ISBN: 978-3-95450-217-2 doi:10.18429/JACoW-ERL2019-MOCOYBS04

ELECTRODISINTEGRATION OF ^{16}O AND THE RATE DETERMINATION OF THE RADIATIVE α CAPTURE ON ^{12}C AT STELLAR ENERGIES

I. Friščić *, T. W. Donnelly, R. G. Milner
Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA

Abstract

For over five decades one of the most important goals of experimental nuclear astrophysics has been to reduce the uncertainty in the S-factor of radiative α capture on ^{12}C at stellar energies. We have developed a simple model, which relates the radiative capture reaction and the exclusive electrodisintegration reaction. We then show that by measuring the rate of electrodisintegration of ^{16}O in a high luminosity experiment using a state-of-the-art jet-target and a new generation of energy-recovery linear (ERL) electron accelerators under development, it is possible to significantly improve the statistical uncertainty of the radiative α capture on ^{12}C in terms of E1 and E2 S-factors in the astrophysically interesting region, which are the key inputs for any nucleosynthesis and stellar evolution models. The model needs to be validated experimentally, but, if successful, it can be used to improve the precision of other astrophysically-relevant, radiative capture reactions, thus opening a significant avenue of research that spans nuclear structure, astrophysics and high-power accelerator technology.

INTRODUCTION

During the stellar evolution, the helium burning stage is dominated by two reactions: radiative triple-α capture and radiative α capture on ^{12}C, *i.e.* ^{12}C$(\alpha,\gamma)^{16}$O. The values of the individual rates will determine the ^{12}C/^{16}O abundance at the end of the helium burning stage, which highly influences the subsequent nucleosynthesis [1]. The current uncertainty in triple-α capture at stellar energies is known with an uncertainty of ~10%, but for the ^{12}C$(\alpha,\gamma)^{16}$O rate the situation is much worse [2]. In the modeling of the stellar evolution, the large uncertainty of the measured ^{12}C$(\alpha,\gamma)^{16}$O rate translates into large range of rates and because of this models give different outcomes in terms of nuclei abundance inside a star of a given mass [1, 2]. Thus, for many decades, the goal of experimental nuclear physics was to improve the precision of measurements of the ^{12}C$(\alpha,\gamma)^{16}$O rate at stellar energies [3]. Attempts were made to constrain the ^{12}C$(\alpha,\gamma)^{16}$O rate using the models and the observed solar abundances [1], implicating that the experimental rate needs to be measured with an uncertainty ≤10% [4]. Such a level of precision has still not been achieved..

At typical helium burning temperature for massive stars ~$2\cdot10^8$ K, the equivalent Gamow energy E_g is ~300 keV and due to large Coulomb barrier the cross section of the ^{12}C$(\alpha,\gamma)^{16}$O reaction is extremely small ~10^{-5} pb, making the direct measurements infeasible. The strategy is to measure the cross section, which is usually expressed in terms of the astrophysical S-factor as a function of α-particle center-of-mass (cm) kinetic energy E_α^{cm}:

$$S = \sigma E_\alpha^{cm} e^{2\pi\mu} \tag{1}$$

where μ is the Sommerfeld parameter, at several larger energies and then to extrapolate to stellar energies. The extrapolation is complicated due the structure of ^{16}O [5] and involves dealing with the interference of subthreshold and above threshold E1/E2 states.

In the past, many different experimental methods have been developed and used to measure the ^{12}C$(\alpha,\gamma)^{16}$O rate, including the direct reaction measurements [6–19], elastic scattering ^{12}C$(\alpha,\alpha)^{12}$C [20, 21], and $\beta-$delayed α-decay of ^{16}N [22–24]. Below $E_\alpha^{cm} < 2$ MeV the data points are increasingly dominated by the statistical uncertainties, due to rapidly falling of the cross section as it approaches the Gamow energy. Recently, researchers have started to investigate the inverse reaction induced by real photons (the photodisintegration of ^{16}O), in order to improve the statistics of low-energy data. One concept uses a bubble chamber [25, 26] and the other an optical time projection chamber [27]. More details about the specific experiments and the astrophysical implications of the ^{12}C$(\alpha,\gamma)^{16}$O rate can be found in the most recent review [2].

Contrary to photodisintegration, where the real photon beam is involved $|\vec{q}| = q = E_\gamma$, the electrodisintegration uses an electron beam with an exchange of a virtual photon $(\omega,\vec{q})$, for details see [28]. In the past, the potential astrophysical application of the electrodisintegration of ^{16}O was discussed in [29] and an storage ring based experiment was proposed in [30], but was never carried out. More recent discussions [31, 32] are motivated by development of a new generation of high intensity (≈ 10 mA) low-energy (≈ 100 MeV) energy-recovery linear (ERL) electron accelerators [33, 34] and which together with modern jet gas targets [35], can deliver luminosity $>10^{35}$ cm^{-2} s^{-1}. By measuring the final state of the scattered electron it is possible to define and fix the α+^{12}C excitation energy, but at the same time control the three-momentum of the virtual photon $\vec{q}$ either by selecting the electron scattering angle θ_e or the beam energy E_e, see Fig 1. The real photon result can be recovered by taking the limit $q/\omega \to 1$.

In this paper, we briefly present a new method to improve the precision of the ^{12}C$(\alpha,\gamma)^{16}$O reaction at stellar energies based on electrodisintegration of ^{16}O, *i.e.* ^{16}O$(e,e'\alpha)^{16}$C. The full description of this method can be found in [36].

* friscic@mit.edu

ISBN: 978-3-95450-217-2 doi:10.18429/JACoW-ERL2019-MOCOYBS04

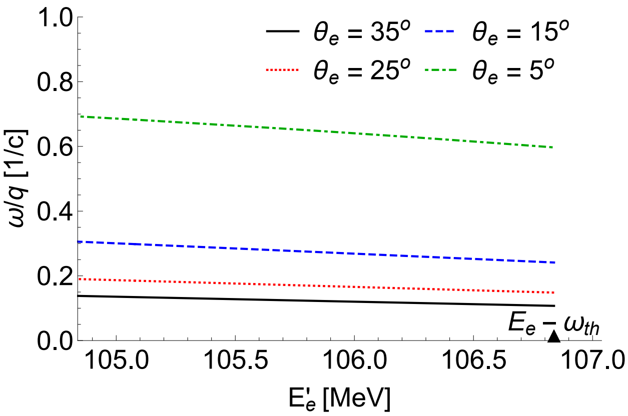

Figure 1: The dependence of the ratio of the transferred energy to the transferred three-momentum ω/q on the scattered electron energy E'_e for kinematics corresponding to 2 MeV above threshold for electron beam energy $E_e = 114$ MeV, ω_{th} denotes the energy of the photon at the threshold.

DIFFERENTIAL CROSS SECTION FOR THE ELECTRODISINTEGRATION

The differential cross section for the reaction $^{16}\mathrm{O}(e, e'\alpha)^{12}\mathrm{C}$ reaction in the *cm* frame can be expressed as [36]:

$$\left[\frac{d\sigma}{d\omega d\Omega_e d\Omega_\alpha^{cm}}\right]_{(e,e'\alpha)} = \frac{M_\alpha M_{^{12}C}}{8\pi^3 W}\frac{p_\alpha^{cm}\sigma_{Mott}}{(\hbar c)^3}$$
$$\times\left(\widetilde{v}_L R_L + \widetilde{v}_T R_T + \widetilde{v}_{TL} R_{TL} + \widetilde{v}_{TT} R_{TT}\right). \qquad (2)$$

where σ_{Mott} is the Mott cross section. In case of the unpolarized exclusive electron scattering we have four nuclear response functions R_K: the longitudinal R_L and transverse R_T components (L and T with respect to the direction of the virtual photon $\vec{q}$), and two interference responses, transverse-longitudinal R_{TL} and transverse-transverse R_{TT}. The functions $\widetilde{v}_K$ are electron kinematic factors [28].

A big advantage of measuring the electrodisintegration reaction over the photodisintegration reaction is, that one can be in the astrophysical interesting region in terms of ω, and at same time transfer enough three-momentum q to the final state α-particles, which can then exit the jet target and be detected. By measuring the angular distribution of produced α-particles, for both reactions, it is possible to separate contributions from various multipoles. In real photon processes close to threshold and involving exclusively ground states of 0^+ nuclei only E1 (electric dipole) and E2 (electric quadrupole) multipole are assumed [6]. By measuring the final state of the scattered electron in coincidence with the final state of the produced α-particle it is possible to determine the final state of the unobserved ^{12}C and separate any excited state. In case of electrodisintegration, both electric and Coulomb multipoles contribute, therefore we are considering C0, C1, C2, E1 and E2 multipoles.

At low values of the momentum transfer q, compared with a typical nuclear momentum q_0 (order of 200–250 MeV/c), each multipole is dominated by its low-q behavior which enters as a specific power of q [36]. Again, by fixing ω and increasing q one may vary the contribution of a particular multipole and thus eventually explore the potential C3/E3 contributions.

In case of real photons only the transverse R_T response function contributes to the cross section and eventually R_{TT} if there are linearly polarized real photons involved (see Sect. III of [36] for more details). R_T and R_{TT} response functions only contain EJ multipoles, longitudinal R_L response function only CJ multipoles, and interference transverse-longitudinal R_{TL} contains combinations of both EJ and CJ multipoles. Their form as functions of α-particle angles θ_α^{cm} (angle between α-particle and momentum $\vec{q}$) and ϕ_α are described in detail in [36].

DEFINITION OF THE MODEL AND MONTE-CARLO SIMULATION

At this point we have developed the general differential cross section formula and from now we are continuing with development of a model for the electrodisintegration reaction. First, we determine the leading-order contribution to the E1 and E2 multipoles by fitting the second order polynomial to all S_{E1} and S_{E2} data from the direct reaction experiments having $E_\alpha^{cm} < 1.7$ MeV. By using current conservation in the low-q limit it is possible to relate the leading-order of the EJ an CJ multipoles (J > 0). For the next-to-leading (NLO) order q-dependence in the C1/E1 and C2/E2 multipoles cannot be related using current conservation, therefore we made assumptions for the q-dependence and similarly in the C0 multipole (see [36] for details). The goal here is to develop a reasonable model in order to study the feasibility of performing the electrodisintegration measurements in the astrophysical interested region. In a real experiment higher-order q-dependences will also be measured and then one will determine the region where the used parameterization can be applied.

Using the described model and assuming the experimental parameters given in Table 1 we have used Monte-Carlo simulation to calculate the rate of the electrodisintegration of ^{16}O. We have assumed a 2 mm wide oxygen cluster-jet target [35] capable of achieving a thickness of 5×10^{18} atoms/cm^2.

We also need an high current (40 mA) electron accelerator which can deliver a beam energy of around 100 MeV. For example MESA, which should be able to deliver a beam current of 10 mA [33] and CBETA which should reach 40 mA [37] for beam energies of 42, 78, 114 and 150 MeV (all energies in between are also possible). Assuming a beam current of 40 mA and a jet target as described above the luminosity amounts to 1.25×10^{36} cm^{-2}s^{-1}.

For the identification of events originating from electrodisintegration of ^{16}O the scattered electron needs to be detected in coincidence with the produced α-particle. Fig. 2 shows a schematic layout of a possible experiment. The

ISBN: 978-3-95450-217-2 doi:10.18429/JACoW-ERL2019-MOCOYBS04

Table 1: Summary of the experimental parameters for the rate calculations used in [36].

Acceptance	Electron	α-particle
In-plane	±2.08°	60°
Out-of-plane	±4.16°	360°
Solid angle	10.5 msr	3.14 sr
Oxygen Target	Thickness	$5{\times}10^{18}$ atoms/cm^2
	Density	$6.65{\times}10^{-4}$ g/cm^3
Electron Beam	Current	40 mA
	Energies (E_e)	78, 114, 150 MeV
Luminosity		$1.25{\times}10^{36}$ cm^{-2}s^{-1}
Integrated Lumi. (100 days)		$1.08{\times}10^{7}$ pb^{-1}
Central electron scatt. angles θ_e		15°, 25°, 35°
E_α^{cm}-range of interest		$0.7{\leq}E_\alpha^{cm}{\leq}1.7$ MeV

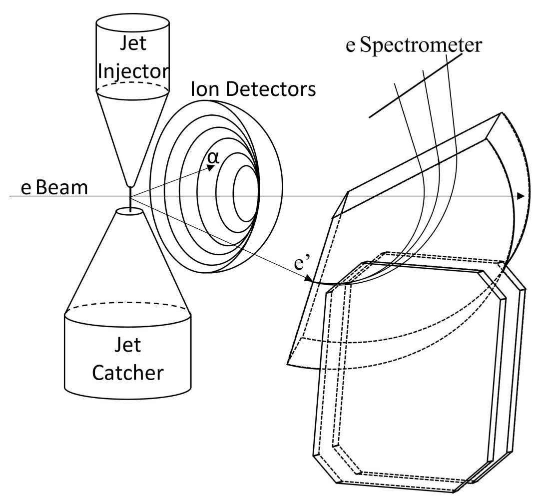

Figure 2: Schematic layout of simulated $^{16}\mathrm{O}(e,e'\alpha)^{12}\mathrm{C}$ experiment: ^{16}O is disintegrated by the electron beam into an α-particle and ^{12}C nuclei. The scattered electron is detected in an electron spectrometer and the produced α-particle in large acceptance ion detectors [36].

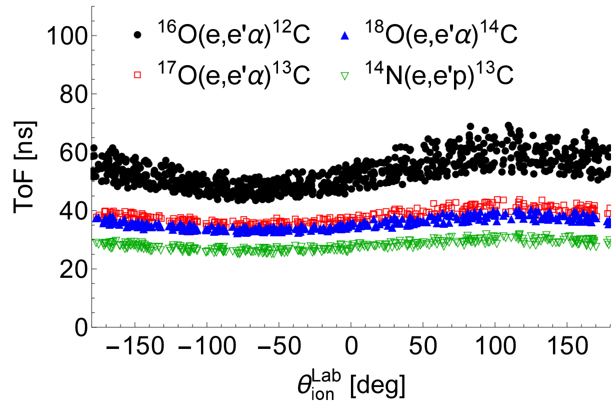

Figure 3: Energy-loss corrected time-of-flight ToF as functions of laboratory ion production angle θ_{ion}^{Lab} assuming that the ions were produced by electrons involved in the electrodisintegration of ^{16}O, at $E_e = 114$ MeV and $\theta_e = 15°$ with a cut on $1.0 \leq E_\alpha^{cm} \leq 1.1$ MeV. The energy-loss of the α-particles and the protons inside the ^{16}O gas jet was simulated by using the SRIM-2013 software [38, 39].

scattered electron is detected by a high precision magnetic spectrometer. We assumed that the spectrometer has an in-plane acceptance of ±2.08° and out-of-plane acceptance of ±4.16°. This corresponds to a solid angle of 10.5 msr.

The large acceptance ion detectors should be based on time-of-flight (ToF) detection in order to be able to distinguish the background α-particles originating from the electrodisintegration of ^{17}O and ^{18}O, as well as the proton background from the electrodisintegration of ^{14}N, as shown in Fig. 3. Furthermore, ion detectors should be centered around the direction of the virtual photon $\vec{q}$ in order to be detect particles having the largest kinetic energy (or lowest ToF like on Fig. 3) and subsequently having the smallest angular spread. For these detectors we assumed that the solid angle is large enough to accept all α-particles having the in-plane scattering angle θ_α^{cm} in range from 0° to 60° and to have the full acceptance for the out-of-plane angle ϕ_α from 0° to 360°.

RESULTS AND DISCUSSION

Monte Carlo simulation was used to calculate the number of events after 100 days of running, which were subsequently used to calculate statistical uncertainties, which were then propagated all the way back to S-factors and the corresponding projected statistical uncertainties. The result of one simulation from [36] for the beam energy $E_e = 114$ MeV and the electron scattering angle $\theta_e = 15°$ is shown in figure 4. One can clearly see a significant improvement in terms of the statistical uncertainties when comparing the electrodisintegration projected data with the previous experiments.

The full set of Monte-Carlo simulations for beam energies $E_e = 74$, 114 and 150 MeV, electron scattering angles $\theta_e = 15°$, 25° and 35°, and two values of modeling of C0 multipole can be found in [36]. The overall conclusion is that when comparing the results from [36] with the most accurate measurements from [14] and [17], the uncertainties in the determination of S_{E1} and S_{E2} at a given energy above threshold are improved by at least ×5.6 and ×23.9, respectively. The significant uncertainty improvement for the S_{E2} comes from two contributions. The dominant one is the fact that C2/E2 matrix elements, compared to C1/E1, enter in response functions $R_{L,T,TL,TT}$ are enhanced by factor q/ω, which for given $E_e = 114$ MeV and $\theta_e = 15°$ amounts to ~3.6 (in real photon experiments $q/\omega = 1$). The other contribution comes from the angular distribution of the multipoles for the selected range of θ_α^{cm} from 0° to 60°, the angular distributions of C2/E2 are larger in magnitude compared to the C1/E1 angular distributions. In the case of

ISBN: 978-3-95450-217-2 doi:10.18429/JACoW-ERL2019-MOCOYBS04

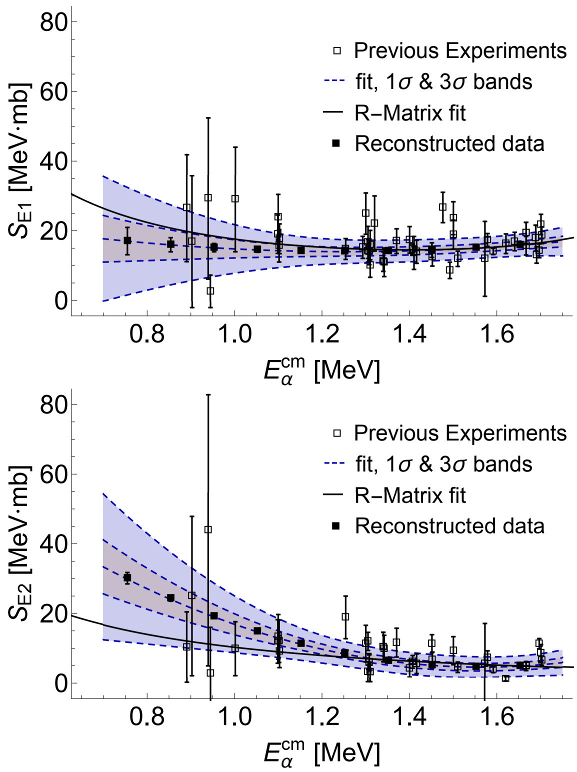

Figure 4: Projected S_{E1}- and S_{E2}-factors with statistical error bars (represented by solid squares) for simulation with $E_e = 114$ MeV and $\theta_e = 15°$ from [36], and previous experiments [6–14, 16, 17, 19]. The solid line represents the AZURE2 [40] R-Matrix fit of the world data set.

real photon experiments, the angular distributions of E1 and E2 behave the same, for example see figure 5. in [2].

OUTLOOK AND CONCLUSION

We have developed a simple model, which allowed us to relate the electrodisintegration of ^{16}O and the α-particle capture on ^{12}C reactions. By considering the optimal kinematics for the electrodisintegration of ^{16}O in terms of the electron beam energy, oxygen jet-target density, the electron spectrometer, and the low-energy α-particle detectors for suppressing the chemical and isotopic background. We showed that the new ERLs are essential to achieve high luminosity, in order to have a high statistics electrodisintegration measurement, which can be used to determine the $^{12}C(\alpha, \gamma)^{16}O$ reaction rate with unprecedented precision.

The running of α-detectors in close proximity of the Megawatt electron beam will be very challenging, but it was already demonstrated that such high power ERL beams can be achieved with a minimal halo [41].

We propose an initial run of $^{16}O(e, e'\alpha)^{12}C$ using an ERL with a beam energy of ~100 MeV. This experiment would be focused on higher energies E_α^{cm}, in the region where the reaction rates are relatively high and the running time would be few weeks long. The first milestone would be to experimentally validate the extrapolation to real photon limit and to determine the rate contributions of the different multipoles. If successful, it would pave the way for a longer experiment with the highest beam current available to determine the $^{12}C(\alpha, \gamma)^{16}O$ reaction rate with unprecedented precision at the stellar energies.

ACKNOWLEDGMENTS

We acknowledge valuable discussions with E. Tsentalovich and H. Weller. This research was supported by the U.S. Department of Energy Office of Nuclear Physics under grant No. DE-FG02-94ER40818.

REFERENCES

[1] T. A. Weaver and S. E. Woosley, *Phys. Rep.*, vol. 227, pp. 65–96, 1993. DOI: 10.1016/0370-1573(93)90058-L.
[2] R. J. deBoer *et al.*, *Rev. Mod. Phys.*, vol. 89, p. 035 007, 2017. DOI: 10.1103/RevModPhys.89.035007.
[3] S. E. Woosley *et al.*, *Nucl. Phys. A*, vol. 718, p. 3c, 2003. DOI: 10.1016/S0375-9474(03)00673-0.
[4] S. E. Woosley, A. Heger, and T. A. Weaver, *Rev. Mod. Phys.*, vol. 74, p. 1015, 2002. DOI: 10.1103/RevModPhys.74.1015.
[5] D. R. Tilley, H. R. Weller, and C. M. Cheves, *Nucl. Phys. A*, vol. 565, pp. 1–184, 1993. DOI: 10.1016/0375-9474(93)90073-7.
[6] P. Dyer and C. Barnes, *Nucl. Phys. A*, vol. 233, p. 495, 1974. DOI: 10.1016/0375-9474(74)90470-9.
[7] A. Redder *et al.*, *Nucl. Phys. A*, vol. 462, p. 385, 1987. DOI: 10.1016/0375-9474(87)90555-0.
[8] R. M. Kremer *et al.*, *Phys. Rev. Lett.*, vol. 60, p. 1475, 1988. DOI: 10.1103/PhysRevLett.60.1475.
[9] J. M. L. Ouellet *et al.*, *Phys. Rev. C*, vol. 54, p. 1982, 1996. DOI: 10.1103/PhysRevC.54.1982.
[10] G. Roters, C. Rolfs, F. Strieder, and H. Trautvetter, *Eur. Phys. J. A*, vol. 6, p. 451, 1999. DOI: 10.1007/s100500050369.
[11] L. Gialanella *et al.*, *Eur. Phys. J. A*, vol. 11, p. 357, 2001. DOI: 10.1007/s100500170075.
[12] R. Kunz *et al.*, *Phys. Rev. Lett.*, vol. 86, p. 3244, 2001. DOI: 10.1103/PhysRevLett.86.3244.
[13] R. W. Kunz, PhD thesis, Univ. of Stuttgart, 2002.
[14] M. Fey, PhD thesis, Univ. of Stuttgart, 2004.
[15] D. Schürmann *et al.*, *Eur. Phys. J. A*, vol. 26, pp. 301–305, 2005. DOI: 10.1140/epja/i2005-10175-2.
[16] M. Assunção *et al.*, *Phys. Rev. C*, vol. 73, p. 055 801, 2006. DOI: 10.1103/PhysRevC.73.055801.
[17] H. Makii *et al.*, *Phys. Rev. C*, vol. 80, p. 065 802, 2009. DOI: 10.1103/PhysRevC.80.065802.
[18] D. Schürmann *et al.*, *Phys. Lett. B*, vol. 703, pp. 557–561, 2011. DOI: 10.1016/j.physletb.2011.08.061.
[19] R. Plag *et al.*, *Phys. Rev. C*, vol. 86, p. 015 805, 2012. DOI: 10.1103/PhysRevC.86.015805.
[20] R. Plaga *et al.*, *Nucl. Phys. A*, vol. 465, pp. 291–316, 1987. DOI: 10.1016/0375-9474(87)90436-2.
[21] P. Tischhauser *et al.*, *Phys. Rev. C*, vol. 79, p. 055 803, 2009. DOI: 10.1103/PhysRevC.79.055803.
[22] L. Buchmann *et al.*, *Phys. Rev. Lett.*, vol. 70, p. 726, 1993. DOI: 10.1016/j.nima.2015.01.060.
[23] R. E. Azuma *et al.*, *Phys. Rev. C*, vol. 50, p. 1194, 1994. DOI: 10.1103/PhysRevC.50.1194.

ISBN: 978-3-95450-217-2 doi:10.18429/JACoW-ERL2019-MOCOYBS04

[24] X. D. Tang *et al.*, *Phys. Rev.C*, vol. 81, p. 045 809, 2010. DOI: 10.1103/PhysRevC.81.045809.

[25] B. DiGiovine *et al.*, *Nucl. Instrum. Methods Phys. Res. A*, vol. 781, pp. 96–104, 2015. DOI: 10.1016/j.nima.2015.01.060.

[26] R. J. Holt *et al.*, 2018. arXiv: 1809.10176 [nucl-ex].

[27] M. Gai *et al.*, *JINST*, vol. 5, P12004, 2010. DOI: 10.1088/1748-0221/5/12/P12004.

[28] A. S. Raskin and T. W. Donnelly, *Ann. Phys.*, vol. 191, pp. 78–142, 1989. DOI: 10.1016/0003-4916(89)90337-0.

[29] T. W. Donnelly, "Electron scattering and the nuclear many-body problem," in *The Nuclear Many-Body Problem 2001*, W. Nazarewicz and D. Vretenar, Eds. Dordrecht: Springer Netherlands, 2002, pp. 19–26. DOI: 10.1007/978-94-010-0460-2_3.

[30] E. Tsentalovich *et al.*, MIT-Bates PAC proposal 00-01, 2000.

[31] I. Friščić, *Electrodisintegration of ^{16}o as a tool for investigating the $^{12}c(\alpha,\gamma)^{16}o$ reaction*, Conf. Abstracts EINN2017, 2017. %7Bhttp://einnconference.org/2017/wp-content/uploads/2017/10/EINN-2017-Conference-Abstracts-2810.pdf%7D

[32] S. Lunkenheimer, *Studies of the nucleosynthesis $^{12}c(\alpha,\gamma)^{16}o$ in inverse kinematics for the MAG-IX experiment at MESA*, 650. WE-Heraeus-Seminar, 2017.

[33] F. Hug *et al.*, *Proc. of Linear Accelerator Conference (LINAC'16)*, vol. 28, pp. 313–315, 2017. DOI: 10.18429/JACoW-LINAC2016-MOP106012.

[34] G. H. Hoffstaetter *et al.*, 2017. arXiv: 1706.04245 [physics.acc-ph].

[35] S. Grieser *et al.*, *Nucl. Instrum. Methods Phys. Res. A*, vol. 906, pp. 120–126, 2018. DOI: 10.1016/j.nima.2018.07.076.

[36] I. Friščić, T. W. Donnelly, and R. G. Milner, *Phys. Rev. C*, vol. 100, p. 025 804, 2019. DOI: 10.1103/PhysRevC.100.025804.

[37] D. Trbojevic *et al.*, *Proc. of International Particle Accelerator Conference (IPAC'17)*, vol. 8, pp. 1285–1289, 2017. DOI: 10.18429/JACoW-IPAC2017-TUOCB3.

[38] J. F. Ziegler, M. D. Ziegler, and J. P. Biersack, *Nucl. Instrum. Methods Phys. Res. B*, vol. 268, pp. 1818–1823, 2010. DOI: 10.1016/j.nimb.2010.02.091.

[39] http://www.srim.org/.

[40] R. E. Azuma *et al.*, *Phys. Rev. C.*, vol. 81, p. 045 805, 2010. DOI: 10.1103/PhysRevC.81.045805.

[41] R. Alarcon *et al.*, *Phys. Rev. Lett.*, vol. 111, p. 164 801, 2013.