Snowmass2021 - Letter of Interest

Neutron yield in (α, n)-reactions in rare-event searches

Thematic Areas: (check all that apply □/■)

Cosmic Frontier

■ (CF1) Dark Matter: Particle Like

Other frontiers

■ Instrumentation Frontier: (IF9) Cross Cutting and Systems Integration

■ Neutrino Physics Frontier: (NF05) Neutrino Properties

■ Rare Event and Precision Physics Frontier: (RF4) Baryon and Lepton Number Violating Processes

■ Accelerator/Technology Frontier: (AF5) Accelerators for PBC and Rare Processes

Contact Information: Shawn Westerdale (INFN Cagliari, Princeton) [shawest@princeton.edu]

Abstract: Calculations of (α, n) yields, neutron spectra, and correlated γ-rays are essential to understanding backgrounds in rare-event studies, like dark matter and neutrino experiments, and for nuclear astrophysics. This Letter discusses plans for a program to improve the accuracy of the estimates of (α, n)-induced backgrounds in astroparticle physics experiments, including novel ways to measure (α, n) cross sections for a variety of materials of interest. The planned research would provide a necessary ingredient for establishing the sensitivity of next-generation physics experiments with keV–MeV measurements.

Authors: Sofia Andringa[1], Federica Agostini[2 3], Daniel Cano Ott[4], Susana Cebrián[5], Daniel Galaviz[13 1], Pietro Di Gangi[2 3], Pablo Garcia Abia[4], Maxim Gromov[6 7], Alexander Chepurnov[8], Alexander Kish[9 10], Holger Kluck[11], Vitaly Kudryavtsev[12], Valentina Lozza[1 13], Andrea Mancuso[2 3], C. Jeff Martoff[14], Emilio Mendoza[4], Brian Mong[15], Vicente Pesudo Fortes[4], Andreas Piepke[16], Andrea Pocar[17], Diego Ramírez García[18], Roberto Santorelli[4], Gabriella Sartorelli[23], Marco Selvi[3], Eric Vázquez-Jáuregui[19], Venkatesh Veeraraghavan[16], Shawn Westerdale[20 21], Guido Zavattini[22]

[1]LIP-Lisbon, Laboratory for Instrumentation and Experimental Particle Physics. 1649-003 Lisbon, Portugal

[2]Department of Physics and Astronomy, University of Bologna, 40126 Bologna, Italy

[3]INFN Bologna, Bologna 40126, Italy

[4]CIEMAT, Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas, Madrid 28040, Spain

[5]Centro de Astropartículas y Física de Altas Energías, Universidad de Zaragoza, Zaragoza 50009, Spain

[6]Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow 119234, Russia

[7]Joint Institute for Nuclear Research, Dubna 141980, Russia

[8]Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow 119234, Russia

[9]Department of Physics and Astronomy, University of Hawai'i, Honolulu, HI 96822, USA

[10]CERN, European Organization for Nuclear Research 1211 Geneve 23, Switzerland, CERN

[11]Institut für Hochenergiephysik der Österreichischen Akademie der Wissenschaften, 1050 Wien, Austria

[12]Department of Physics and Astronomy, University of Sheffield, Sheffield S3 7RH, United Kingdom

[13]Univesidade de Lisboa, Faculdade de Ciências, Departamento de Física, 1749-016 Lisboa, Portugal

[14]Physics Department, Temple University, Philadelphia, PA 19122, USA

[15]SLAC National Accelerator Laboratory, Menlo Park, California 94025, USA

[16]Department of Physics and Astronomy, University of Alabama, Tuscaloosa, Alabama 35487, USA

[17]Amherst Center for Fundamental Interactions & Physics Department, University of Massachusetts, Amherst, MA 01003, USA

[18]Physikalisches Institut, Universität Freiburg, 79104 Freiburg, Germany

[19]Instituto de Física, Universidad Nacional Autónoma de México, México 01000, Mexico

[20]INFN Cagliari, Cagliari 09042, Italy

[21]Physics Department, Princeton University, Princeton, NJ 08544, USA

[22]Department of Physics and Earth Sciences, University of Ferrara, Ferrara, 44100, Italy

1 Motivation and goals

Accurate estimates of (α, n) neutron production rates, energy spectra, and correlated γ-rays are fundamental to understanding backgrounds in future rare-event studies, such as dark matter and neutrino experiments. Neutrons are highly penetrating, and neutron-induced nuclear recoils can pose irreducible backgrounds to dark matter searches [1–13]. Low-energy neutrino experiments also suffer from neutron backgrounds due to (1) γ-rays, produced when neutrons capture on detector materials, creating signals in the energy region of interest, (2) delayed coincidences between neutron-induced nuclear recoils and these γ-rays mimicking a potential neutrino signal, or (3) neutrons activating β-decaying nuclei [14–26]. The low-energy physics ($<10\,\mathrm{MeV}$) programs in future neutrino experiments like DUNE are affected by (n, γ) reactions, as well [27–29].

Extensive assay campaigns are often performed to determine the radiopurity of detector components and the corresponding neutron backgrounds in an experiment, and to design low-background materials [30–35]. Neutron fluxes are computed based on these assays with software like NeuCBOT [36], SaG4n [37], SOURCES [38] (updated with extended libraries as described, for example, in Refs. [11,39]; now also available within ORIGEN [40]), and NEDIS [41], which combine stopping power calculations with (α, n) cross sections, either from measurements or from nuclear model codes like EMPIRE [42] or TALYS [43]. Significant uncertainties in (α, n) yields ultimately limit the ability to constrain radiogenic neutron background predictions in large experiments [39,44,45]. These uncertainties, often of $\mathcal{O}(10\,\%)$ to $\mathcal{O}(100\,\%)$, largely stem from nuclear model uncertainties, missing or highly uncertain cross section measurements (especially for branching ratios to excited final states), and significant disagreements between similar measurements. These differences may sometimes be explained by different models and experimental corrections while interpreting measurements or by differences between setups. For future low-backgrounds experiments to reach their ultimate sensitivities, these neutron-induced backgrounds must be better understood.

The goal of this Letter is to unite nuclear and particle physicists interested in (α, n) reactions, including $(\alpha, n\gamma)$, in order to improve (α, n) yield and neutron spectrum calculations and to take new measurements that further this goal. Planning for the activities discussed in this Letter initiated at a topical meeting held in Madrid on November 2019 [46]. Our goals are to: (1) sytematically compare, benchmark, and verify existing (α, n) reaction codes, (2) create a common repository of cross sections, in different formats, which allows their use by different codes, (3) define a common approach to uncertainties, with a consistent treatment of experiment and model parameters, (4) investigate the impact of model parameters on comparisons of (α, n) calculations and measurements, (5) unify (α, n) yield calculations and uncertainty estimates across experiments, (6) plan and execute a program for measuring key (α, n) reactions for the intended applications.

In addition to their use in low-background experiments, (α, n) yields are important for nuclear physics [47–49], nuclear astrophysics [50–55] and nuclear energy-related applications [56–60]. They are also used in neutron safety assessments [61] and nuclear safeguards [62].

2 Improving the interpretation of existing data

Experimental measurements of (α, n) cross sections are available in the EXFOR database [63,64]. Uncertainties $\mathcal{O}(10\,\%)$ or more are common, and different measurements of the same cross section often significantly disagree [65,66]. Beyond these uncertainties, experimental data exist only for a limited number of isotopes, and nuclear models are required for the remainder. There are two main sets of evaluated (α, n) cross section libraries available: (1) JENDL-AN-2005, an evaluated experimental nuclear data library with cross sections available for a limited number of isotopes [67], and (2) the TENDL libraries [68] (latest release is TENDL-2019 [69]), generated for virtually all isotopes using the TALYS nuclear model-based simulation code.

Measurements of (α, n) cross sections exist beyond those included in the JENDL library and EXFOR database, such as those compiled in[70] and the measurements in[71–74], though some important isotopes still lack data. TALYS[43] can calculate cross sections for transitions to different final states, as well as the energy distributions of emitted neutrons. EMPIRE[42] can also calculate cross sections and branching ratios to excited states. Both codes rely on parameterized nuclear models to describe reactions of interest, tuned to available experimental data. For many isotopes, significant difference exists between measurements, evaluated cross section libraries, and calculations performed by these codes[39].

Improving the accuracy to which (α, n) and $(\alpha, n\gamma)$ calculations can be performed requires the following actions: (1) identify the highest priority targets for different applications, (2) begin a nuclear data evaluation program, starting with existing data not currently covered by other evaluations, with the goal to release a comprehensive library of evaluated cross sections that will be kept up-to-date, (3) improve and benchmark (α, n) codes, with a full and consistent evaluation of uncertainties, and add $(\alpha, n\gamma)$ yields, and (4) launch an experimental program to measure nuclides and materials for which there is currently insufficient or inaccurate data, with dedicated infrastructure and new detectors and beam facilities as needed.

3 Performing new measurements

Due to limitations in the available data, new measurements are needed to fill gaps in our current knowledge. These measurements are needed to resolve conflicts in the current data, determine neutron yields to higher precision and for more isotopes, and to measure partial cross sections to excited final states.

Accomplishing these goals requires samples with well-controlled compositions, α beams reaching energies up to $\sim 10\,\mathrm{MeV}$, and detectors with fast timing response, energy and angular resolution, electronic and nuclear recoil discrimination, and a high neutron tagging efficiency with minimal energy dependence. Recent advances in neutron detection and photon detection technologies, such as cheap and highly efficient silicon photomultipliers, have made it possible to design detectors that excel at the desired goals, and advances in purification and assay techniques make it possible to create samples with well-controlled compositions.

A list of high-priority isotopes is currently being developed, and measurements of (α, n) cross sections on these targets are being planned; contributions from other interested groups would also be welcomed. Several facilities have been identified where suitable accelerators can be used for these measurements. Candidate facilities include the Institute for Structure and Nuclear Astrophysics (ISNAP) at University of Notre Dame, the Michigan Ion Beam Laboratory at University of Michigan, the National Superconducting Cyclotron Laboratory (NSCL) at Michigan State University, the John D. Fox Laboratory at Florida State University, the Edwards Accelerator Laboratory at Ohio State University, the Tandem Laboratory at TUNL, and the *Laboratorio Acelerador Van de Graaf* at *Universidad Nacional Autónoma de México* in Mexico City, among others. Opportunities to collaborate with European facilities are being explored, as well. Further details of this experimental program are still under development.

4 Conclusions

Understanding (α, n) yields is essential for low-background experiments, and improving (α, n) yield calculations will also benefit nuclear physics, nuclear astrophysics, and nuclear energy. A program is being developed to improve (α, n) yield calculations, including an evaluation and a full and consistent treatment of uncertainties in current data, and to take additional measurements to strengthen such calculations.

References

[1] G. Angloher et al. (CRESST Collaboration), Eur. Phys. J. C **72**, 1971 (2012).
[2] P. Agnes et al. (DarkSide Collaboration), J. Instrum. **11**, P03016 (2016).
[3] R. Ajaj et al. (DEAP Collaboration), Phys. Rev. D **100**, 022004 (2019).
[4] E. Armengaud et al. (EDELWEISS Collaboration), J. Cosmol. Astropart. Phys. **2016**, 019 (2016).
[5] D. S. Akerib et al. (LUX Collaboration), Astropart. Phys. **62**, 33 (2015).
[6] X. Cui et al. (PandaX-II Collaboration), Phys. Rev. Lett. **119**, 181302 (2017).
[7] C. Amole et al. (PICO Collaboration), Phys. Rev. Lett. **118**, 251301 (2017).
[8] R. Calkins and B. Loer (SuperCDMS Collaboration), arXiv:1506.01922, (2015).
[9] E. Aprile et al. (XENON Collaboration), J. Phys. G **40**, 115201 (2013).
[10] D. C. Malling et al., arXiv:1305.5183, (2013).
[11] V. Tomasello, V. A. Kudryavtsev, and M. Robinson, Nucl. Instrum. Methods Phys. Res. A **595** (2008).
[12] M. J. Carson et al., Astropart. Phys. **21**, 667 (2004).
[13] G. Gerbier et al., Astropart. Phys. **11**, 287 (1999).
[14] M. Agostini et al. (Borexino Collaboration), Phys. Rev. D **101**, 012009 (2020).
[15] M. Agostini et al. (Borexino Collaboration), Phys. Rev. D **101**, 062001 (2020).
[16] F. Bellini et al. (CUORE Collaboration), Astropart. Phys. **33**, 169 (2010).
[17] W. Q. Gu et al. (Daya Bay Collaboration), Nucl. Instrum. Methods Phys. Res. A **833**, 27 (2016).
[18] M. Agostini et al. (GERDA Collaboration), Eur. Phys. J. C **74**, 2764 (2014).
[19] K. Eguchi et al. (KamLAND Collaboration), Phys. Rev. Lett. **90** (2003).
[20] J. B. Albert et al. (nEXO Collaboration), Phys. Rev. C **97**, 065503 (2018).
[21] A. Bellerive et al. (SNO Collaboration), Nucl. Phys. B **908**, 30 (2016).
[22] S. Andringa et al. (SNO+ Collaboration), Adv. High Energy Phys. **2016**, e6194250 (2016).
[23] H. Watanabe et al. (Super-Kamiokande Collaboration), Astropart. Phys. **31**, 320 (2009).
[24] A. Kozlov and D. Chernyak, Nucl. Instrum. Methods Phys. Res. A **903**, 162 (2018).
[25] M. Wurm et al., Astropart. Phys. **35**, 685 (2012).
[26] J. A. Formaggio and C. Martoff, Annu. Rev. Nucl. Part. Sci. **54**, 361 (2004).
[27] F. Capozzi, S. W. Li, G. Zhu, and J. F. Beacom, Phys. Rev. Lett. **123**, 131803 (2019).
[28] G. Zhu, S. W. Li, and J. F. Beacom, Phys. Rev. C **99**, 055810 (2019).
[29] A. Ankowski et al., arXiv:1608.07853 [astro-ph, physics:hep-ex, physics:hep-ph], (2016), arXiv: 1608.07853.
[30] P. A. Amaudruz et al., Astropart. Phys. **108**, 1 (2019).
[31] R. Ajaj et al., Phys. Rev. D **100**, 072009 (2019).
[32] J. B. Albert et al. (EXO-200 Collaboration), Phys. Rev. C **92**, 015503 (2015).
[33] K.-H. Ackermann et al., Eur. Phys. J. C **73**, 2330 (2013).
[34] E. Aprile et al., Eur. Phys. J. C **75**, 1 (2015).
[35] W. Maneschg et al., Nucl. Instrum. Methods Phys. Res. A **593**, 448 (2008).
[36] S. Westerdale and P. D. Meyers, Nucl. Instrum. Methods Phys. Res. A **875**, 57 (2017).
[37] E. Mendoza et al., Nucl. Instrum. Methods Phys. Res. A **960**, 163659 (2020).
[38] W. B. Wilson et al., Radiat. Prot. Dosim. **115**, 117 (2005).
[39] V. A. Kudryavtsev, P. Zakhary, and B. Easeman, Nucl. Instrum. Methods Phys. Res. A **972**, 164095 (2020).
[40] *Oak Ridge Isotope GENeration (ORIGEN) code*, URL `https://www.ornl.gov/project/origen`.
[41] G. N. Vlaskin, Y. S. Khomyakov, and V. I. Bulanenko, At. Energy **117**, 357 (2015).
[42] M. Herman et al., Nucl. Data Sheets **108**, 2655 (2007).
[43] A. J. Koning and D. Rochman, Nucl. Data Sheets **113**, 2841 (2012).

[44] J. Cooley et al., Nucl. Instrum. Methods Phys. Res. A **888**, 110 (2018).
[45] M. T. Pigni, S. Croft, and I. C. Gauld, Prog. Nucl. Energy **91**, 147 (2016).
[46] (α, n) *yields in low background experiments* (2019), CIEMAT, Madrid, Spain, URL https://agenda.ciemat.es/event/1127/timetable/?view=standard.
[47] J. K. Bair and H. B. Willard, Phys. Rev. **128**, 299 (1962).
[48] W. Gruhle, W. Schmidt, and W. Burgmer, Nucl. Phys. A **186**, 257 (1972).
[49] Q. Liu et al., Phys. Rev. C **100**, 034601 (2019).
[50] M. R. Anderson, L. W. Mitchell, M. E. Sevior, and D. G. Sargood, Nucl. Phys. A **405**, 170 (1983).
[51] B. Holmqvist and E. Ramström, Phys. Scr. **33**, 107 (1986).
[52] A. W. Obst, T. B. Grandy, and J. L. Weil, Phys. Rev. C **5**, 738 (1972).
[53] C. Sneden, J. J. Cowan, and R. Gallino, Annu. Rev. Astron. Astrophys. **46**, 241 (2008).
[54] R. Longland, C. Iliadis, and A. I. Karakas, Phys. Rev. C **85**, 065809 (2012).
[55] J. L. Tain et al., J. Phys. Conf. Ser. **665**, 012031 (2016).
[56] T. Murata and K. Shibata, J. Nucl. Sci Technol. **39**, 76 (2002).
[57] D. P. Griesheimer et al., Nucl. Eng. Technol. **49**, 1199 (2017).
[58] T. E. Sampson, Nucl. Sci. Eng. **54**, 470 (1974).
[59] J. Bliss, A. Arcones, F. Montes, and J. Pereira, J. Phys. G **44**, 054003 (2017).
[60] B. Pérot et al., EPJ Nucl. Sci. & Technol. **4**, 3 (2018).
[61] Y. Feige, B. G. Oltman, and J. Kastner, J. of Geophys. Res. **73**, 3135 (1968).
[62] S. P. Simakov and Q. Y. van den Berg, Nucl. Data Sheets **139**, 190 (2017).
[63] V. V. Zerkin and B. Pritychenko, Nucl. Instrum. Methods Phys. Res. A **888**, 31 (2018).
[64] N. Otuka et al., Nucl. Data Sheets **120**, 272 (2014).
[65] T. Khromyleva et al., Nucl. Sci. Eng. **191**, 282 (2018).
[66] N. Soppera, E. Dupont, M. Bossant, and M. Flemming, OECD NEA Data Bank, (2018).
[67] K. Shibata et al., J. Nucl. Sci. Technol. **48**, 1 (2011).
[68] A. J. Koning and D. Rochman, Nucl. Data Sheets **113**, 2841 (2012).
[69] A. J. Koning et al., Nucl. Data Sheets **155**, 1 (2019).
[70] R. Heaton, H. Lee, P. Skensved, and B. C. Robertson, Nucl. Instrum. Meth. Phys. Res. A **276**, 529 (1989).
[71] P. H. Stelson and F. K. McGowan, Phys. Rev. **133**, B911 (1964).
[72] N. A. Roughton et al., At. Data Nucl. Data Tables **28**, 341 (1983).
[73] J. K. Bair and J. G. d. Campo, Nucl. Sci. Eng. **71**, 18 (1979).
[74] J. K. Bair and F. X. Haas, Phys. Rev. C **7**, 1356 (1973).