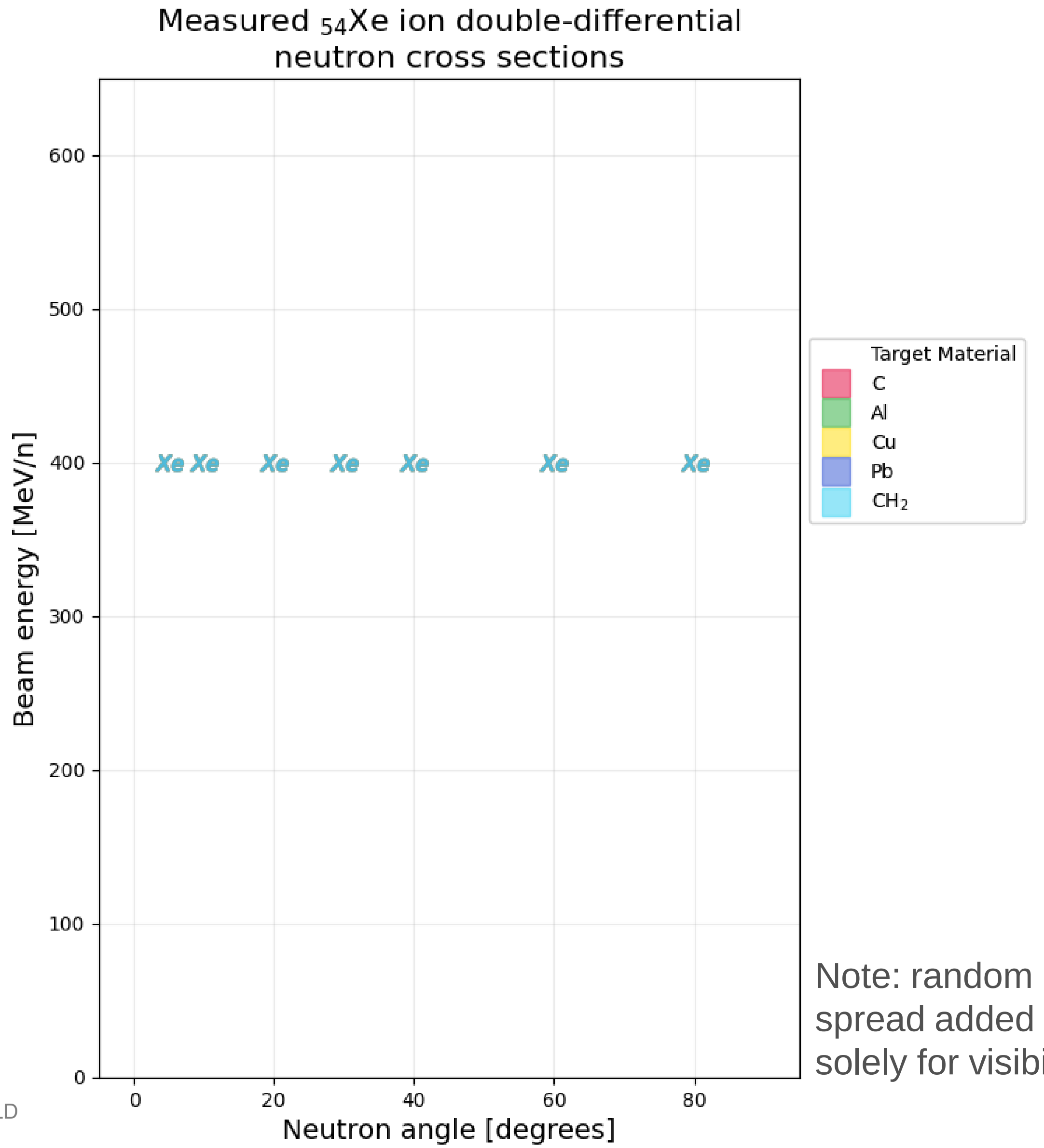

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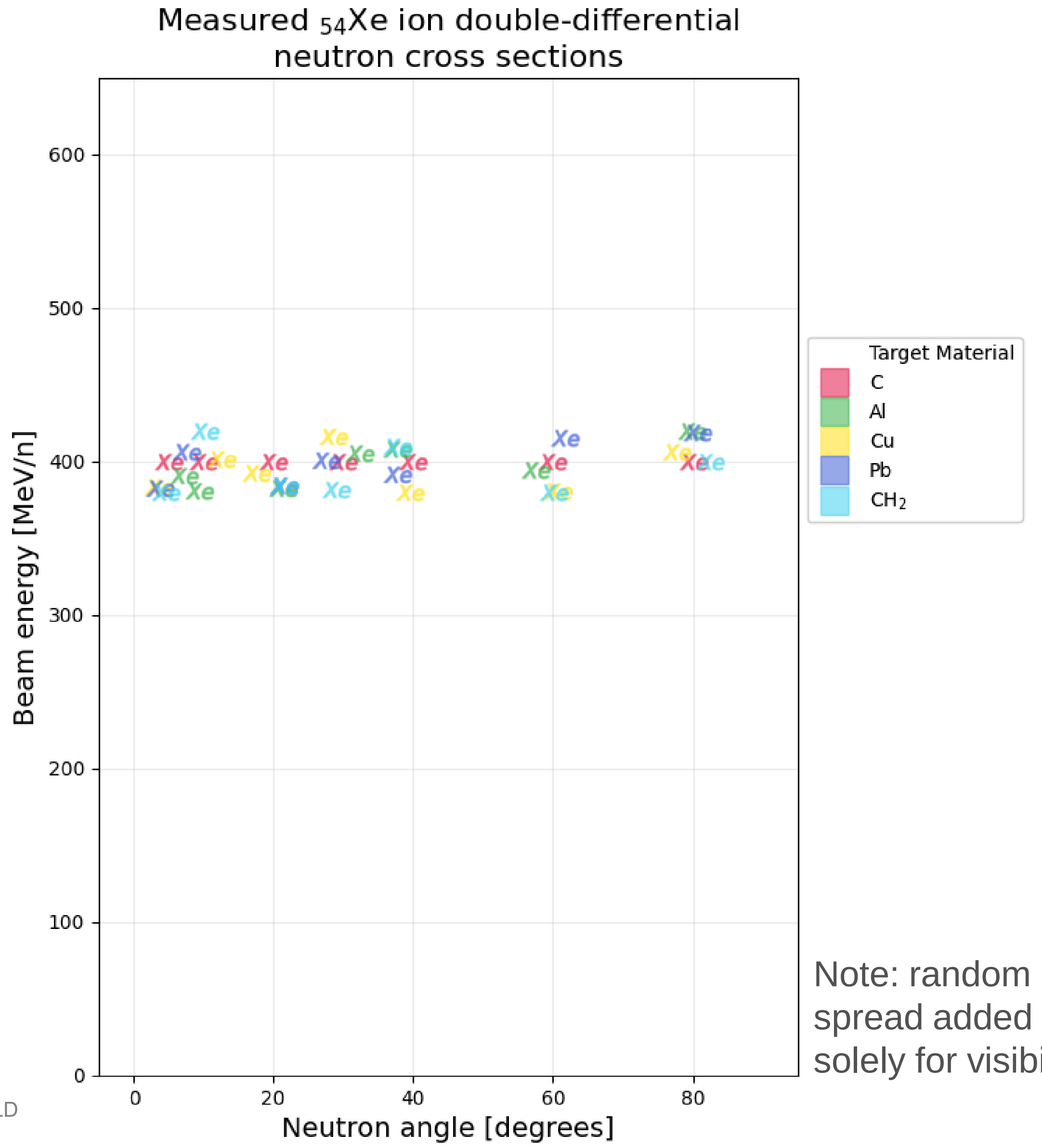

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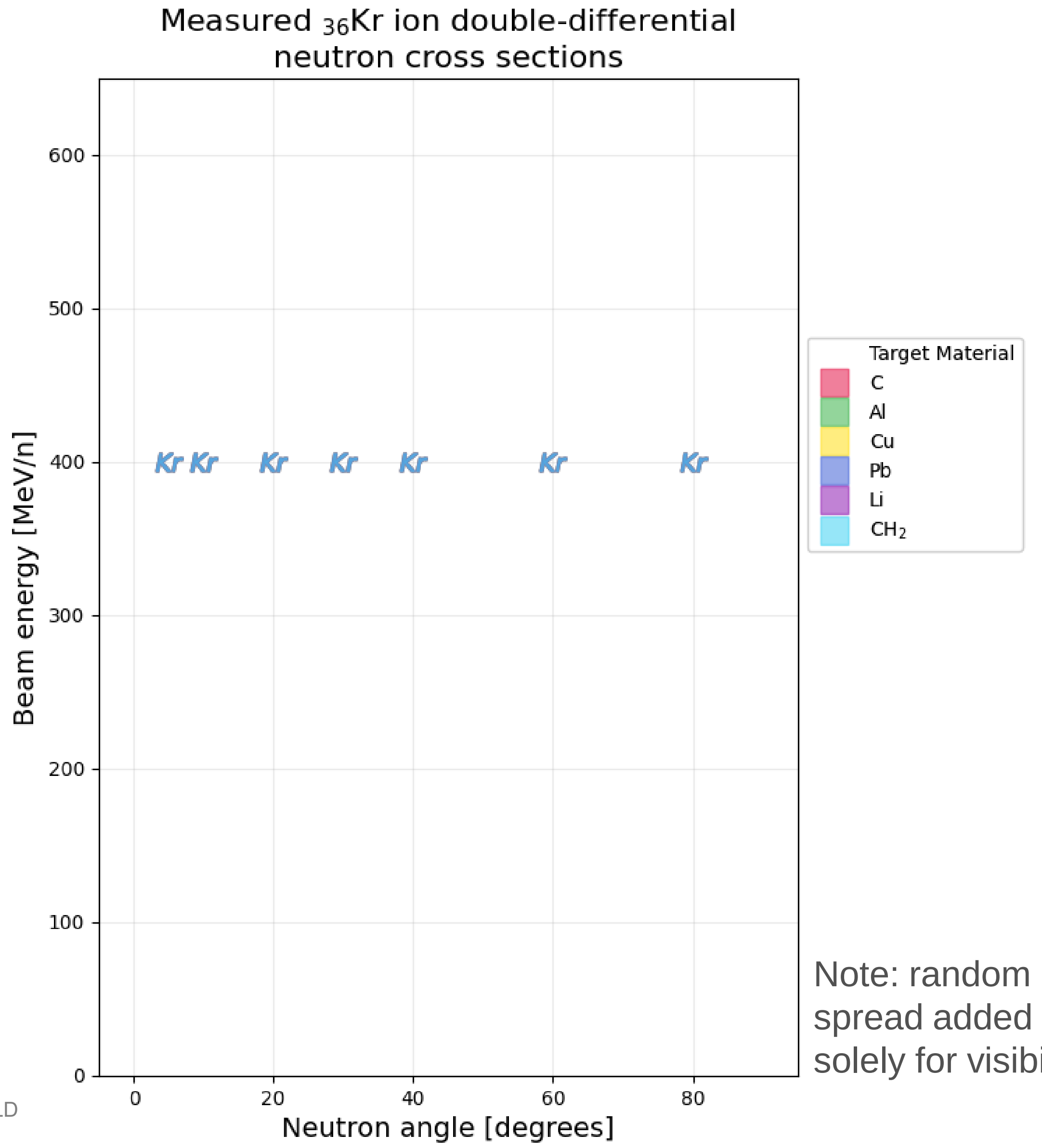

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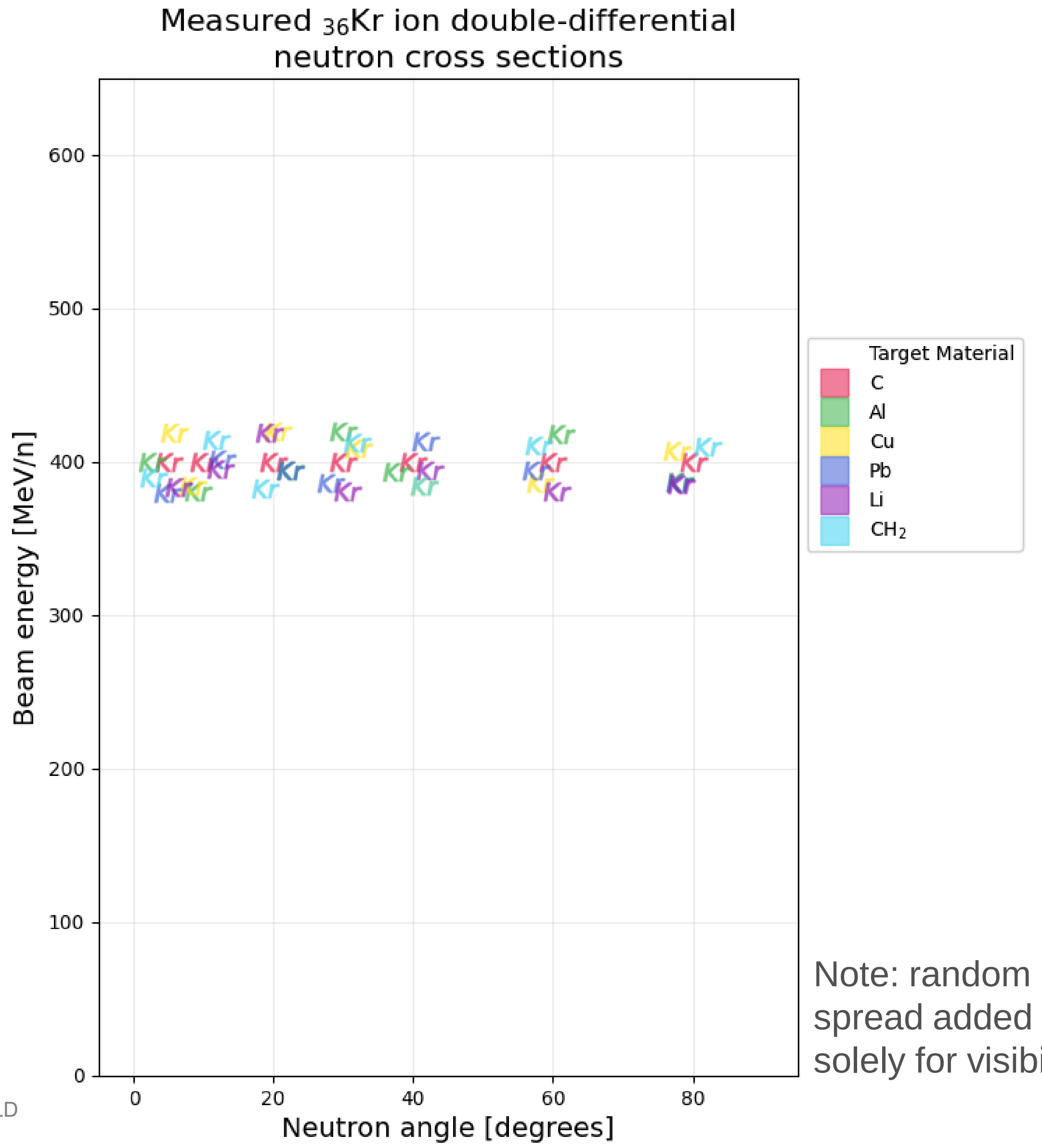

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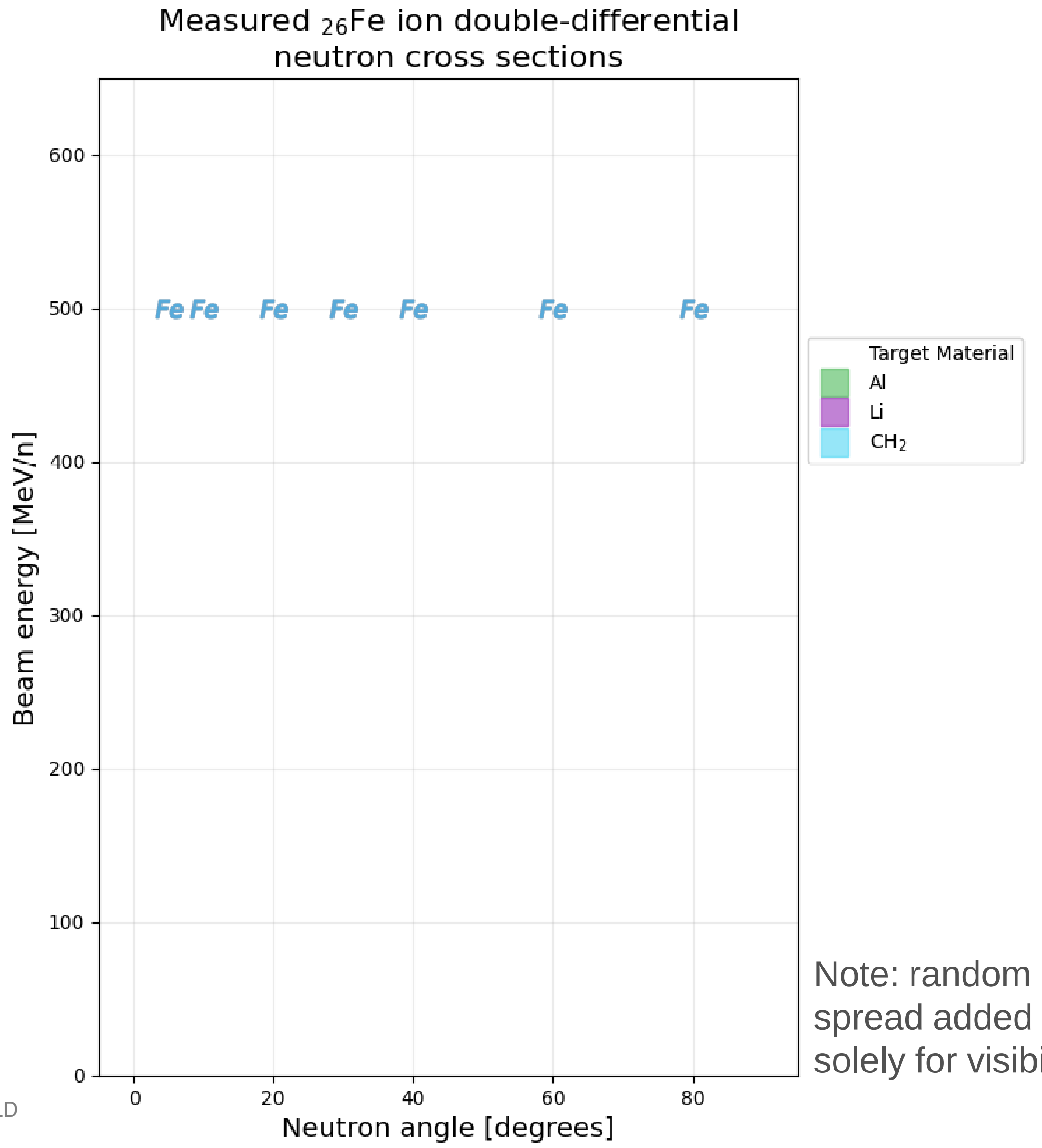

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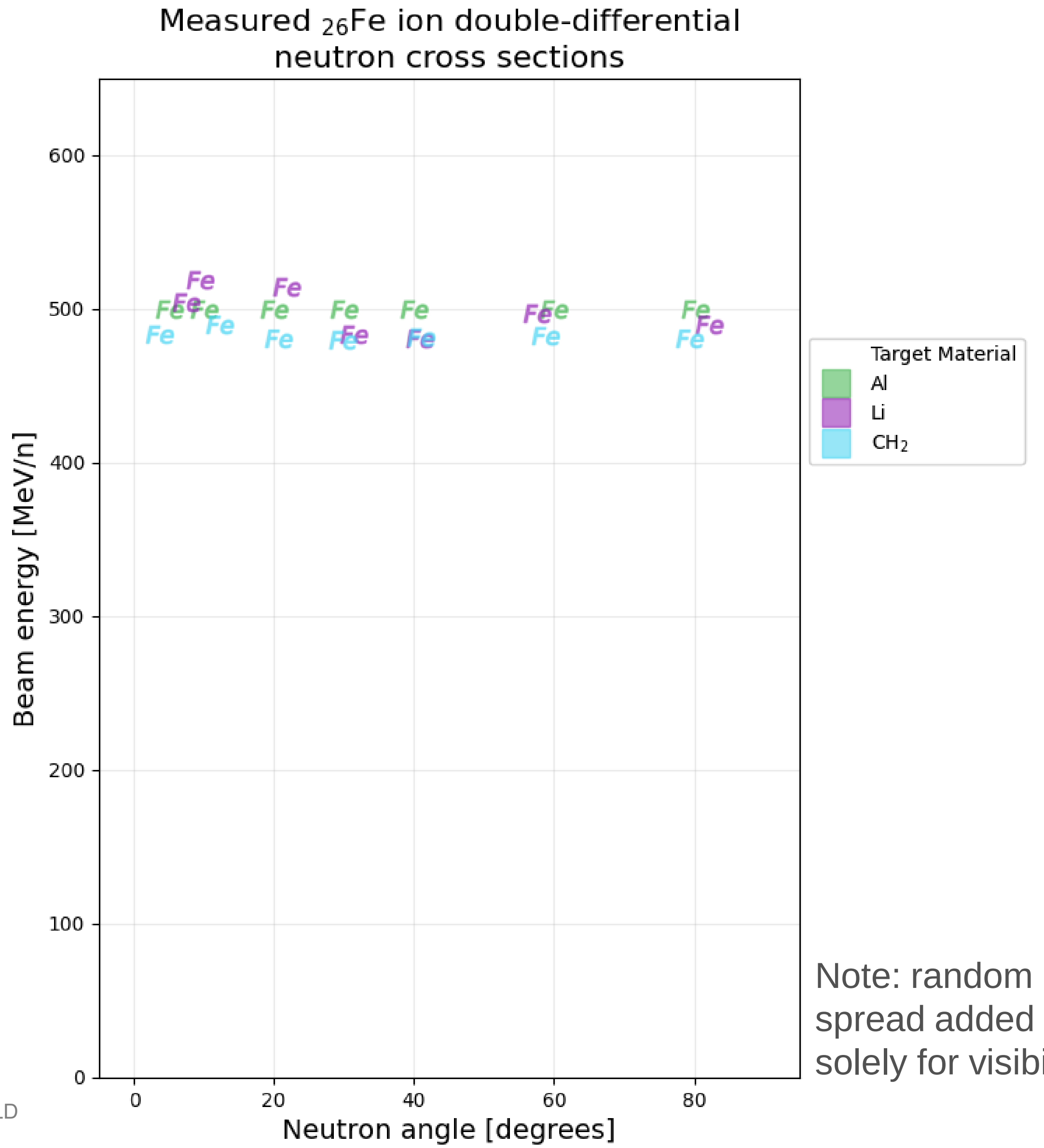

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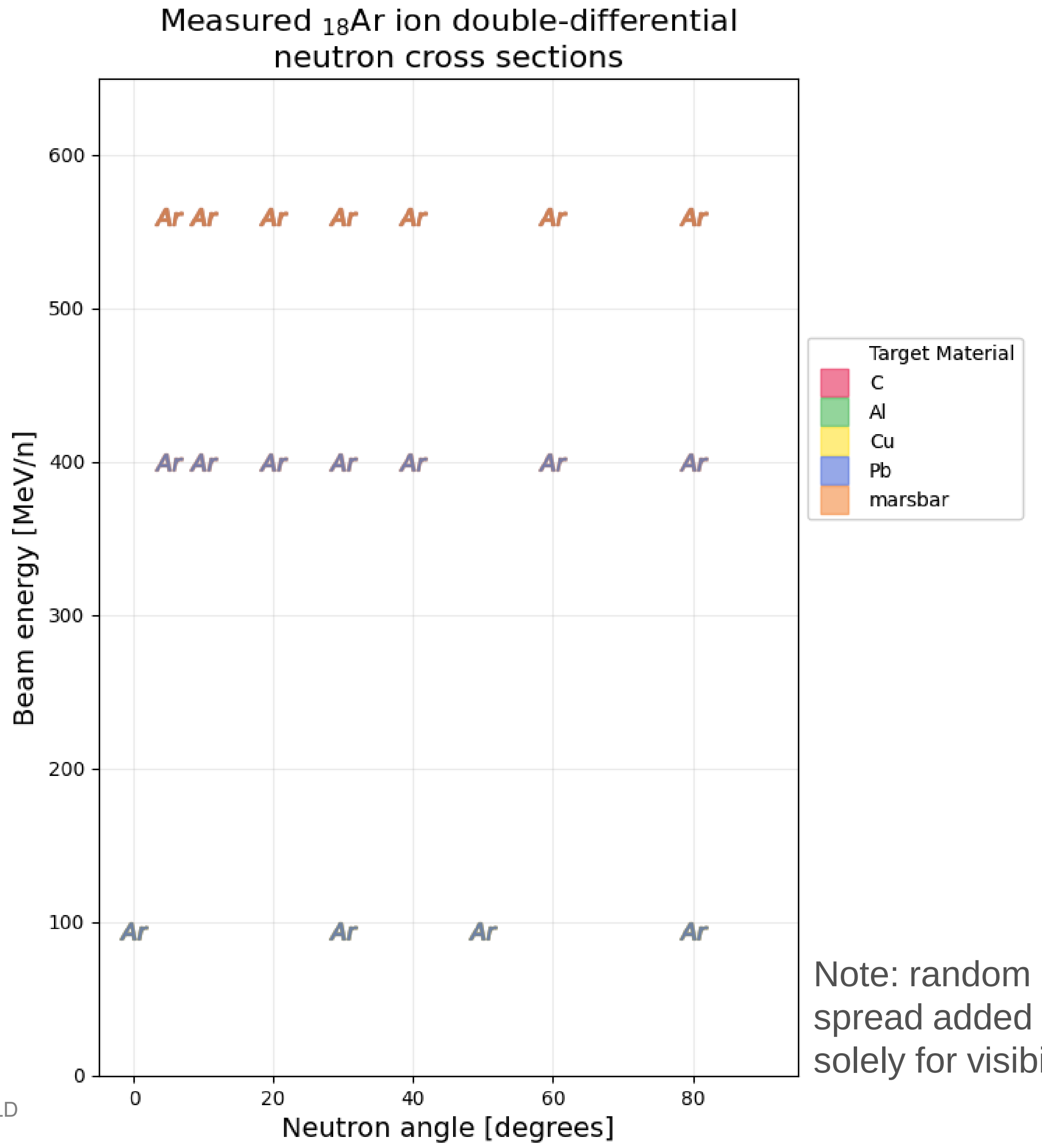

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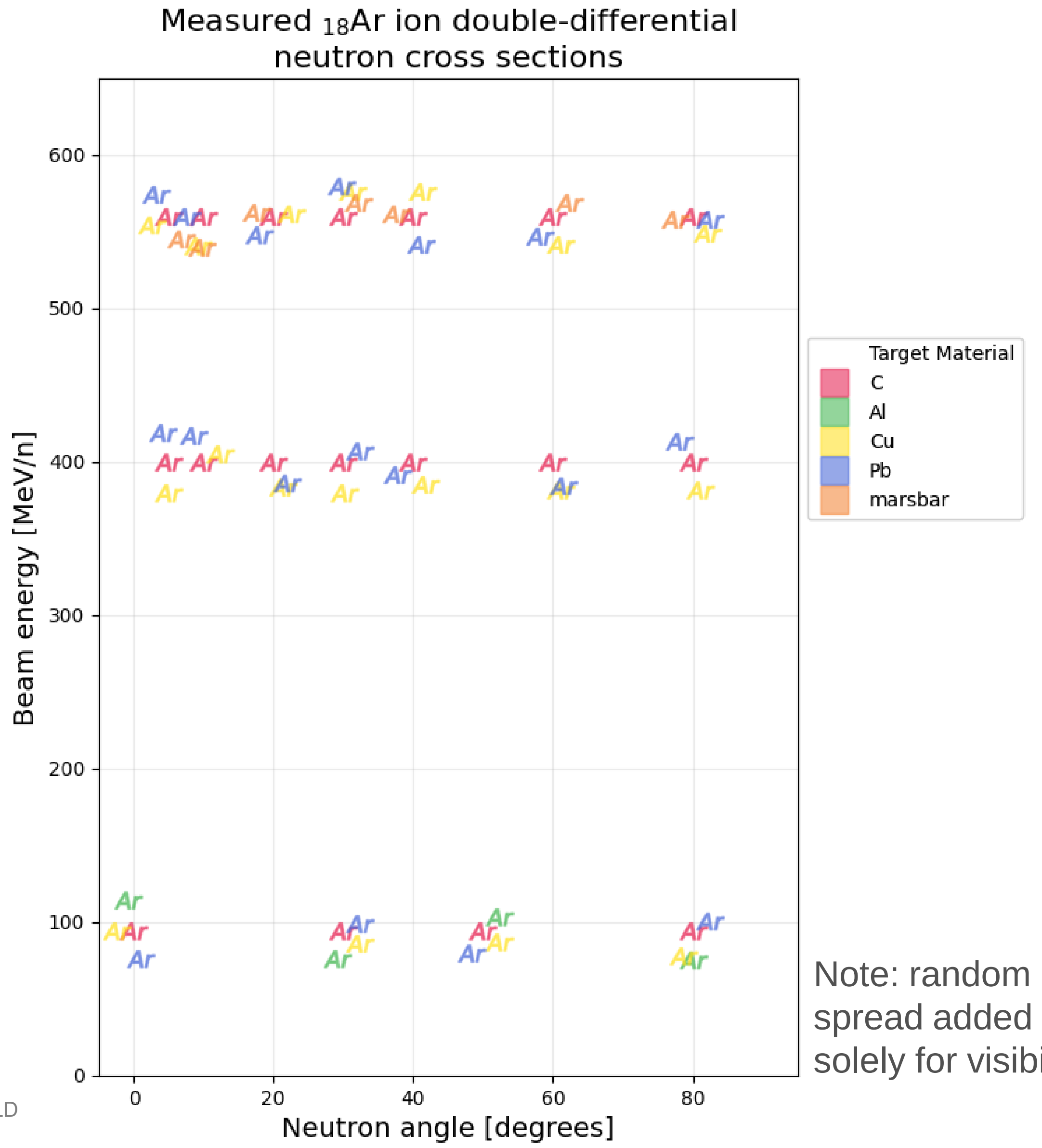

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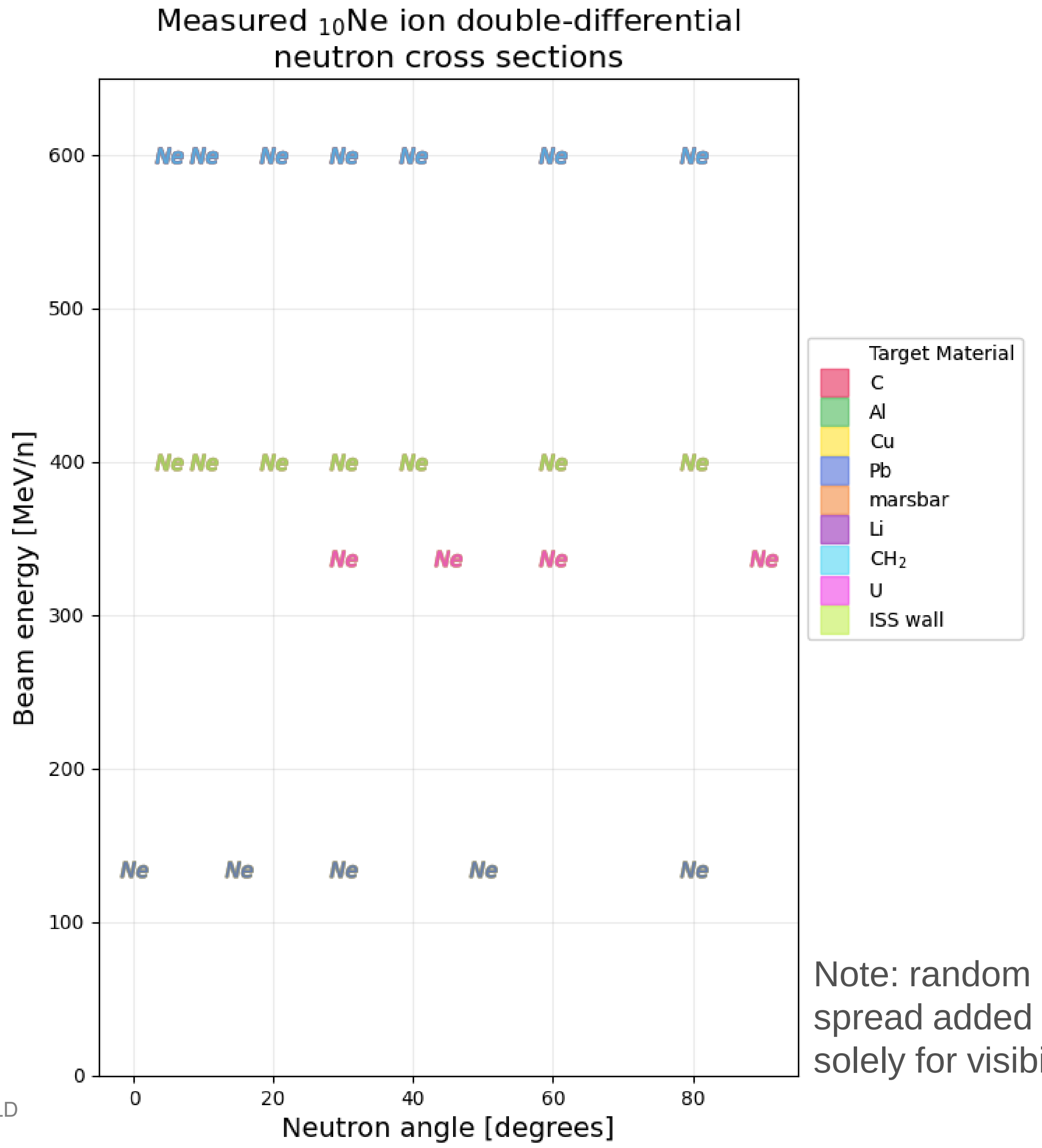

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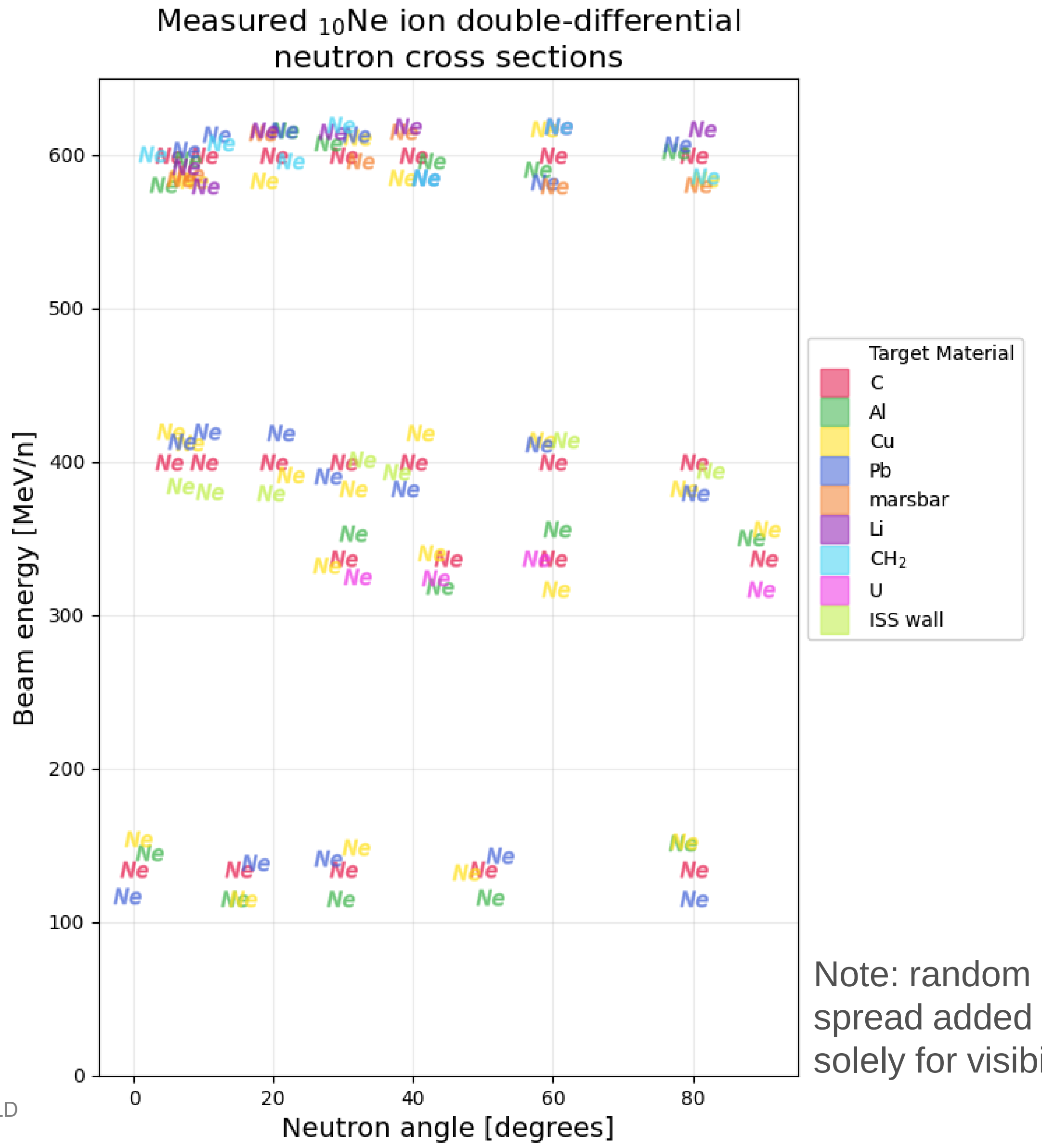

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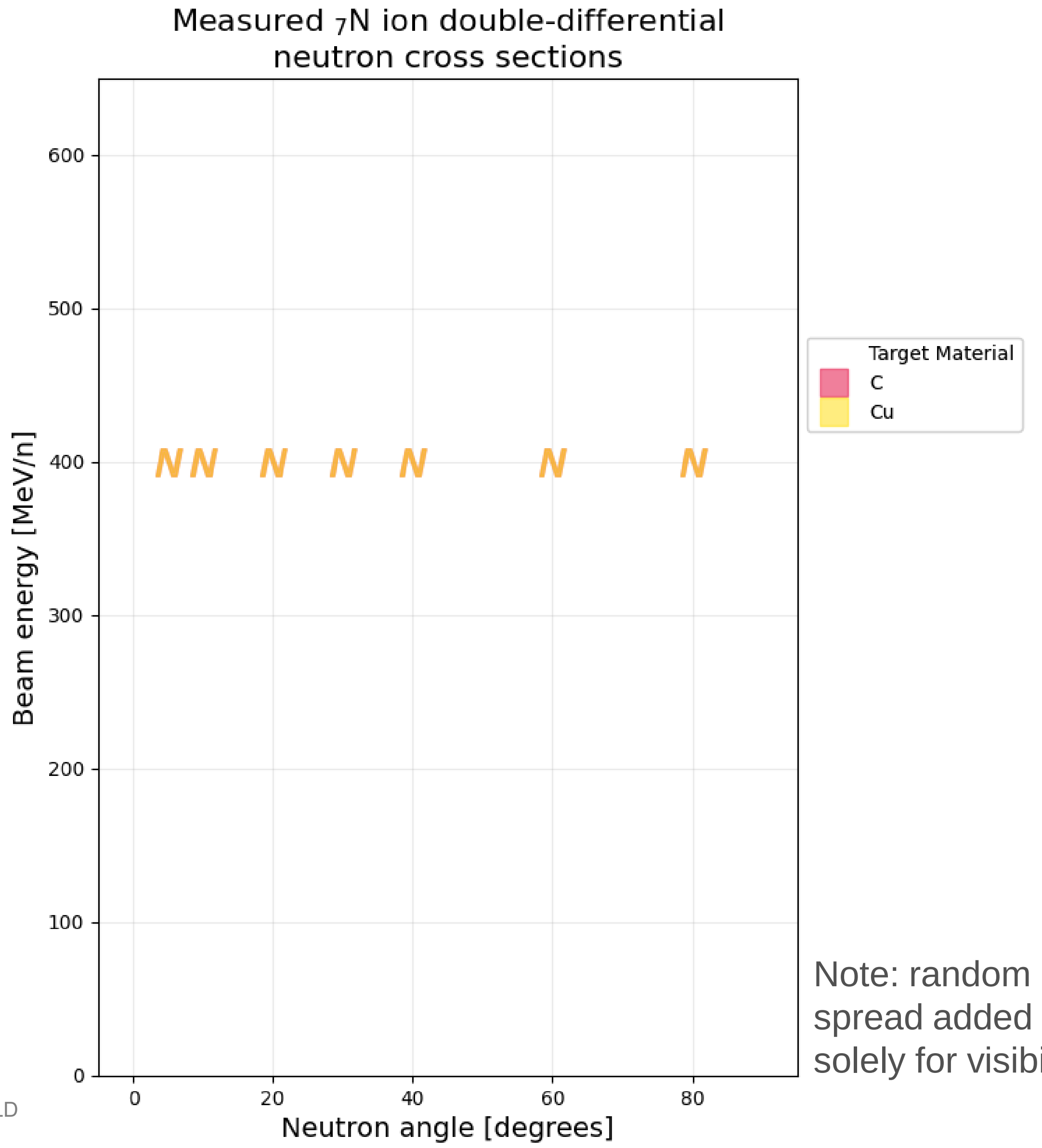

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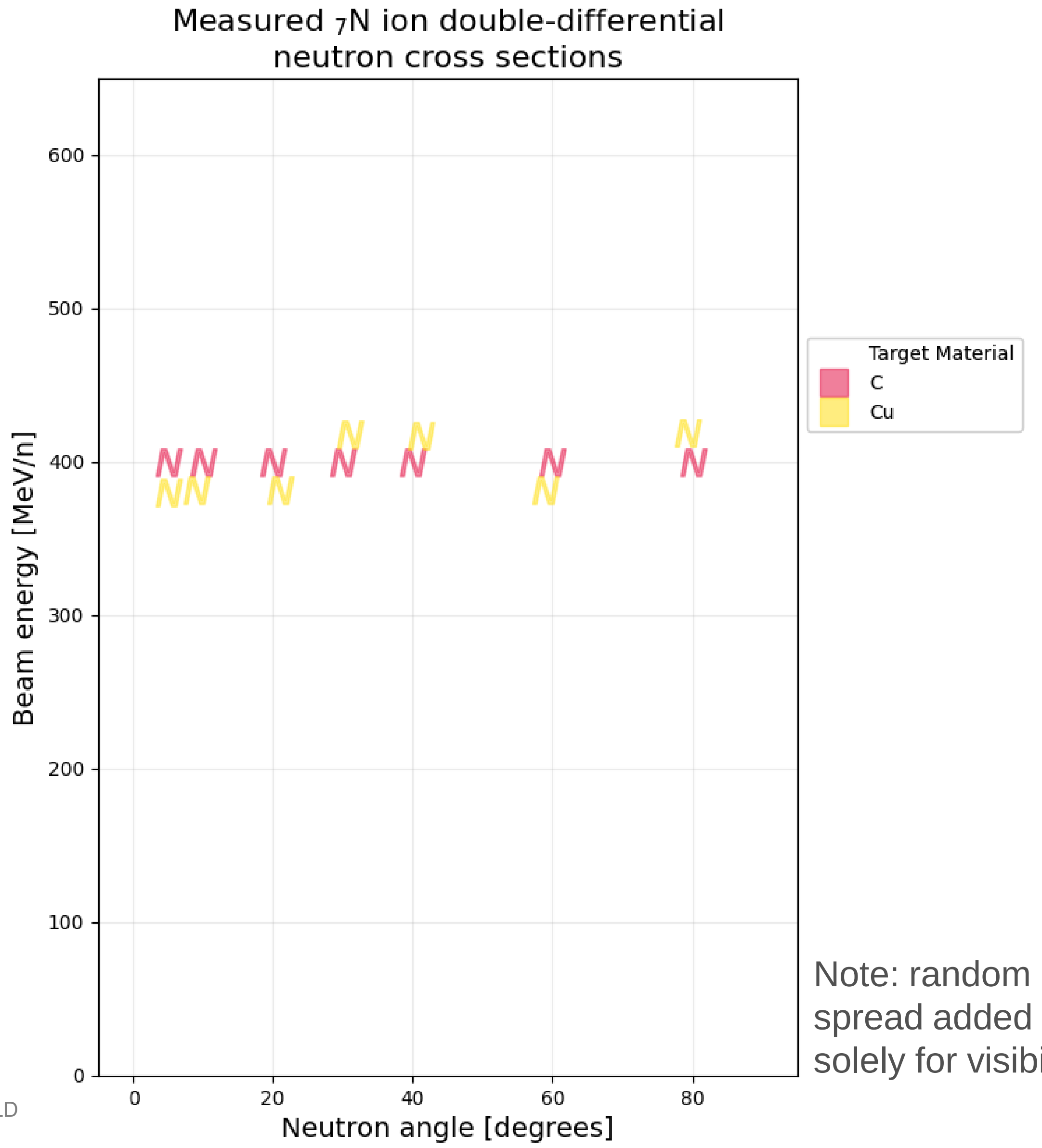

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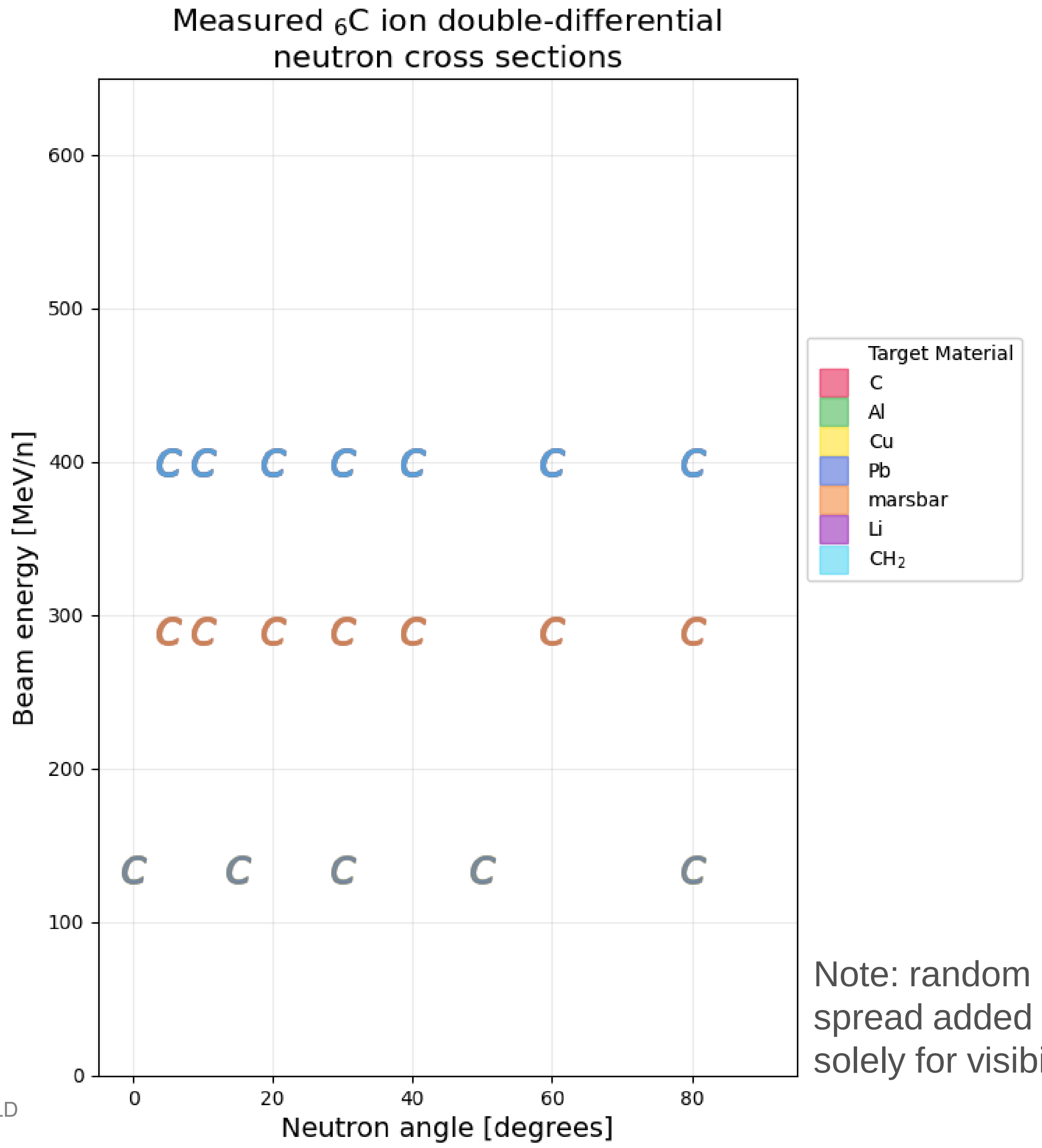

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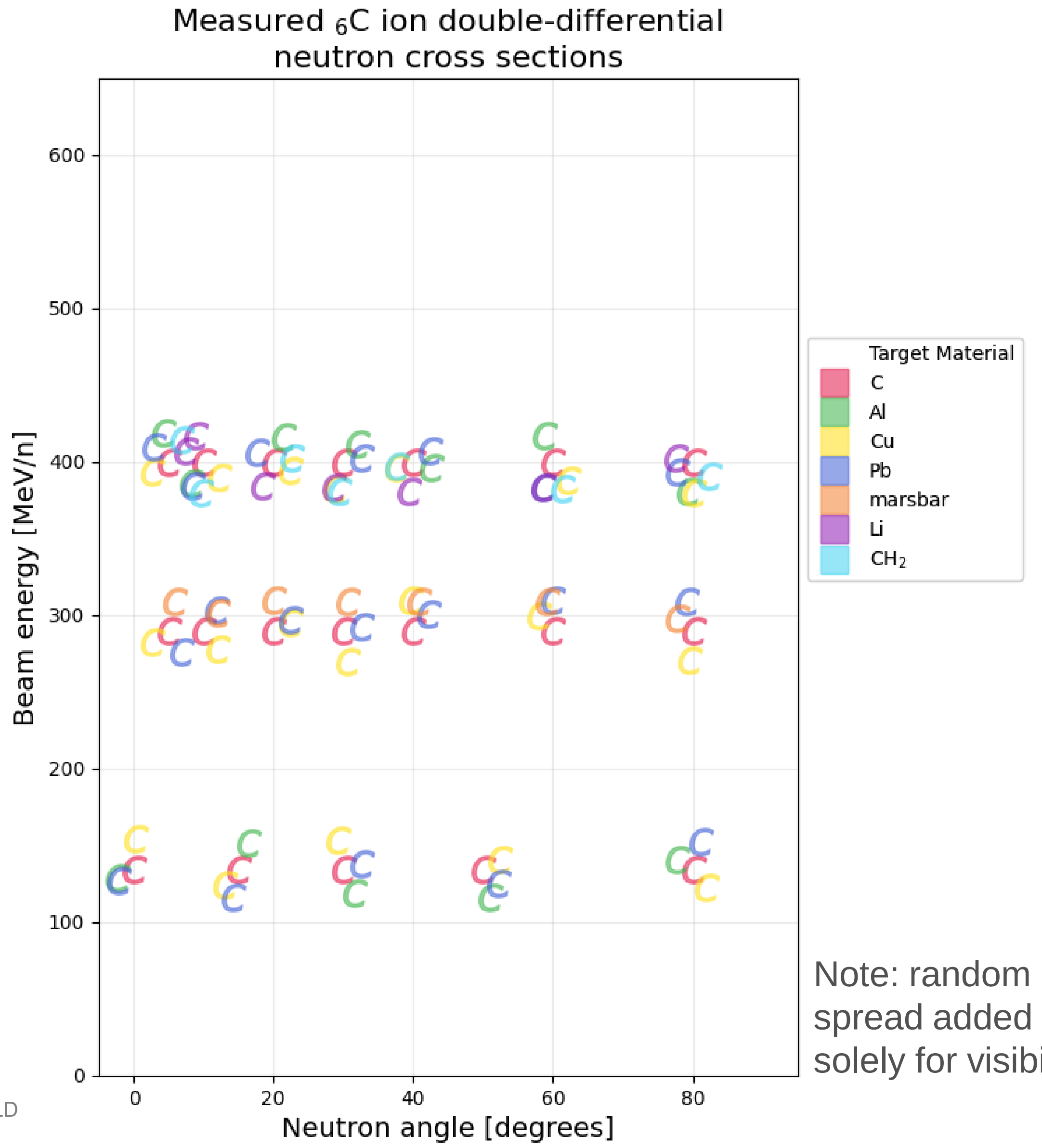

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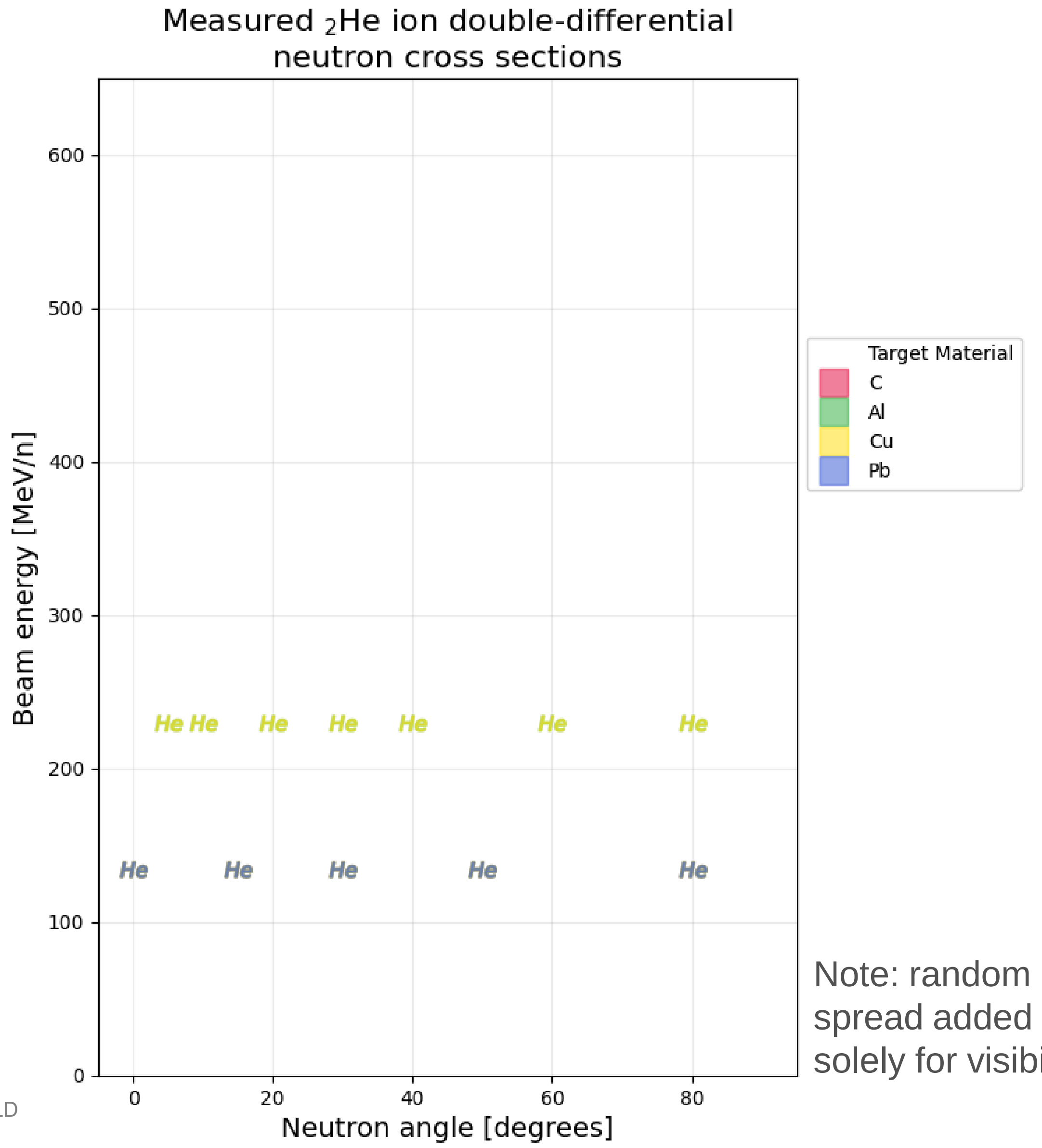

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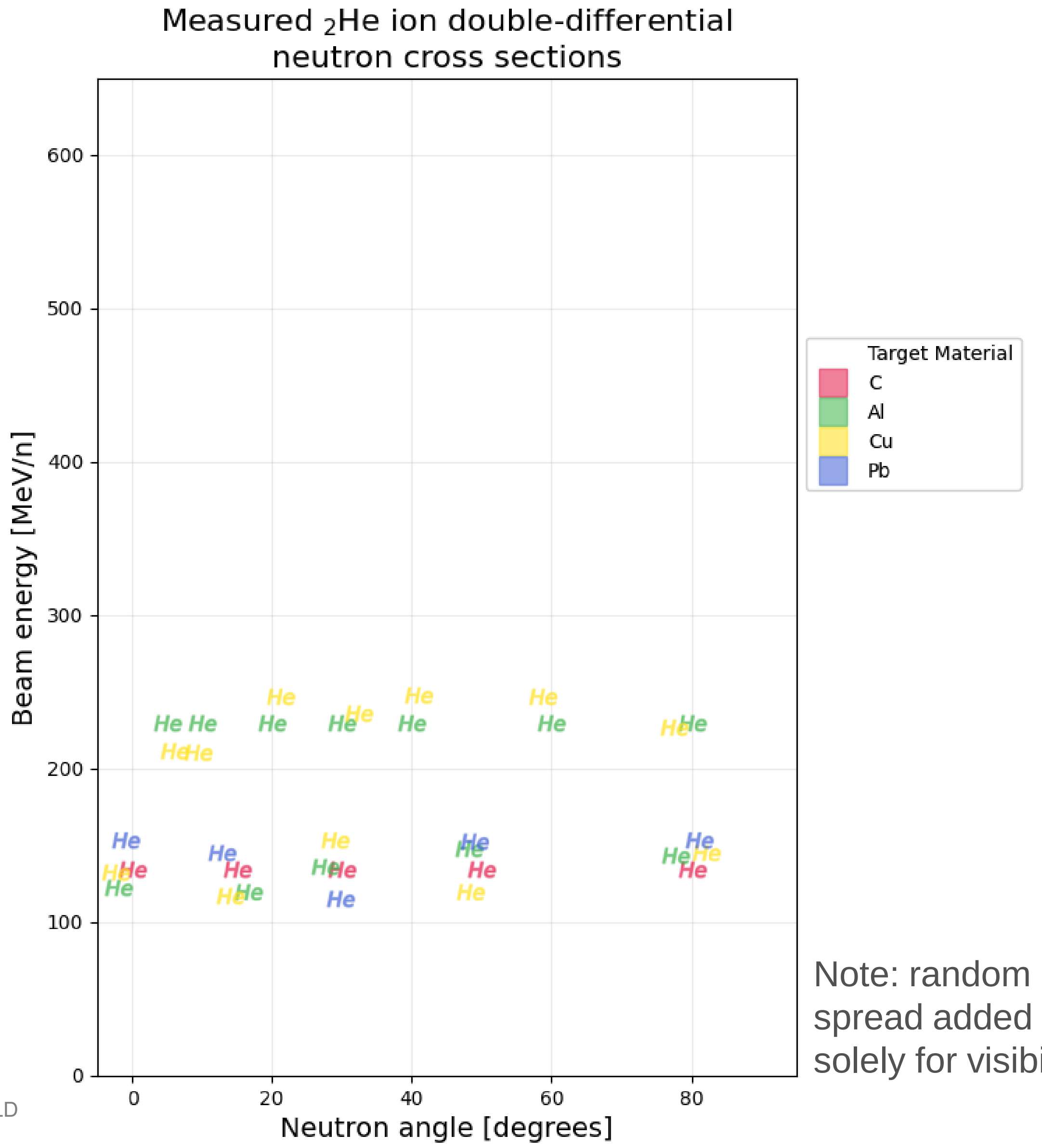

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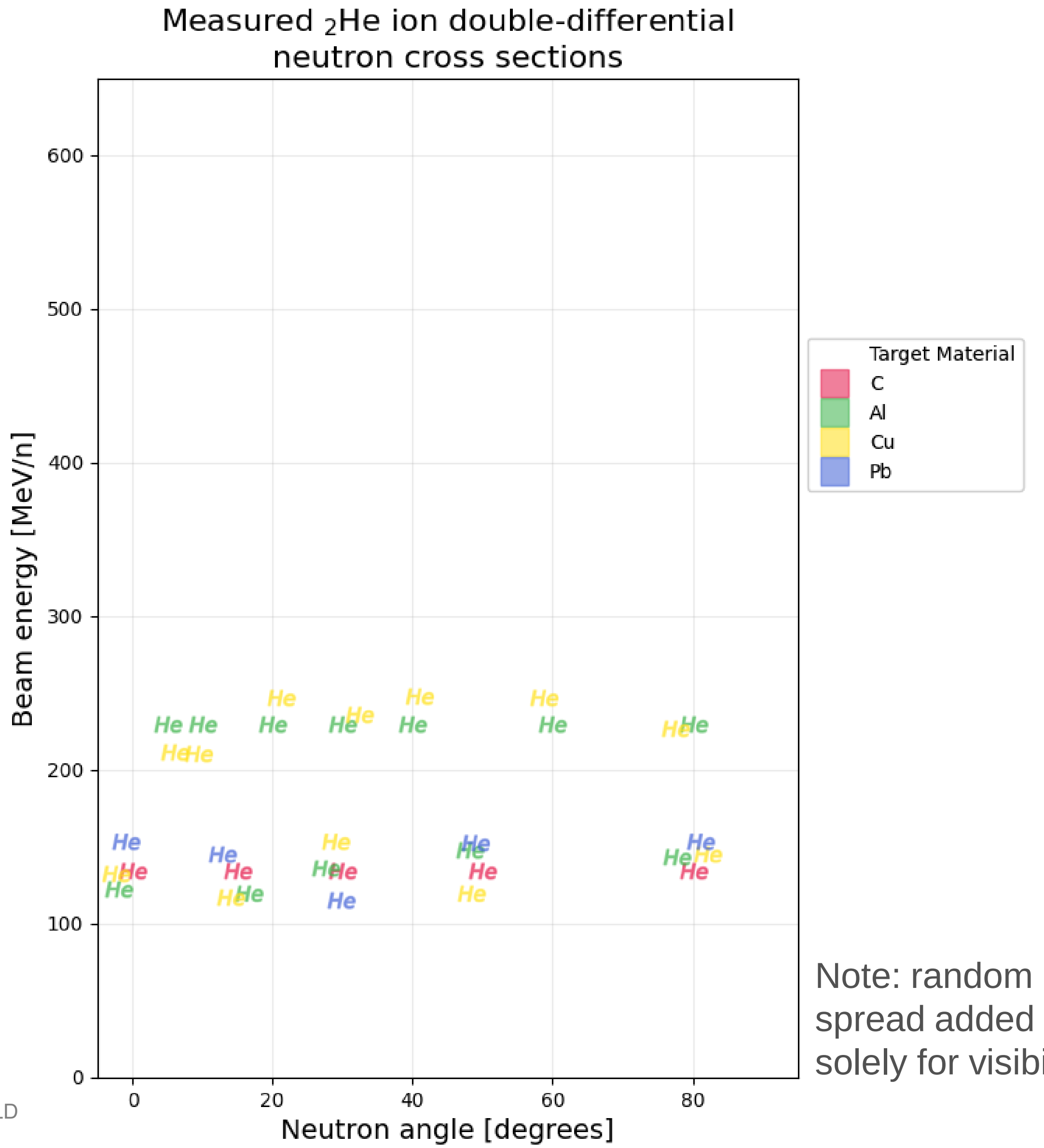
- C and Al targets well sampled
- Targets containing O, H, and Fe not very well / not at all represented



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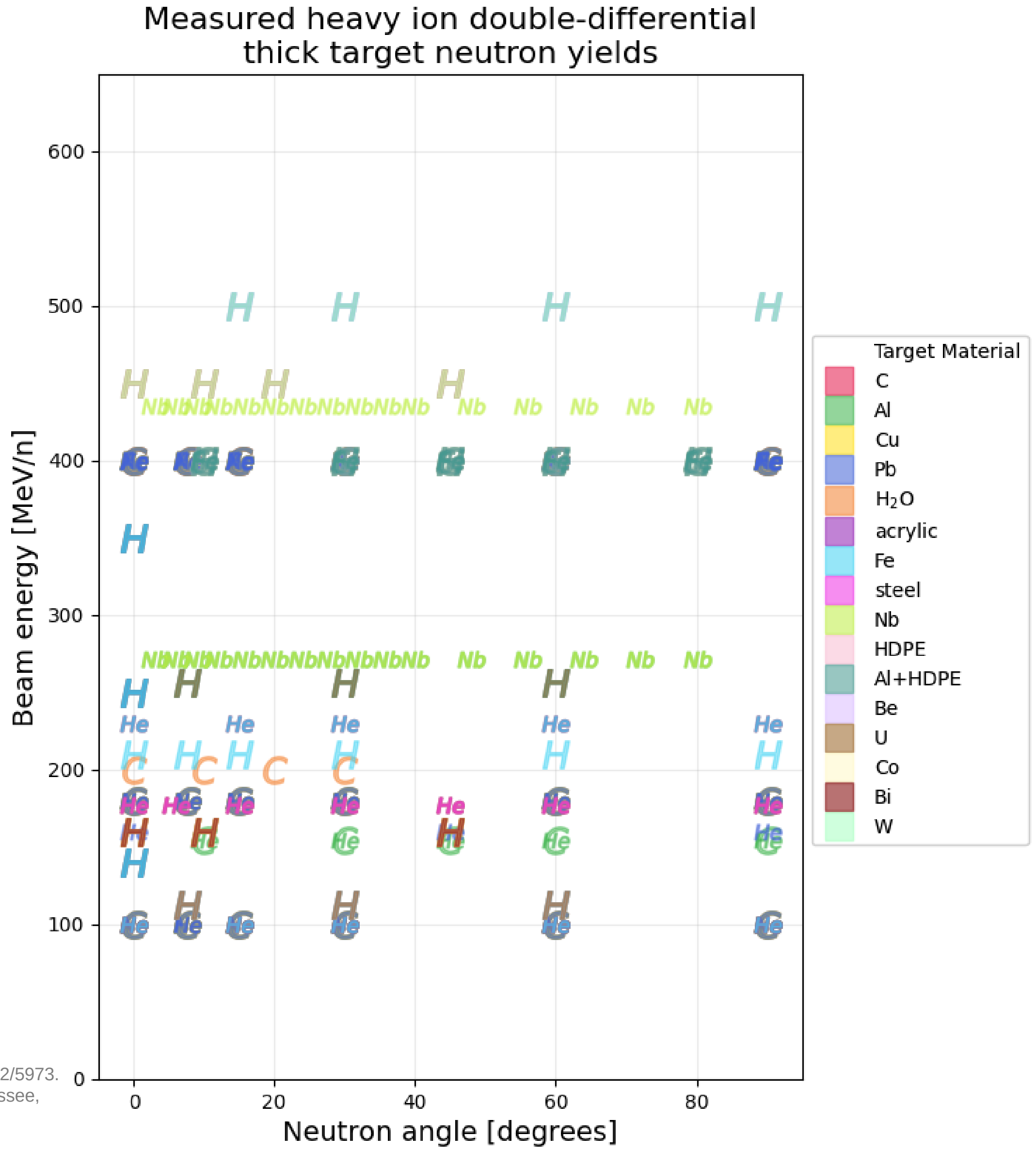

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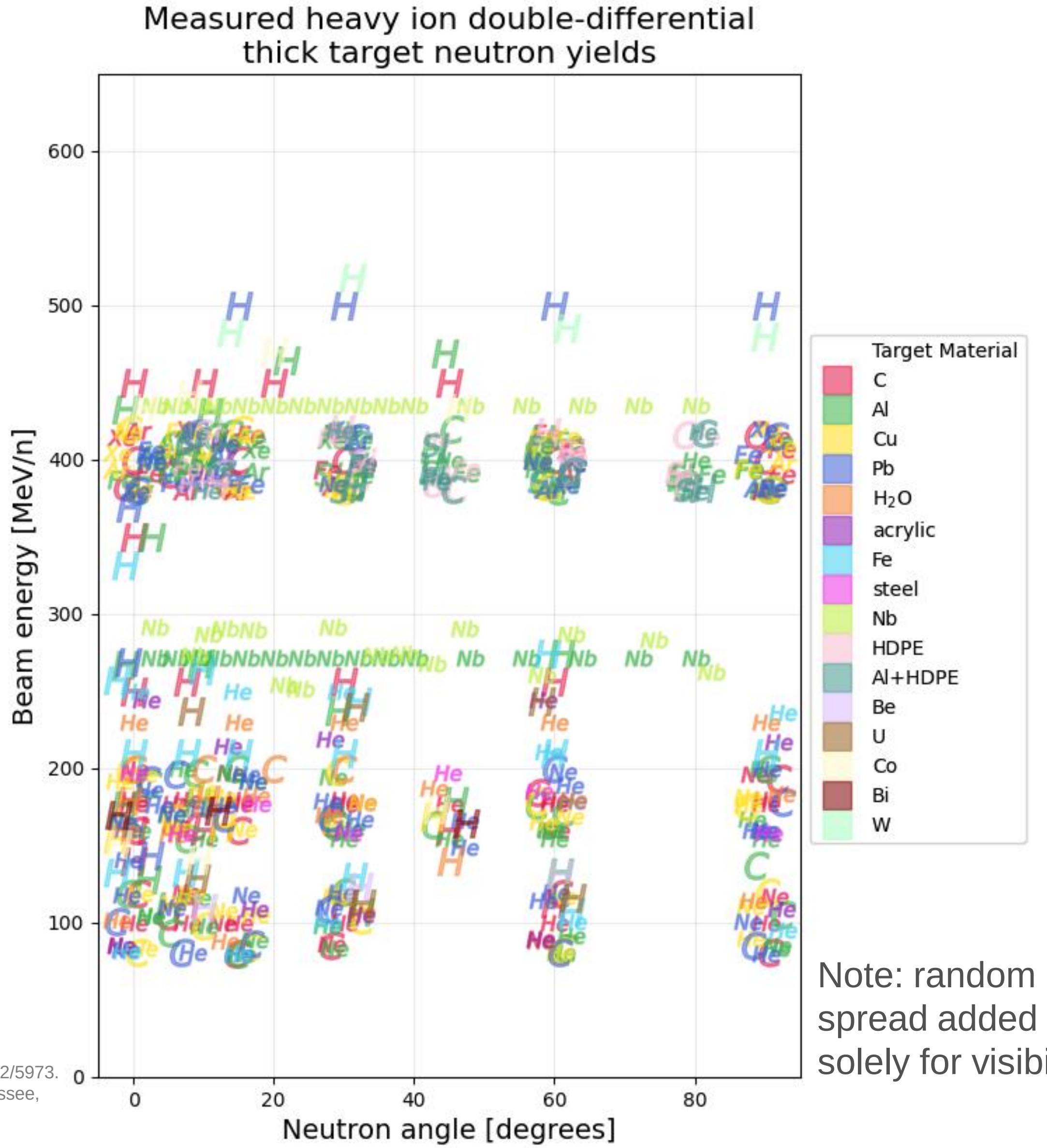

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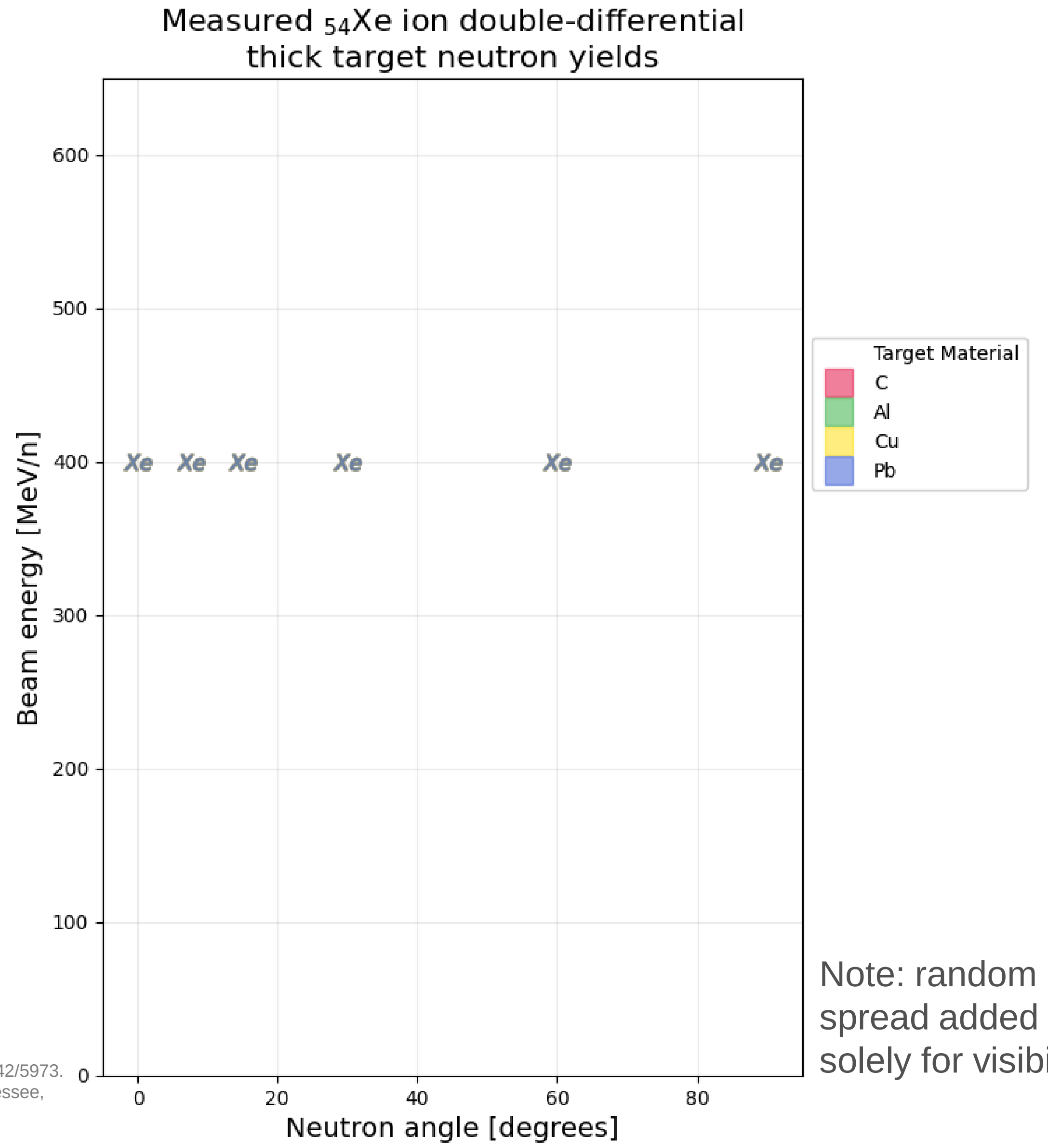

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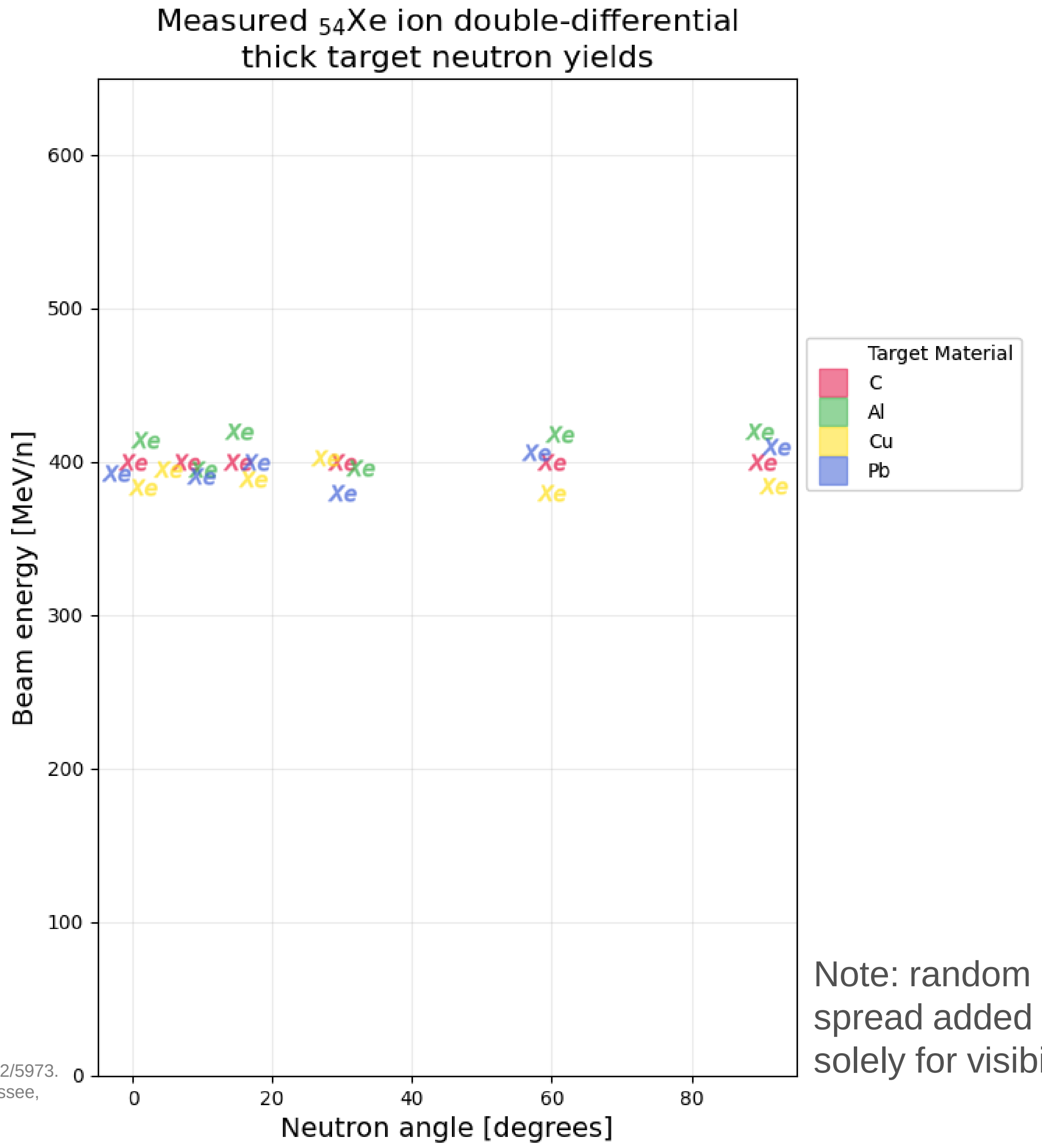

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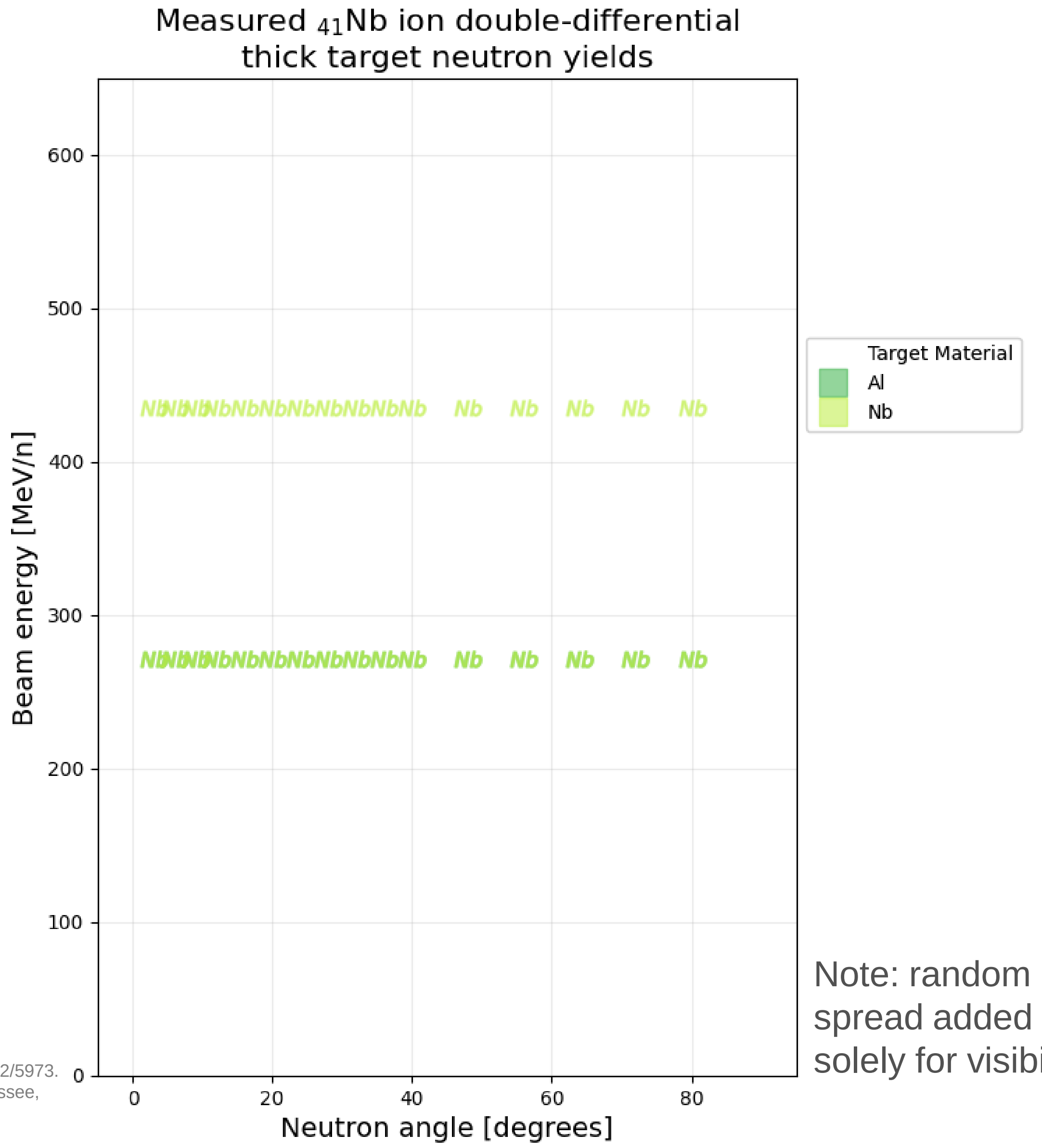

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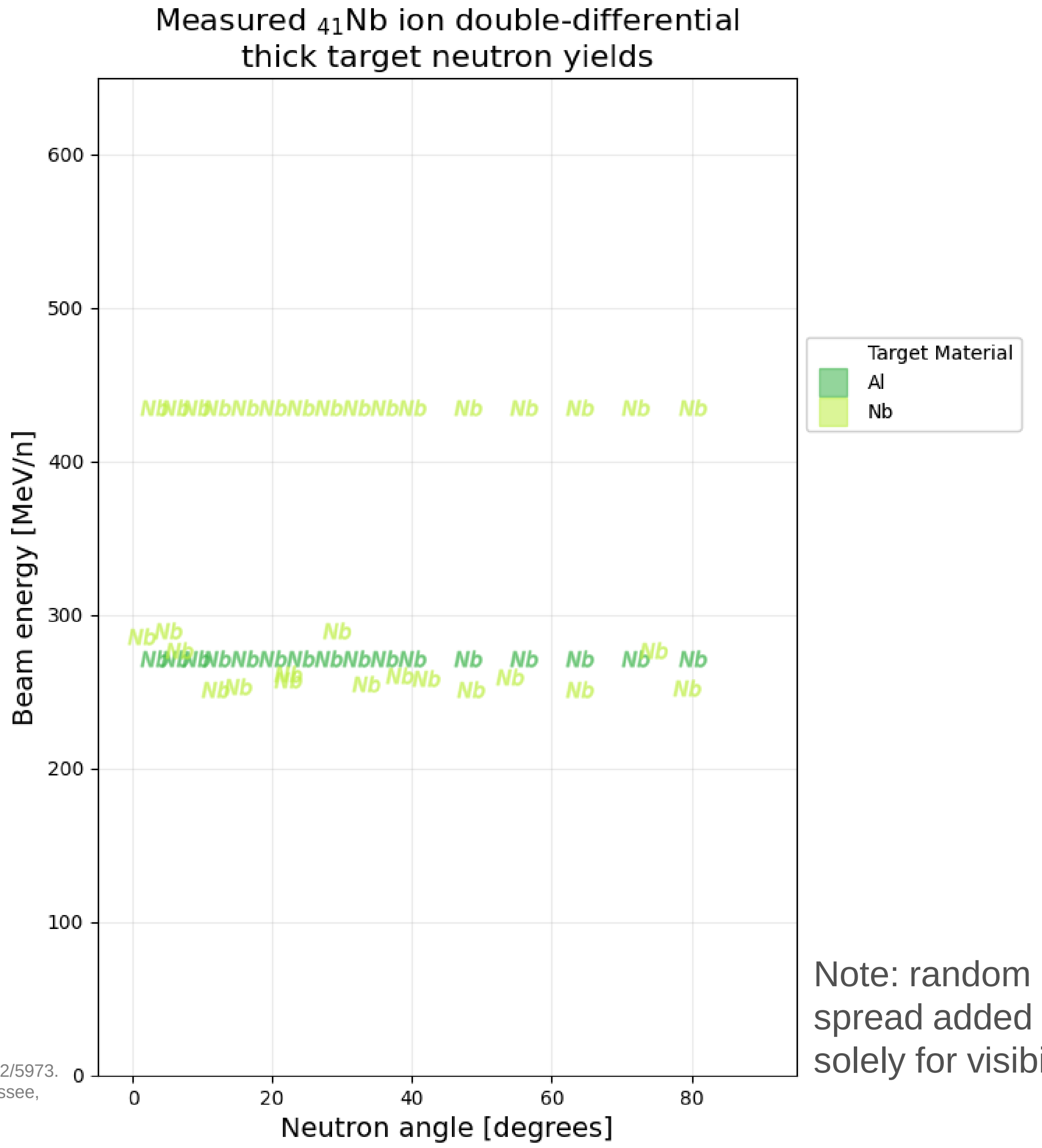

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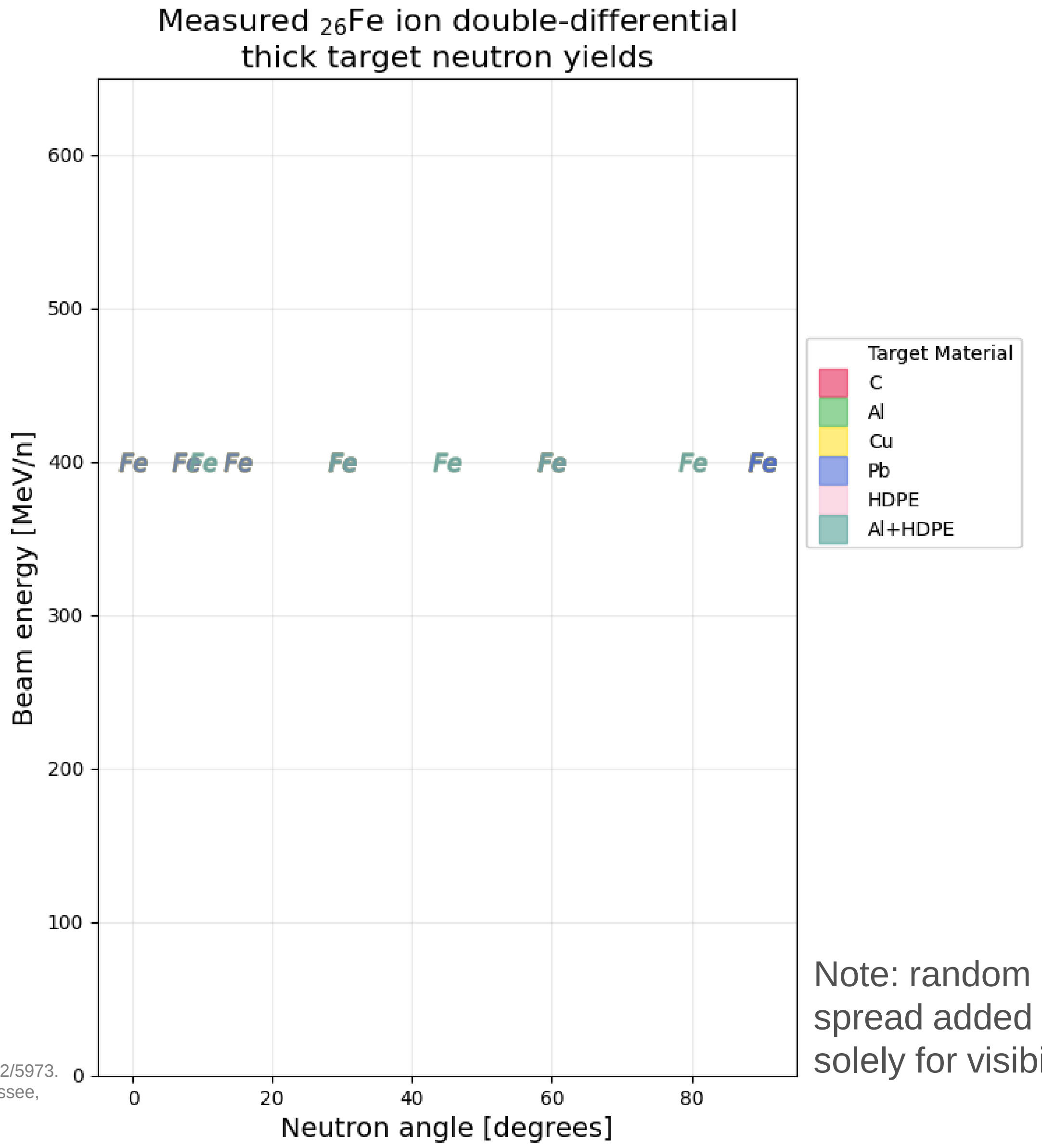

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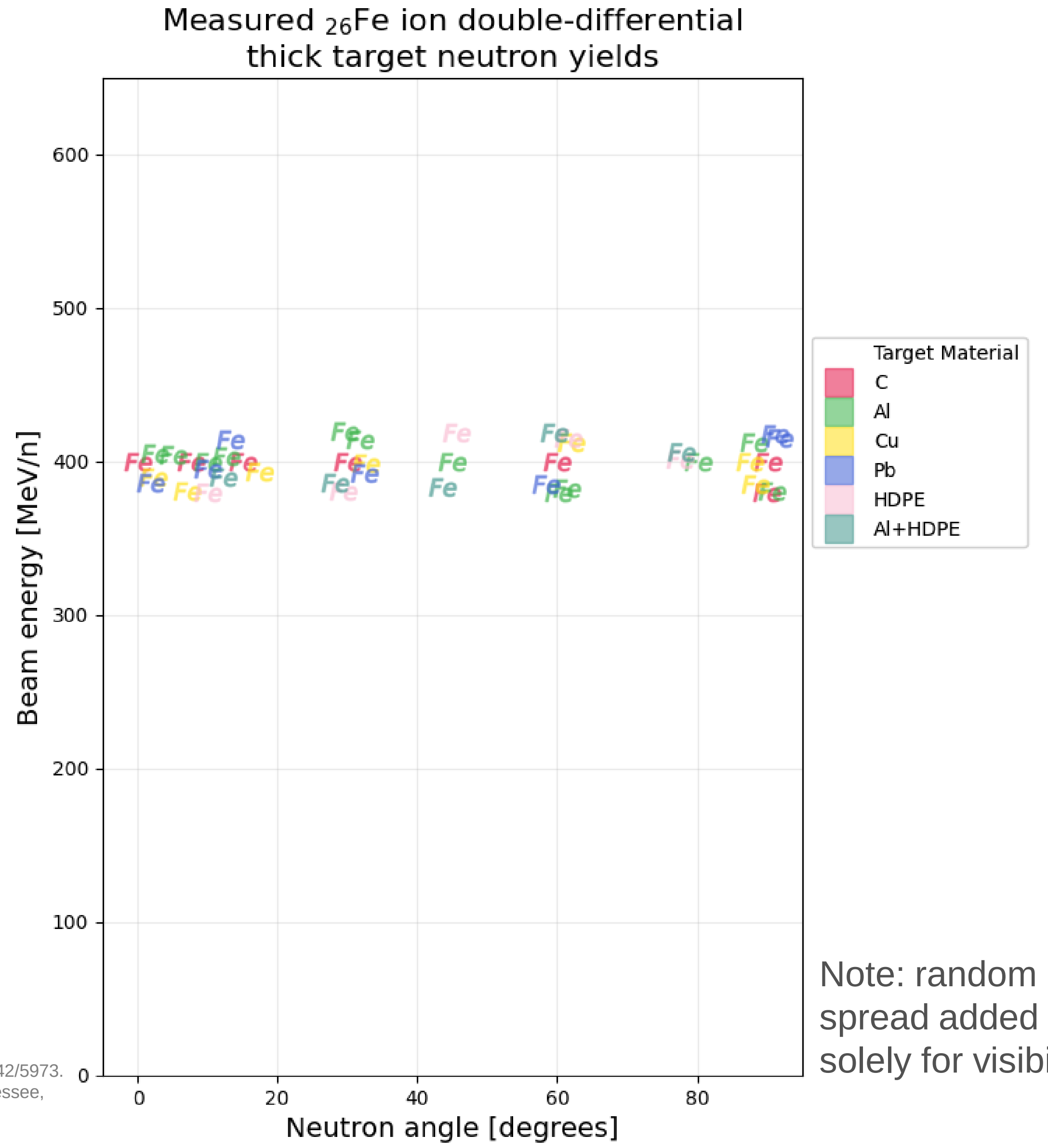

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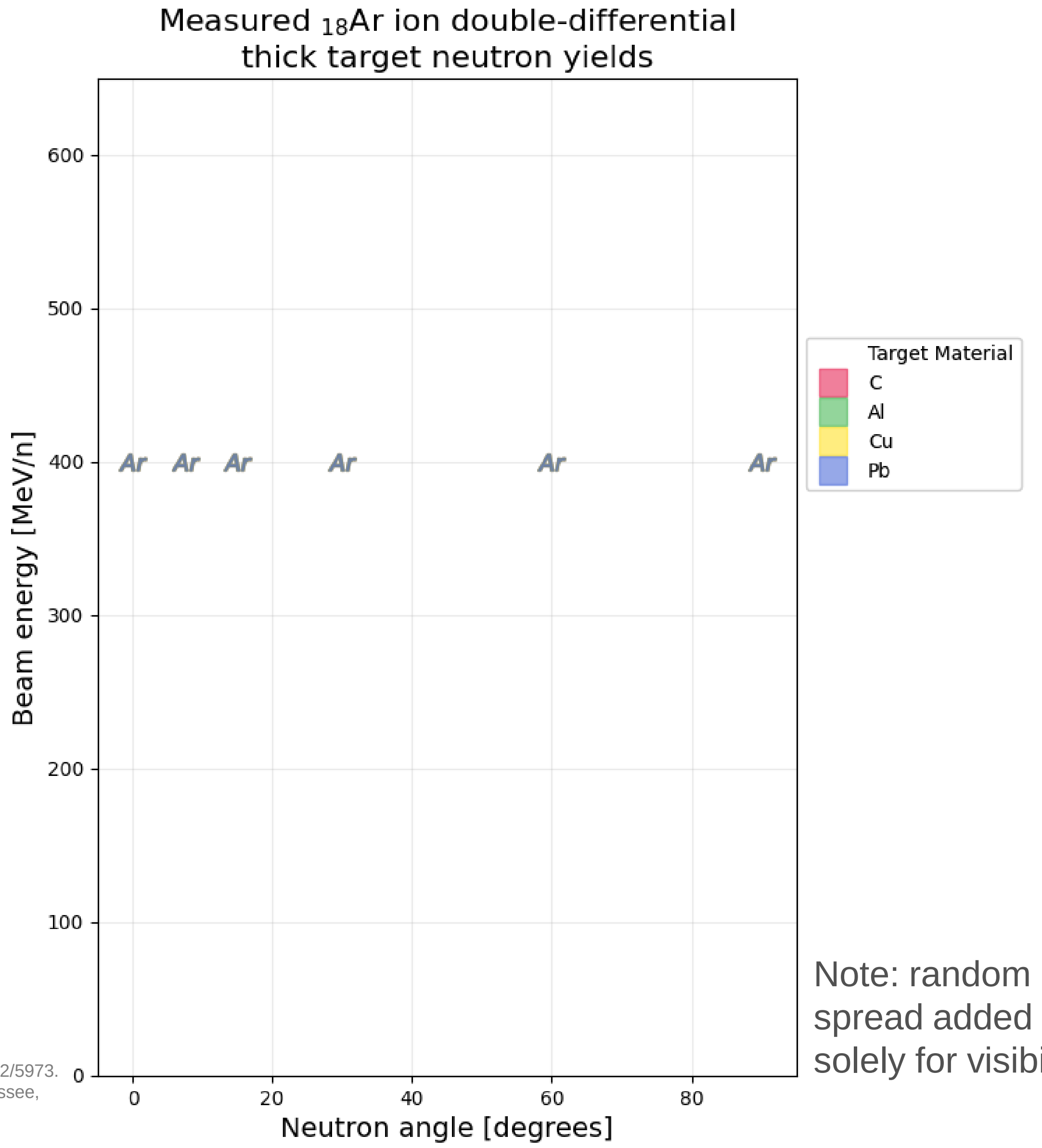

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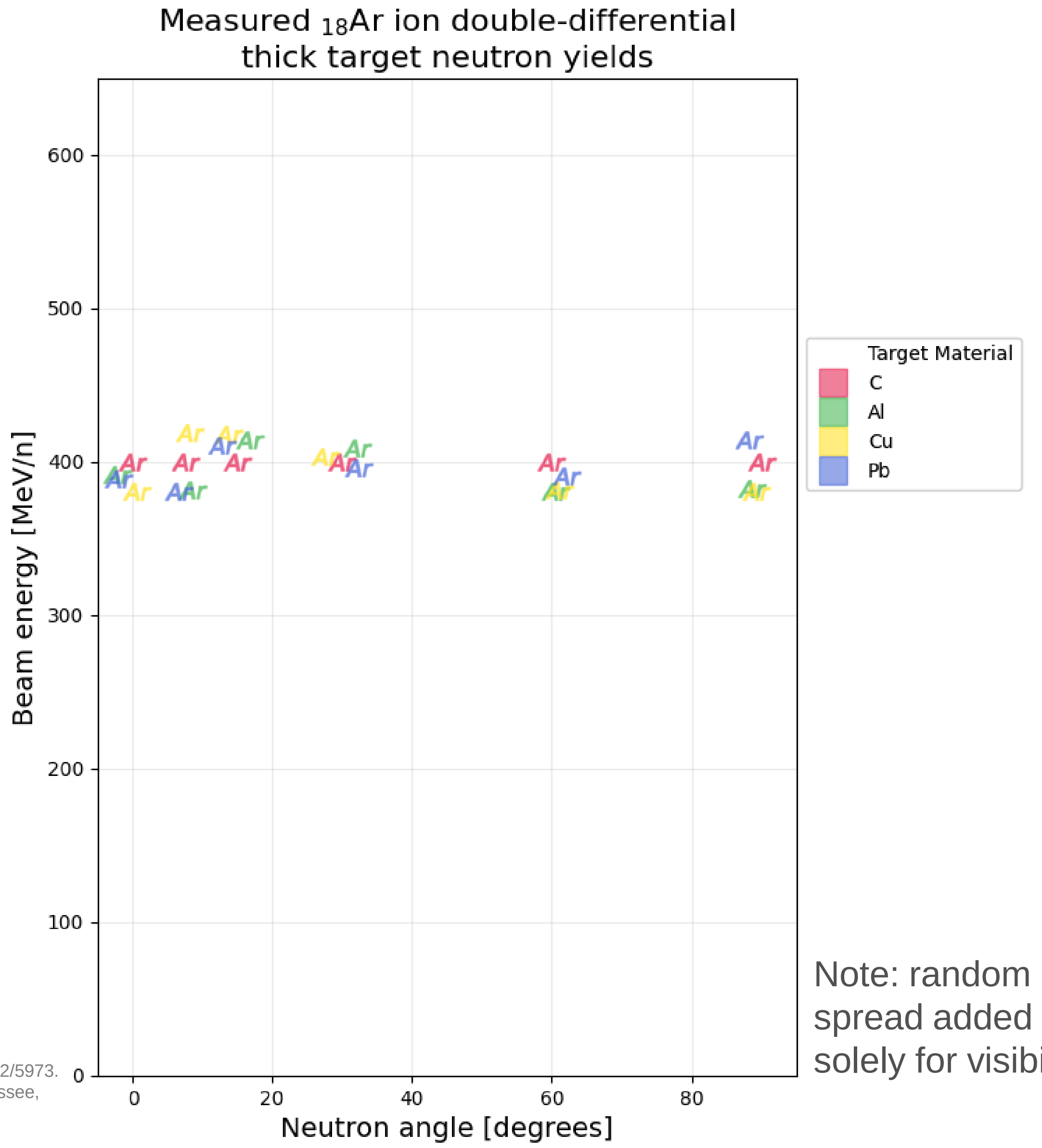

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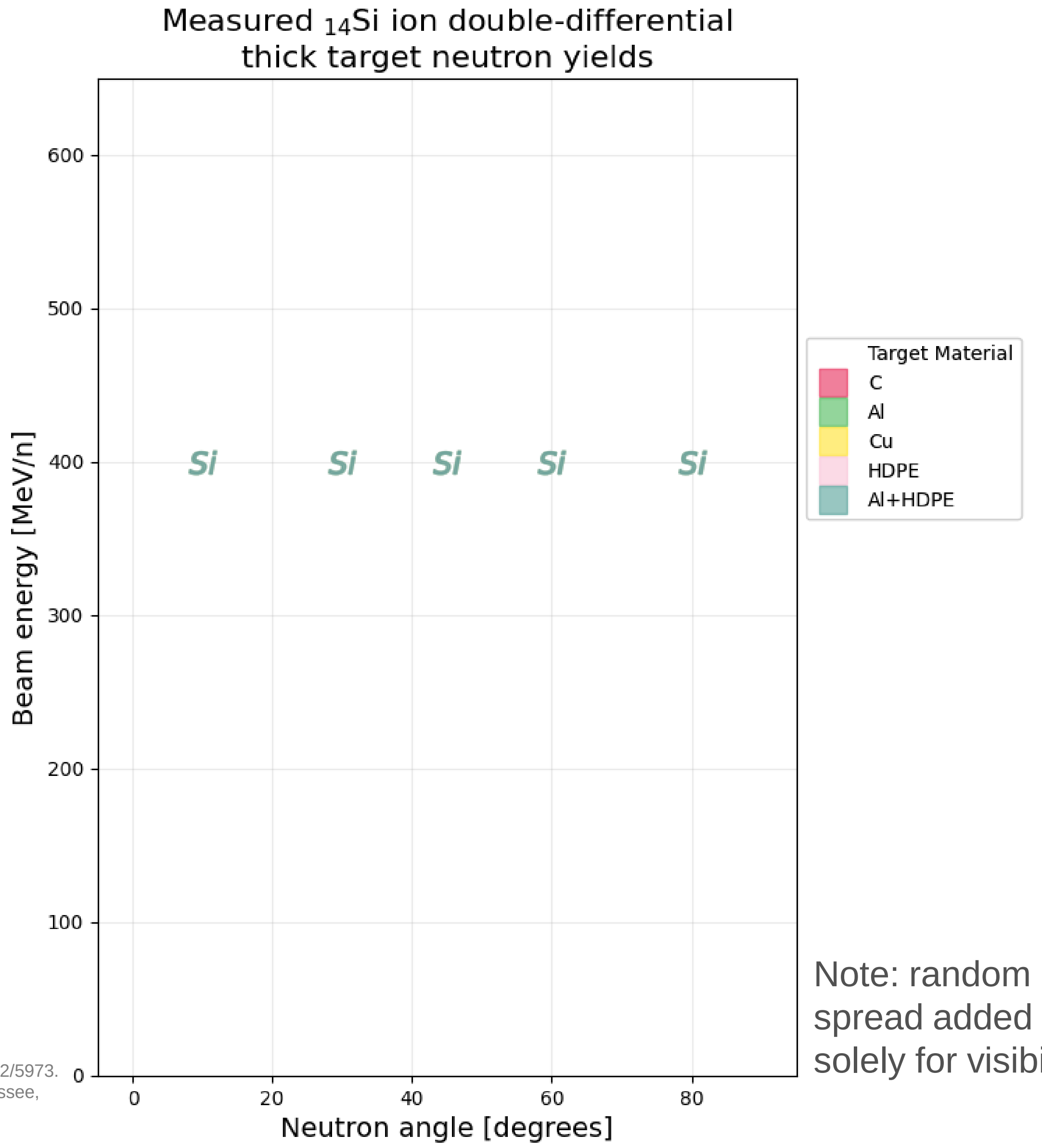

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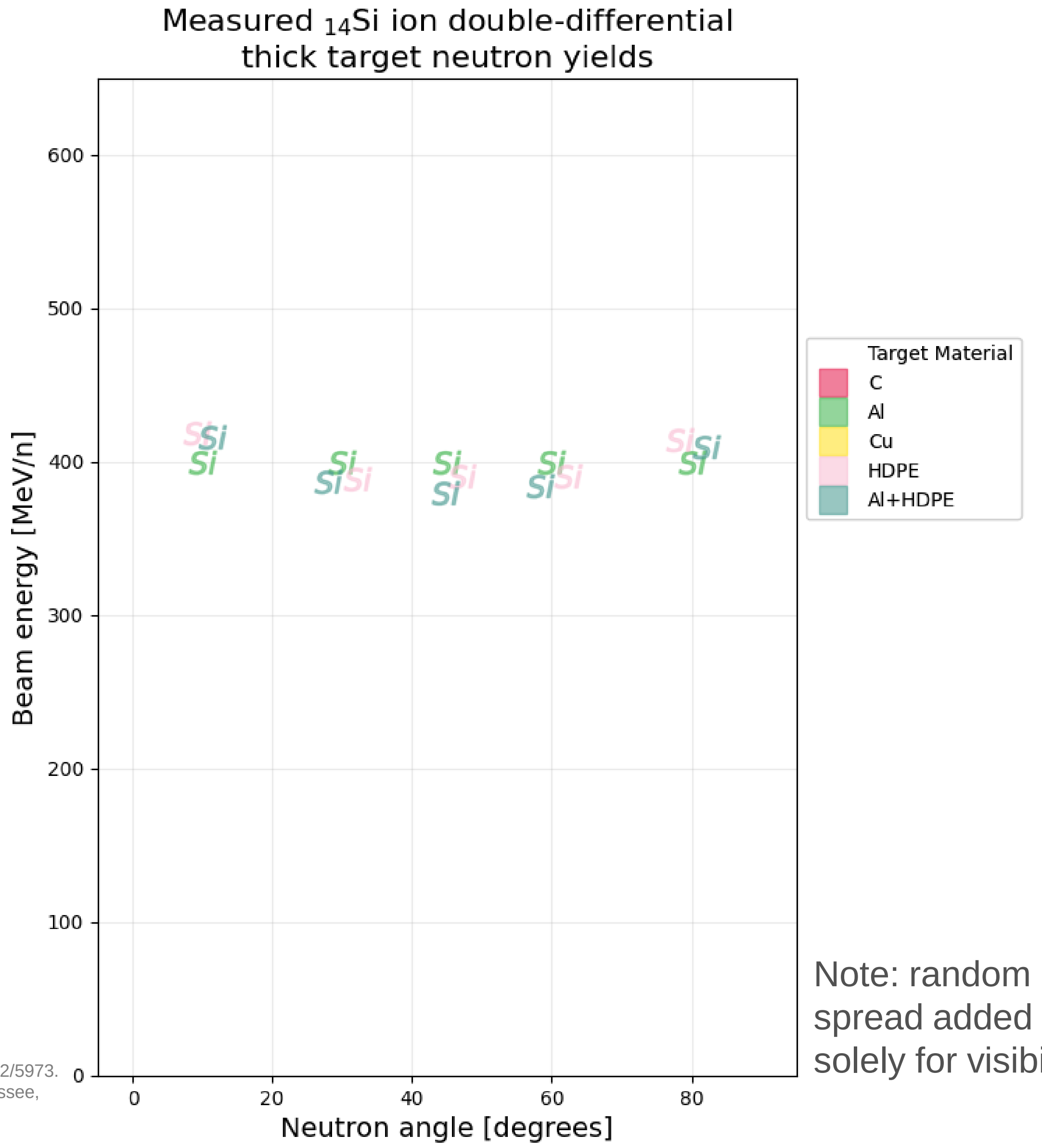

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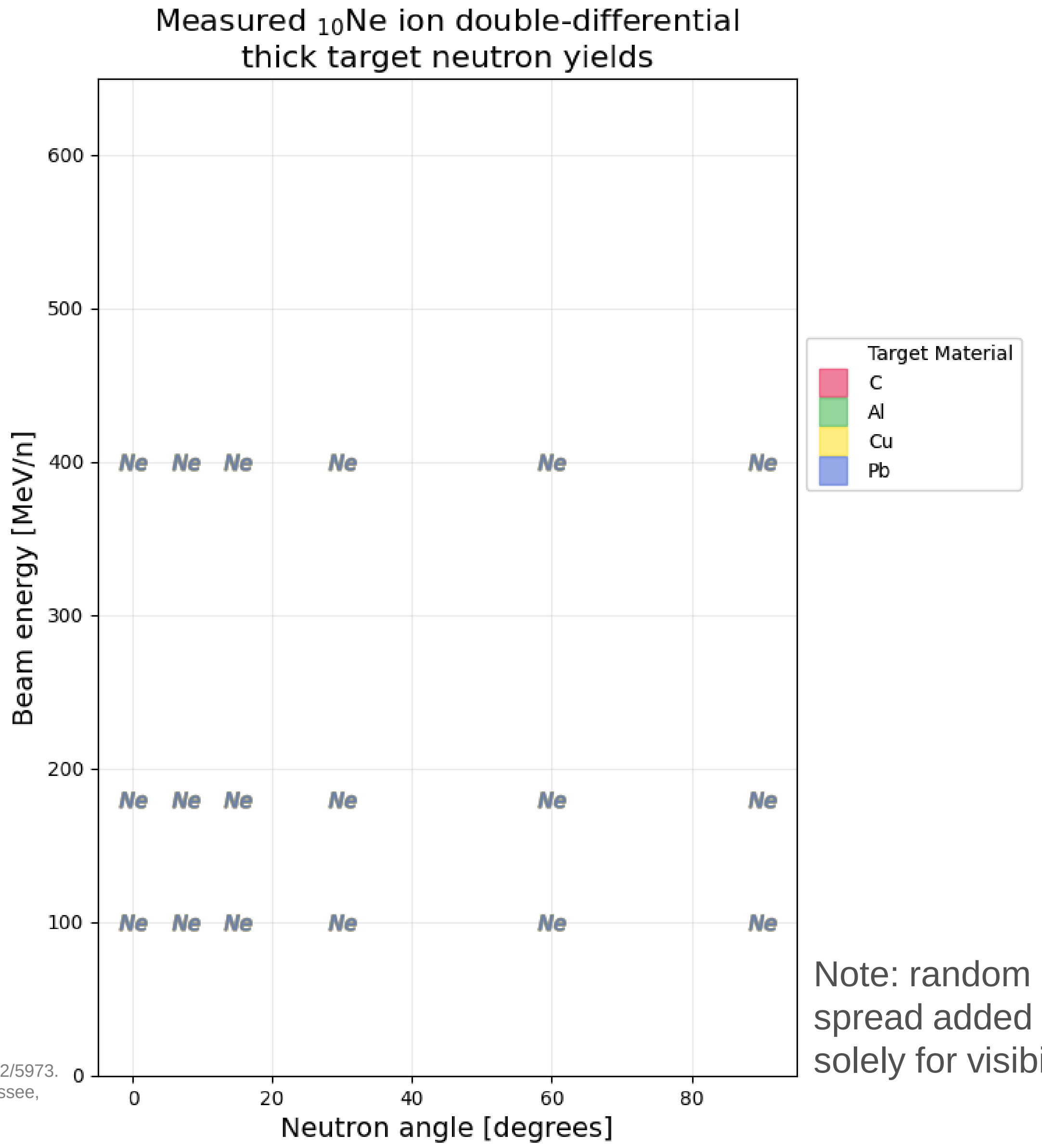

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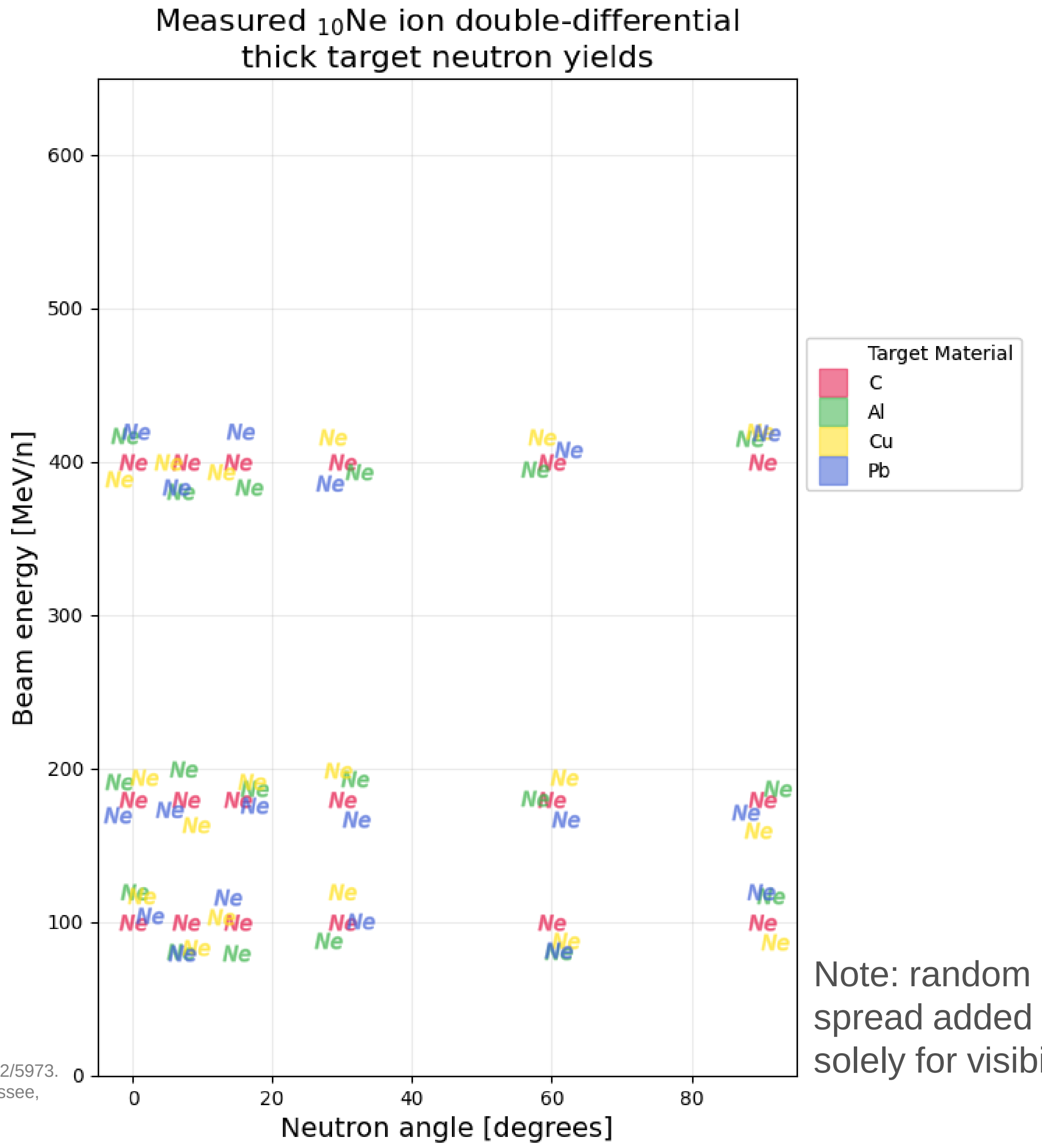

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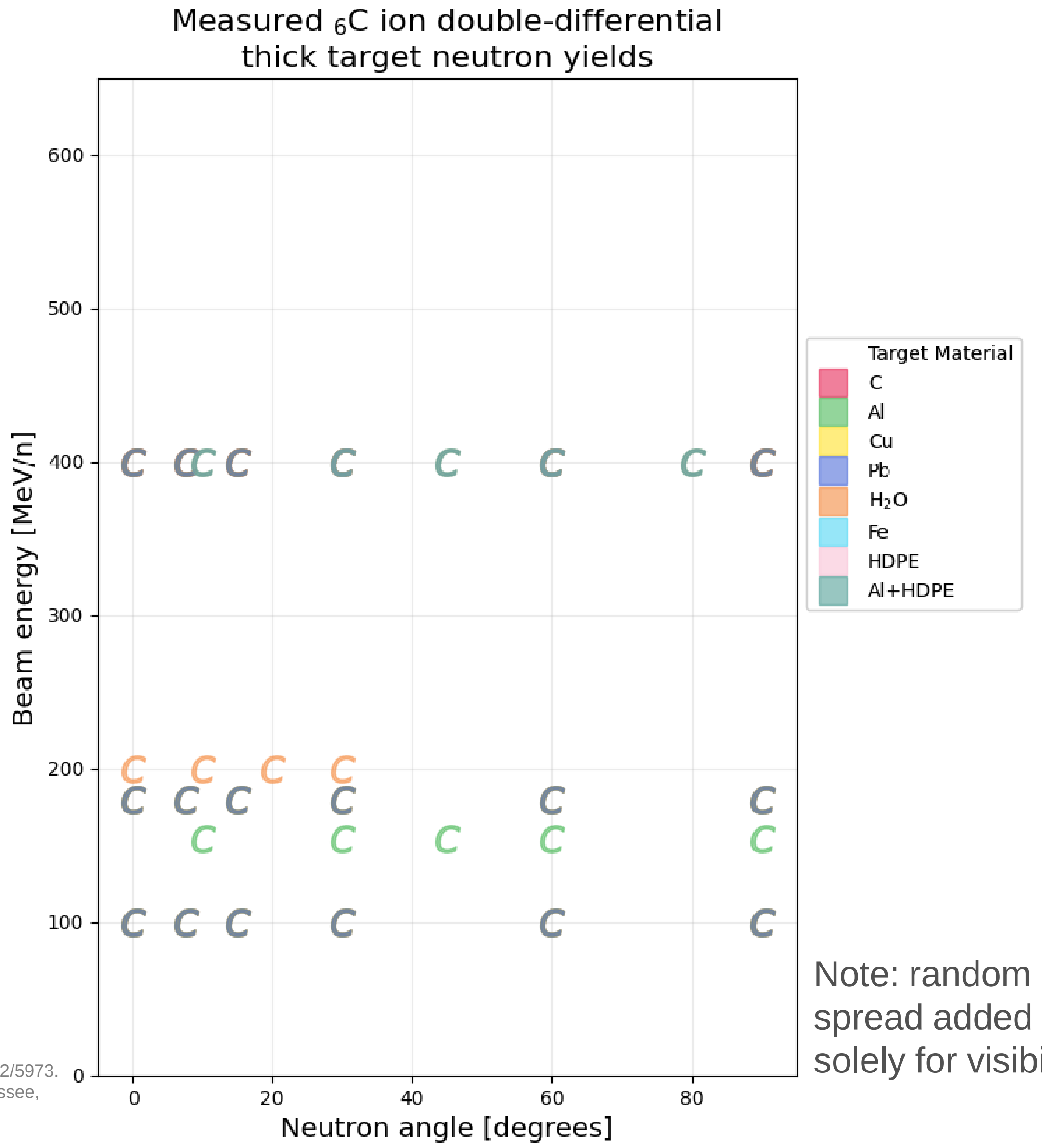

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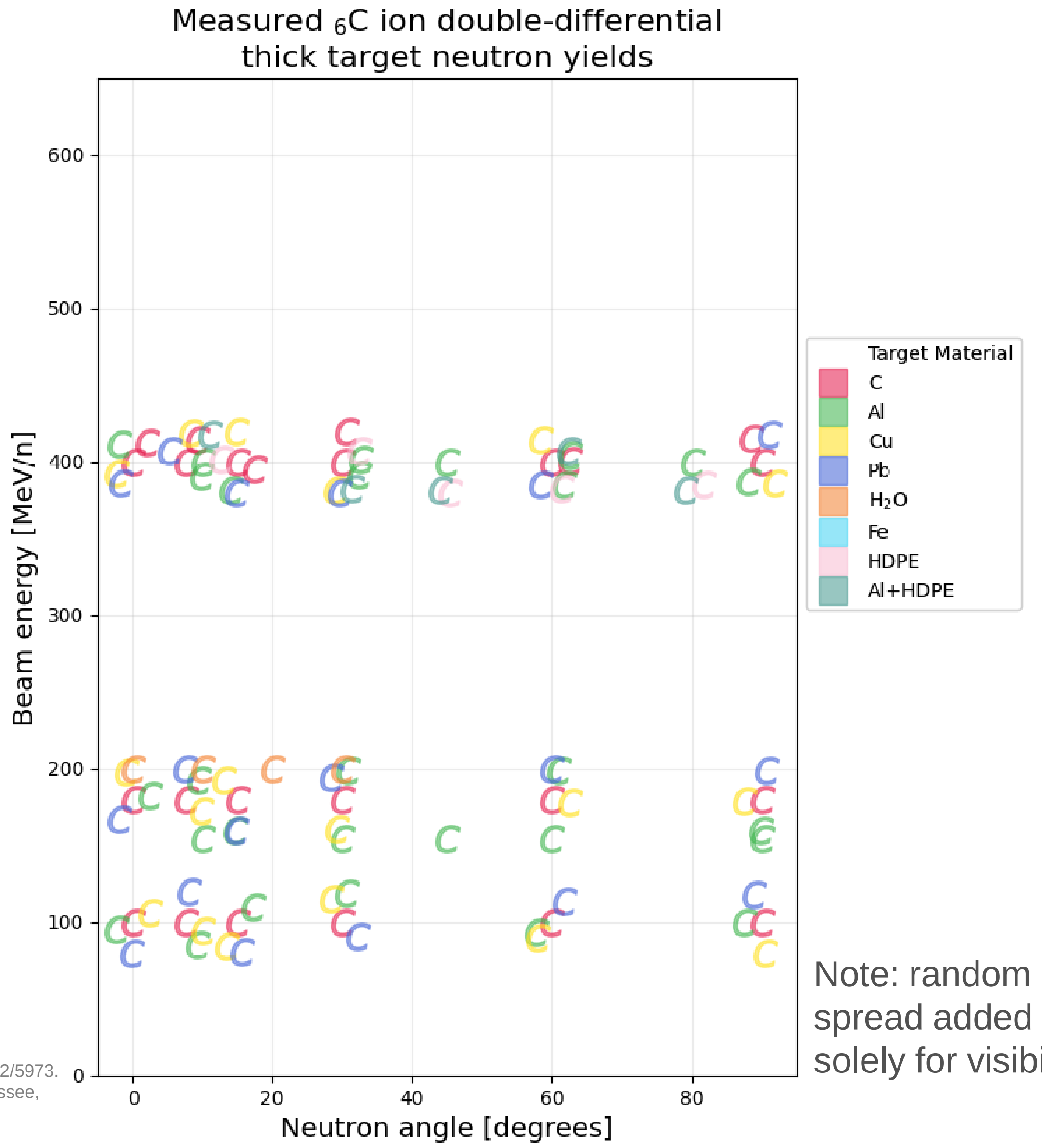

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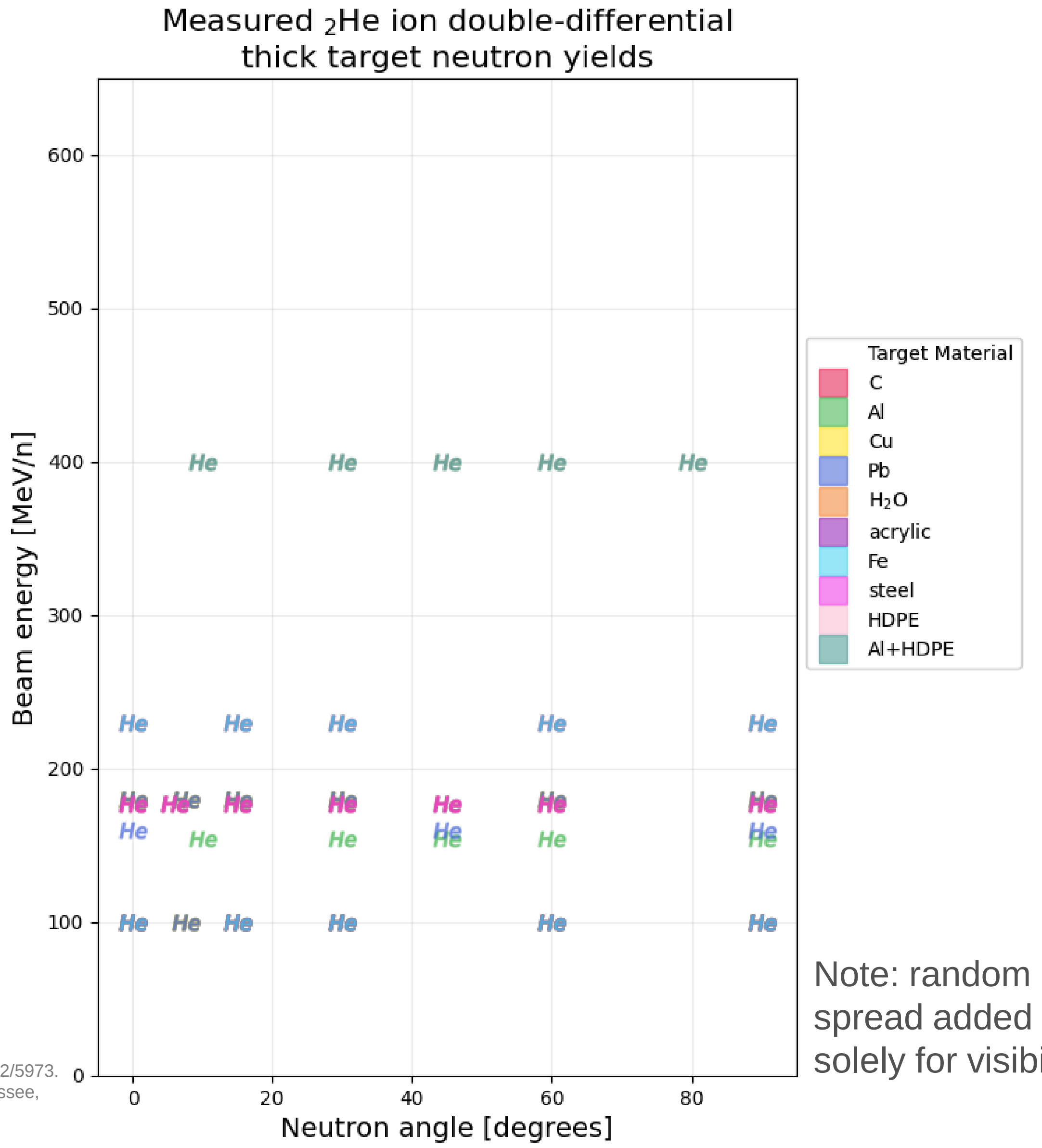

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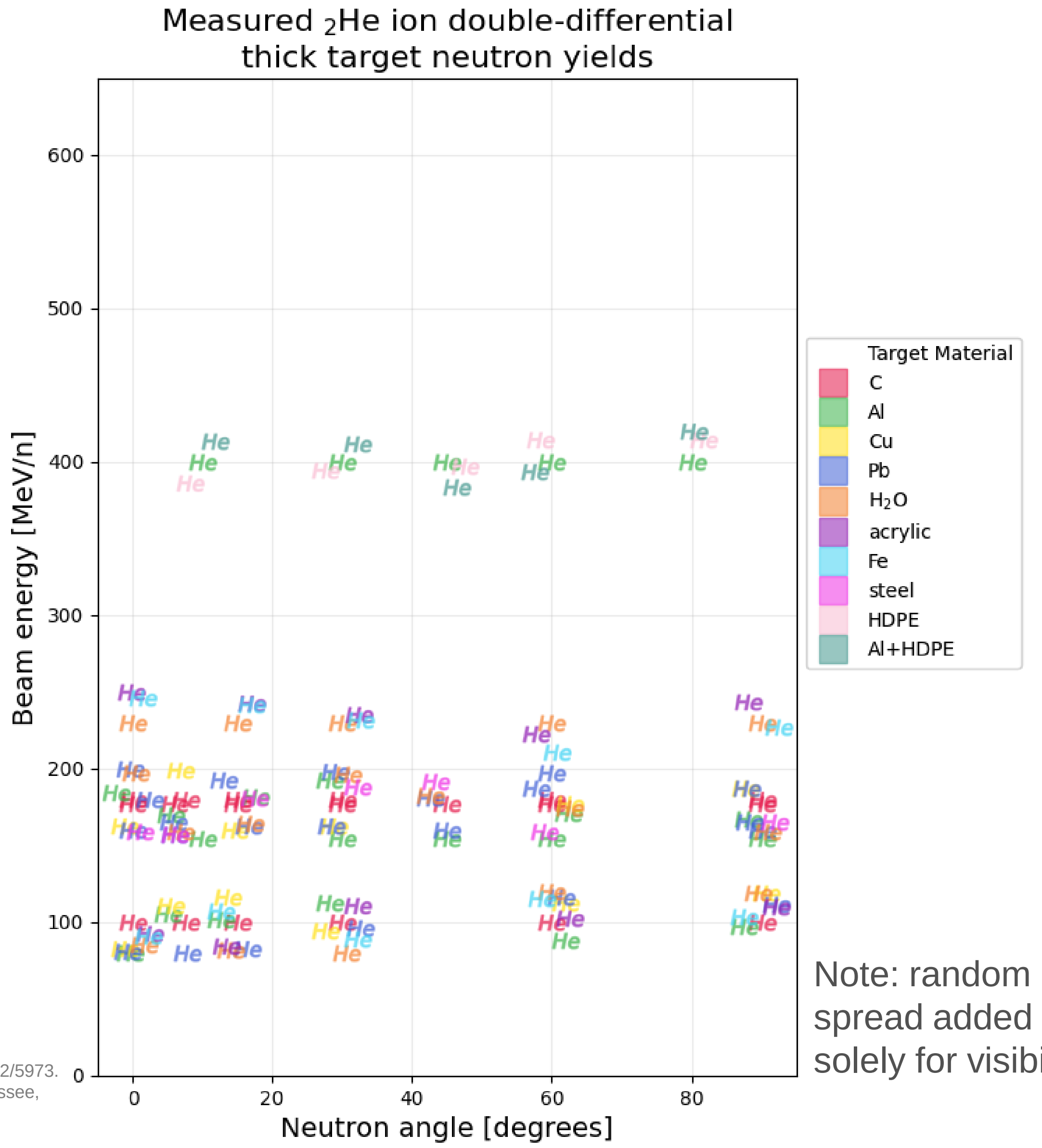

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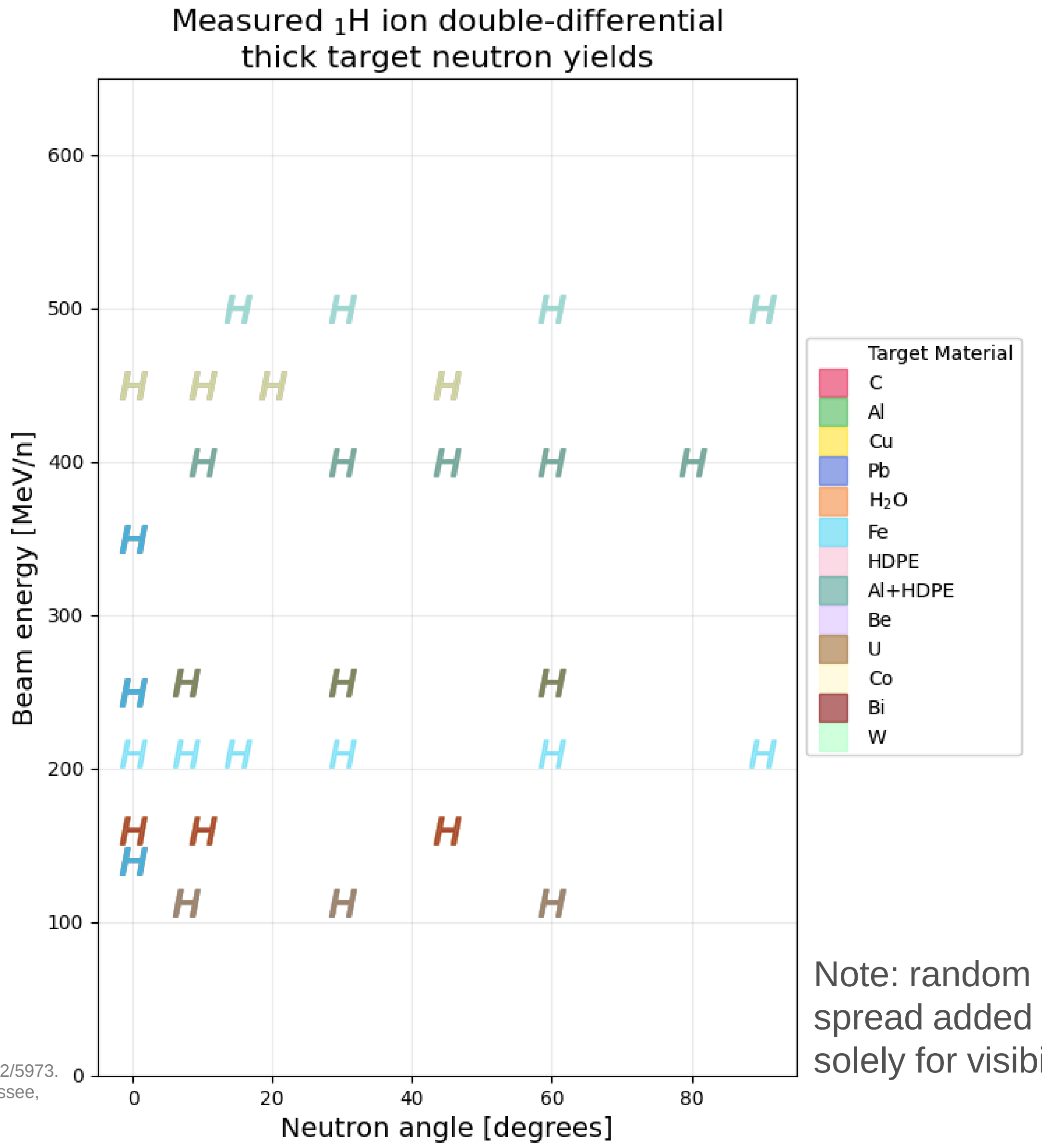

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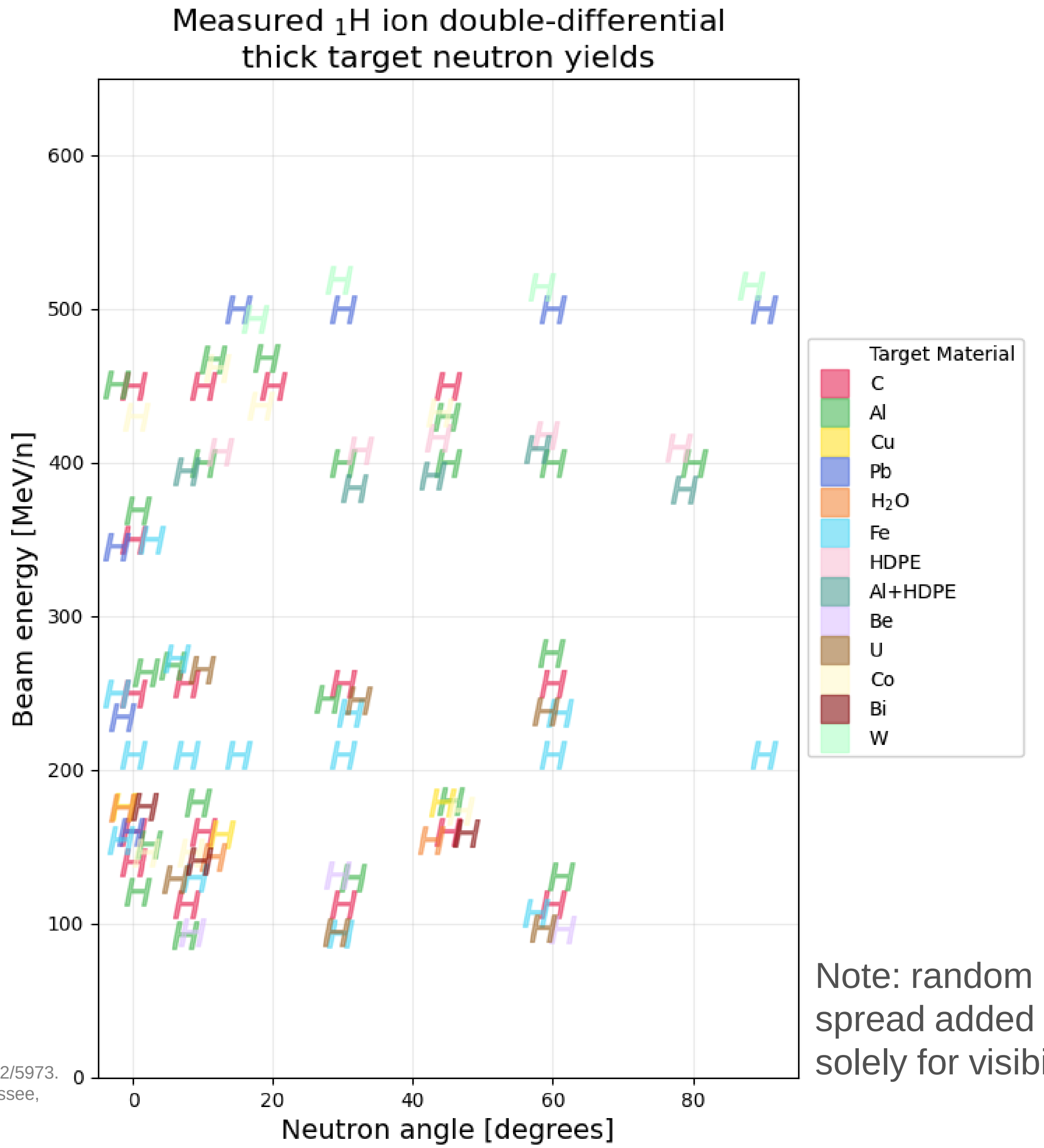

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- Existing cross section measurements have minimum neutron energies from 3 MeV to 20 MeV
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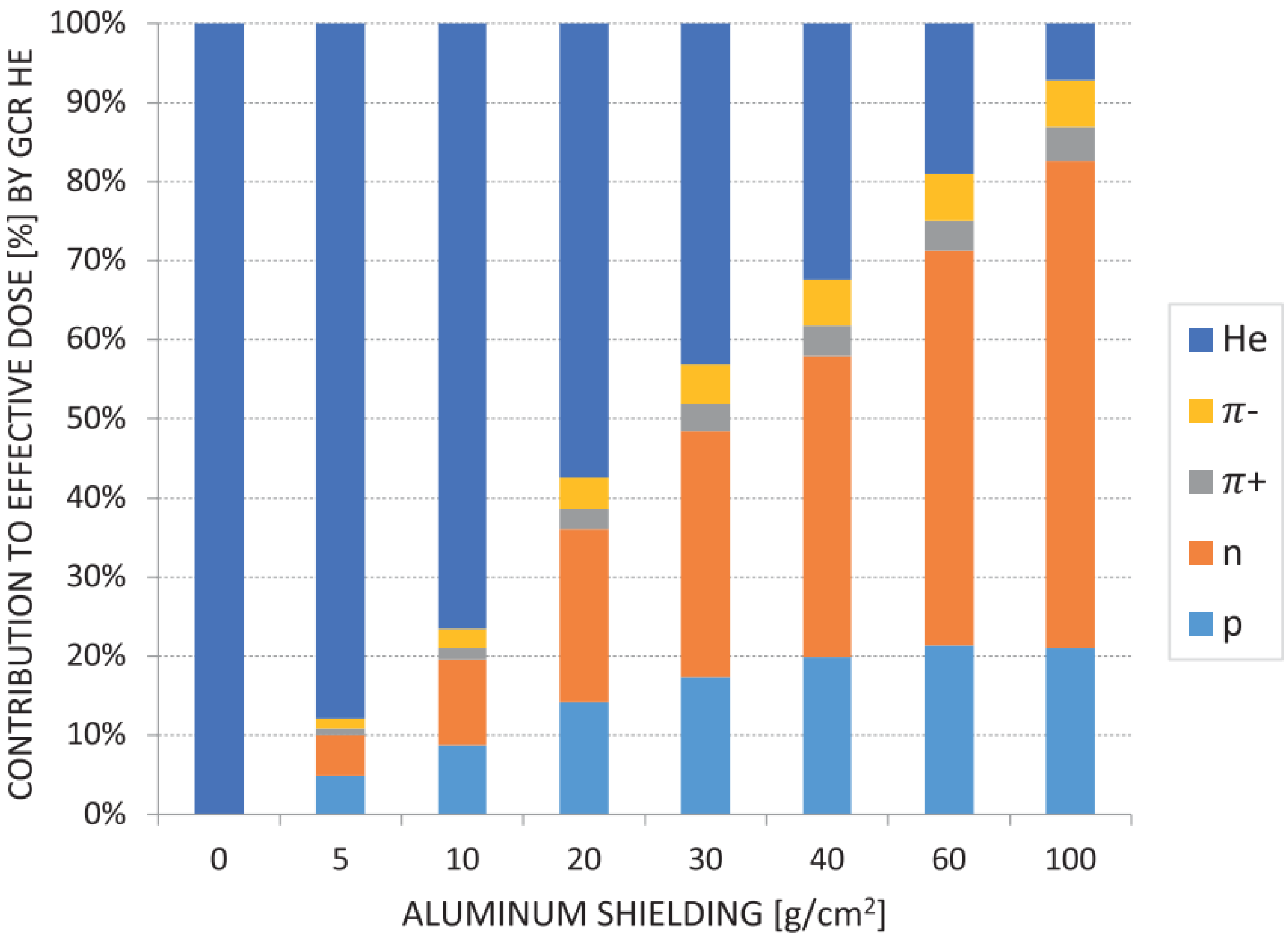
Thank you!

Dose by secondary vs shielding thickness for He component of GCR



[6] J. W. Norbury et al., "Are Further Cross Section Measurements Necessary for Space Radiation Protection or Ion Therapy Applications? Helium Projectiles," Frontiers in Physics, vol. 8. Frontiers Media SA, Nov. 30, 2020. doi: 10.3389/fphy.2020.565954.

Dose to BFO by primary/secondary Z for various geometries

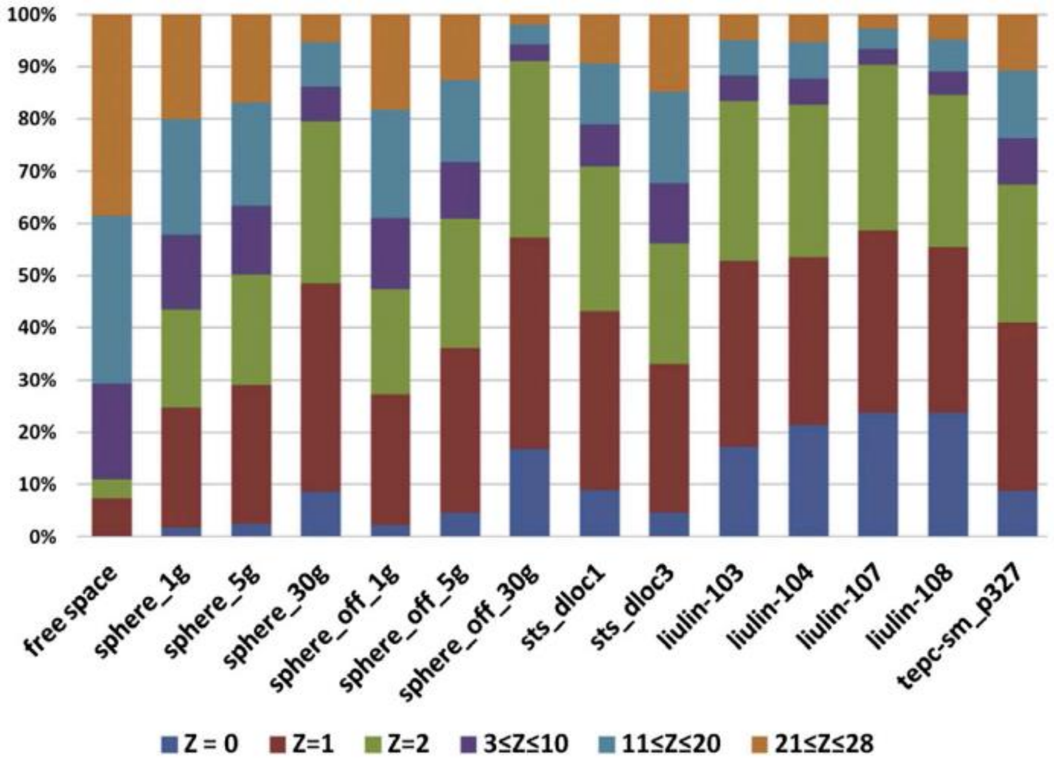


FIGURE 1 | Calculated percent contribution to blood-forming organ (BFO) dose equivalent for free space (far left), simple spherical geometries in free space, and detector locations inside the space shuttle (STS) and the International Space Station (ISS) in free space. The vehicles included three aluminum spheres with areal densities 1, 5, and 30 g/cm^2 where the body was placed at the center of the sphere (sphere_1g, sphere_5g, and sphere_30g) and three spheres of the same areal densities where the body was placed against the wall of the sphere (sphere_ off_1g, sphere_off_5g, and sphere_off_30g). For the latter cases, the spheres were constructed so that they would each have the same habitable volume as the Multi-Purpose Crew Vehicle (MPCV), 316 cubic feet (8.95 m^3). Thus, each sphere had an inner radius of 1.288 m. Also, six locations were studied in the STS (shuttle) where detectors have historically been placed (sts_dloc1-6). Five locations in the ISS 6A configuration were also used: two points in the Destiny (Lab) module laboratory area (Liulin_103, Liulin_107); two points in the Unity (Node1) module (Liulin_104, Liulin_108); and one point in the Zvezda (SM; service module) module on panel number 327 (TEPC-sm_p327). Reprinted from Walker et al. [8].

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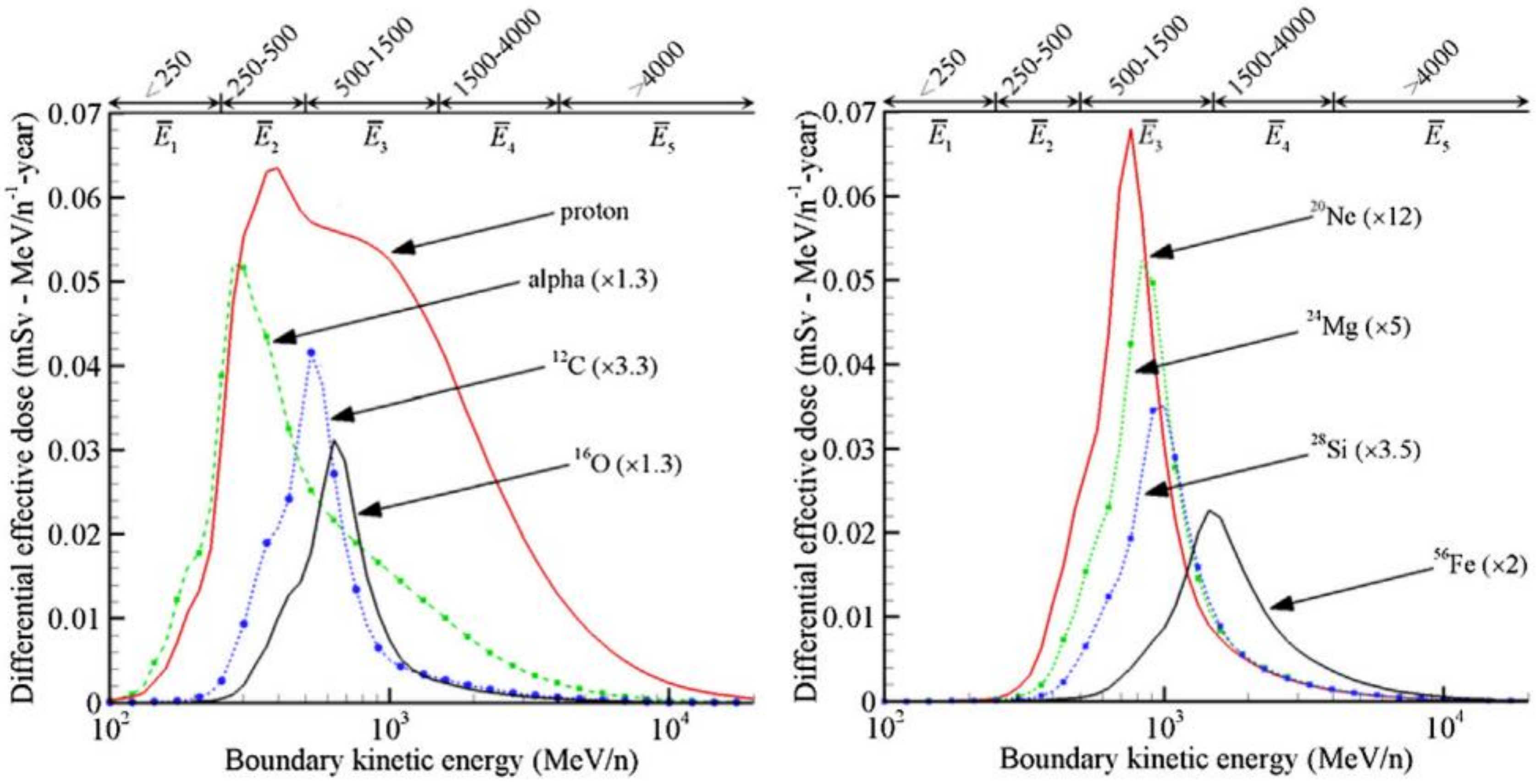

FIGURE 8 | Effective dose contributions as a function of external GCR energy behind 20 g/cm^2 of aluminum exposed to solar minimum GCR. Reprinted from Slaba and Blattnig [46].

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Dose attributed to GCR He by energy slice vs Al shielding thicknes

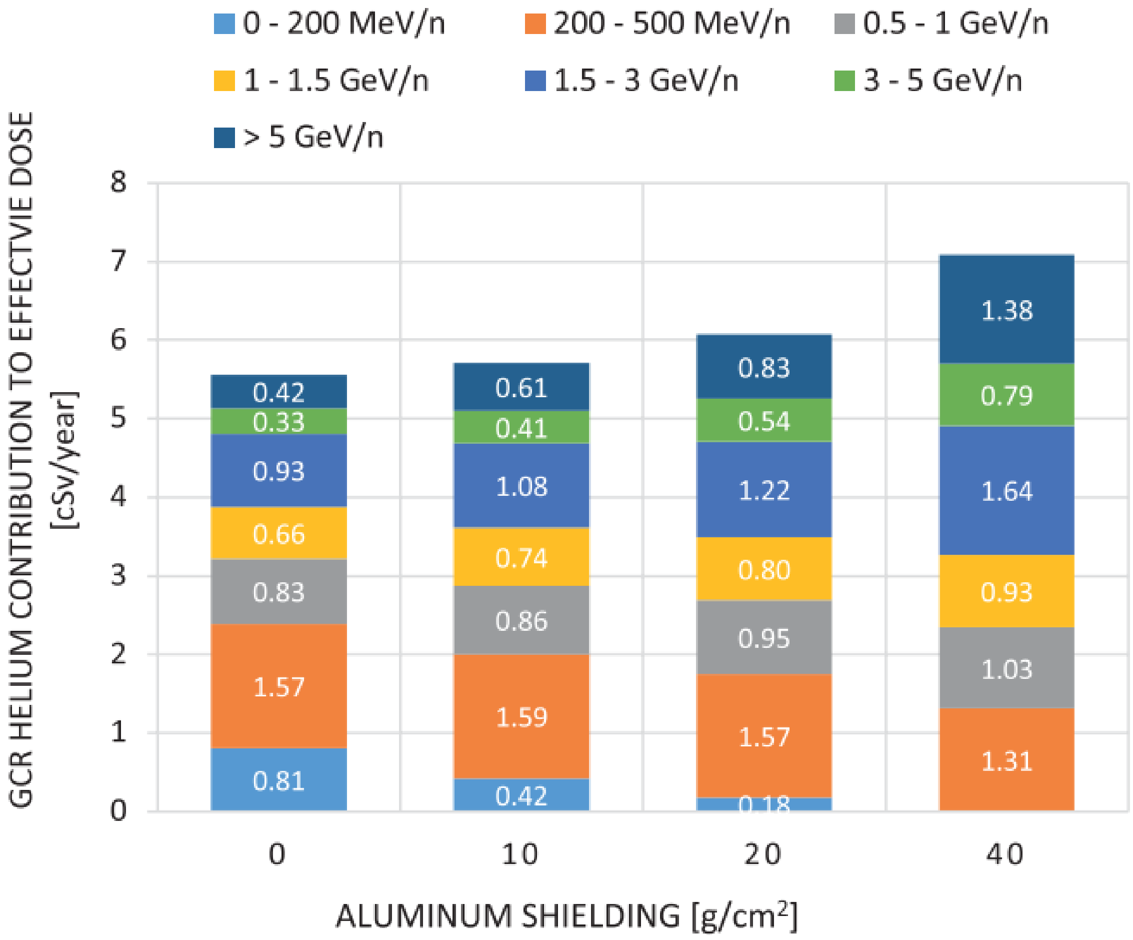

FIGURE 11 | GCR He energy ranges contributing to the 1 year NASA male effective dose for different thickness, using fluence to dose conversion factors from ICRP Publication 123.

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