Light-ion production in the interaction of 96 MeV neutrons with oxygen

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Abstract

Double-differential cross sections for light-ion (p, d, t, \(^3\)He and \(\alpha\)) production in oxygen, induced by 96 MeV neutrons are reported. Energy spectra are measured at eight laboratory angles from 20° to 160° in steps of 20°. Procedures for data taking and data reduction are presented. Deduced energy-differential and production cross sections are reported. Experimental cross

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sections are compared to theoretical reaction model calculations and experimental data at lower neutron energies in the literature.
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1 Introduction

Fast-nucleon induced reactions provide useful means to investigate nuclear structure, to characterize reaction mechanisms and to impose stringent constraints on nuclear model calculations. Although oxygen is a light nucleus with doubly closed shells, it can be expected that many statistical assumptions hold for nucleon-induced reactions at several tens of MeV, because the level density at high excitation energies is sufficiently high that shell effects and other nuclear structure signatures are washed out. Light nuclei also have low Coulomb barrier, implying that the suppression of charged-particle emission is weak. Therefore, nuclear reaction models for equilibrium and pre-equilibrium decay can be tested and benchmarked. Experimental data on reactions in oxygen in the literature at incident neutron energies of 27, 40, and 60 MeV [1, 2] and between 25 and 65 MeV [3, 4, 5] offer possibilities to test the predictions of reaction models.

In recent years, an increasing number of applications involving fast neutrons have been developed or are under consideration, e.g., radiation treatment of cancer [6, 7, 8], neutron dosimetry at commercial aircraft altitudes [9], soft-error effects in computer memories [10, 11], accelerator-driven transmutation of nuclear waste and energy production [12, 13], and determination of the response of neutron detectors [14]. Data on light-ion production in light nuclei such as carbon, nitrogen and oxygen are particularly important in calculations of dose distributions in human tissue for radiation therapy at neutron beams, and for dosimetry of high energy neutrons produced by high-energy cosmic radiation interacting with nuclei (nitrogen and oxygen) in the atmosphere [9, 15]. When studying neutron dose effects in radiation therapy and at high altitude, it is especially important to consider oxygen, because it is the dominant element (65 % by weight) in average human tissue.

In this paper, we present experimental double-differential cross sections (inclusive yields) for protons, deuterons, tritons, $^3$He and alpha particles produced by 96 MeV neutrons incident on oxygen. The measurements have been performed at the cyclotron of The Svedberg Laboratory (TSL), Uppsala, using the MEDLEY experimental setup [16]. Spectra have been measured at 8 laboratory angles, ranging from $20^\circ$ to $160^\circ$ in $20^\circ$ steps. Extrapolation procedures are used to obtain coverage of the full angular range, and consequently energy-differential and production cross sections are deduced, the
latter by integrating over energy and angle. The experimental data are com-
pared to results of calculations with nuclear reaction codes and to existing
experimental data at lower incident neutron energies.

The experimental methods are briefly discussed in Sec. 2 and data re-
duction and correction procedures are presented in Sec. 3. The theoretical
framework is summarized in Sec. 4. In Sec. 5 the experimental results are
reported and compared with theoretical and previous experimental data.
Conclusions and an outlook are given in Sec. 6.

2 Experimental methods

The experimental setup, procedures for data reduction and corrections have
been described in detail recently [17, 18] and therefore only brief summaries
are given here.

The neutron beam facility at The Svedberg Laboratory (TSL) uses the
$^7\text{Li}(p,n)^7\text{Be}$ reaction to produce a quasi-monoenergetic neutron beam [19].
The lithium target was 8 mm thick in the present experiment and enriched
to 99.98 $\%$ in $^7\text{Li}$. The 98.5±0.3 MeV protons from the cyclotron impinge on
the lithium target, producing neutrons with a full-energy peak of 95.6±0.5
MeV with a width of 1.6 MeV (FWHM). With a beam intensity of 5 $\mu$A, the
neutron flux in the full-energy peak is about $5 \cdot 10^4$ neutrons/(s·cm$^2$) at
the target location. The collimated neutron beam has a diameter of 80 mm at
the location of the target, where it is monitored by a thin film breakdown counter
(TFBC) [20]. Relative monitoring was obtained by charge integration of the
proton beam in a Faraday cup located in the proton beam dump. The two
beam monitor readings were in agreement during the measurements.

The charged particles are detected by the MEDLEY setup [16]. It consists
of eight three-element telescopes mounted inside a 100 cm diameter evacuated
reaction chamber. Each telescope consists of two fully depleted $\Delta E$ silicon
surface barrier detectors and a CsI(Tl) crystal. The thickness of the first
$\Delta E$ detector ($\Delta E_1$) is either 50 or 60 $\mu$m, while the second one ($\Delta E_2$) is
either 400 or 500 $\mu$m. They are all 23.9 mm in diameter (nominal). The
cylindrical CsI(Tl) crystal, 50 mm long and 40 mm in diameter, serves as the
$E$ detector.

A 22 mm diameter 500 $\mu$m thick (cylindrical) disk of SiO$_2$ is used as the
oxygen target. For the subtraction of the silicon contribution, measurements
using a silicon wafer having a 32·32 mm$^2$ quadratic shape and a thickness of
303 $\mu$m are performed.

For absolute cross section normalization, a 25 mm diameter and 1.0 mm
thick polyethylene ($\text{CH}_2)_n$ target is used. The $np$ cross section at 20$^\circ$ labora-
tory angle provides the reference cross section [21]. Instrumental background is measured by removing the target from the neutron beam. It is dominated by protons produced by neutron beam interactions with the beam tube and reaction chamber material, especially at the entrance and exit of the reaction chamber and in the telescope housings. Therefore, the telescopes at 20° and 160° are most affected.

The time-of-flight (TOF) obtained from the radio frequency of the cyclotron (stop signal for TDCs) and the timing signal from each of the eight telescopes (start signal), is registered for each charged-particle event. Typical count rates for target-in and target-out runs were 10 and 2 Hz, respectively. The dead time of the data acquisition system was typically 1 − 2 % and never exceeded 10 %.

3 Data reduction procedures and corrections

The $\Delta E - E$ technique is used to identify light charged particles ranging from protons to lithium ions. Good separation of all particles is obtained over their entire energy range and particle identification is straightforward.

Energy calibration of all detectors is obtained from the data themselves [17, 18]. Events in the $\Delta E - E$ bands are fitted with respect to the energy deposited in the two silicon detectors. This energy is determined from the detector thicknesses and tabulated energy loss values in silicon [22]. The $\Delta E_1$ detectors are further calibrated and checked using a 5.48 MeV alpha source. For the energy calibration of the CsI(Tl) detectors, two parameterizations of the light output versus energy of the detected particle [16, 17, 18] are used, one for hydrogen isotopes and another one for helium isotopes. Supplementary calibration points are provided by the H(n,p) reaction, as well as transitions to the ground state and low-lying states in the $^{12}$C(n,d)$^{11}$B, $^{16}$O(n,d)$^{15}$N and $^{28}$Si(n,d)$^{27}$Al reactions. The energy of each particle type is obtained by adding the energy deposited in each element of the telescope.

Low-energy charged particles are stopped in the $\Delta E_1$ detector leading to a low-energy cutoff for particle identification of about 3 MeV for hydrogen isotopes and about 8 MeV for helium isotopes. The helium isotopes stopped in the $\Delta E_1$ detector are nevertheless analyzed, and a remarkably low cutoff, about 4 MeV, can be achieved for the experimental alpha-particle spectra. These alpha-particle events could obviously not be separated from $^3$He events in the same energy region, but the yield of $^3$He is about a factor of 30 smaller than the alpha-particle yield in the region of 8 MeV, where the particle identification works properly. The assumption that the relative yield of $^3$He is small is supported by the theoretical calculations in the evaporation peak re-
gion. In conclusion, the $^3$He yield is within the statistical uncertainties of the alpha-particle yield for alpha energies between 4 and 8 MeV. A consequence of this procedure is that the $^3$He spectra have a low-energy cutoff of about 8 MeV.

Knowing the energy calibration and the flight distances, the flight time for each charged particle from target to detector can be calculated and subtracted from the measured total TOF. The resulting neutron TOF is used for selection of charged-particle events induced by neutrons in the main peak of the incident neutron spectrum.

Background events, collected in target-out runs and analyzed in the same way as target-in events, are subtracted from the corresponding target-in runs, with SiO$_2$ and silicon targets, after normalization to the same neutron fluence.

Due to the finite target thickness, corrections for energy loss and particle loss are applied to both targets individually. Details of the correction methods are described in Refs. [17, 23]. The cross sections for oxygen are obtained after subtraction of the silicon data from the SiO$_2$ data with proper normalization with respect to the number of silicon nuclei in the two targets.

Even if a majority of the neutrons appears in the narrow full-energy peak at 95.6 MeV, a significant fraction (about 25 %) belongs to a tail extending towards lower energies, remaining after the TOF cut. The average neutron energy with these tail neutrons included is 92.4 MeV. This effect has been taken into account in the normalization of the data.

Other corrections of the data are performed in analogy with the similar experiment dealing with silicon and described in detail in the corresponding publication [17].

Absolute double-differential cross sections are obtained by normalizing the oxygen data to the number of recoil protons emerging from the CH$_2$ target. After selection of events in the main neutron peak and proper subtraction of the target-out and $^{12}$C(n,p) background contributions, the latter taken from a previous experiment, the cross section can be determined from the recoil proton peak, using $np$ scattering data [21]. All data have been normalized using the $np$ scattering peak in the 20$^\circ$ telescope.

## 4 Theoretical models

Data have been compared with nuclear theory predictions, computed with the two nuclear reaction codes GNASH [24, 25] and TALYS [26]. While GNASH has been widely used during the last years, TALYS is a new code that has just been released. The GNASH calculation is performed with parameters
given in a recent evaluation \cite{27} as described in Ref. \cite{17}. Since oxygen is at the boundary of the mass range the TALYS code is aimed for, it is described in some detail below.

Both GNASH and TALYS integrate direct, pre-equilibrium, and statistical nuclear reaction models into one calculation scheme and thereby give predictions for all the open reaction channels. Both codes use the Hauser-Feshbach model for sequential equilibrium decay and the exciton model for pre-equilibrium emission. The angular distributions are obtained using the Kalbach systematics \cite{28}.

The purpose of TALYS is to simulate nuclear reactions that involve neutrons, photons, protons, deuterons, tritons, $^3$He and alpha particles in the 1 keV – 200 MeV energy range. Predicted quantities include integrated, single- and double-differential cross sections, for both the continuum and discrete states, residue production and fission cross sections, gamma-ray production cross sections, etc. For the present work, single- and double-differential cross sections are of interest. To predict these, a calculation scheme is invoked which consists of a direct + pre-equilibrium reaction calculation followed by subsequent compound nucleus decay of all possible residual nuclides calculated by means of the Hauser-Feshbach model.

For the optical model potentials (OMP) of both neutrons and protons on $^{16}$O up to 200 MeV, the global OMP of Ref. \cite{29} was used. These potentials provide the necessary transmission coefficients for the statistical model calculations. Although the global neutron OMP has been validated for $A > 24$, at the high incident energy considered in this work, an adequate description of the basic scattering observables is expected. For complex particles, the optical potentials were directly derived from the nucleon potentials using the folding approach of Watanabe \cite{30}. Finally, since applying the charged-particle OMP’s for nuclides as light as $^{16}$O may be physically dubious, we renormalize the obtained OMP transmission coefficients with the empirical non-elastic cross sections of Ref. \cite{31}.

The high-energy end of the ejectile spectra are described by pre-equilibrium emission, which takes place after the first stage of the reaction but long before statistical equilibrium of the compound nucleus is attained. It is imagined that the incident particle step-by-step creates more complex states in the compound system and gradually loses its memory of the initial energy and direction. The default pre-equilibrium model of TALYS is the two-component exciton model \cite{32,33} which has been tested against basically all available experimental nucleon spectra for $A > 24$. We recall the basic
formula of Ref. \[32\] for the exciton model cross section,

\[
d\sigma_{k}^{EM} / dE_k = \sigma^{CF} \sum_{p_\pi=p_\pi^0} \sum_{p_\nu=p_\nu^0} w_k(p_\pi, h_\pi, p_\nu, h_\nu, E_k) S_{pre}(p_\pi, h_\pi, p_\nu, h_\nu),
\] (1)

where \(p_\pi(p_\nu)\) is the proton (neutron) particle number and \(h_\pi(h_\nu)\) the proton (neutron) hole number, \(\sigma^{CF}\) is the compound formation cross section, and \(S_{pre}\) is the time-integrated strength which determines how long the system remains in a certain exciton configuration. The initial proton and neutron particle numbers are denoted \(p_\pi^0 = Z_p\) and \(p_\nu^0 = N_p\) with \(Z_p(N_p)\) being the proton (neutron) number of the projectile. In general, \(h_\pi = p_\pi - p_\pi^0\) and \(h_\nu = p_\nu - p_\nu^0\), so that the initial hole numbers are zero, i.e. \(h_\pi^0 = h_\nu^0 = 0\), for primary pre-equilibrium emission. The pre-equilibrium part is calculated by Eq. (1) using \(p_\pi^0 = p_\nu^0 = 6\), whereas the remainder of the reaction flux is distributed through the Hauser-Feshbach model. In addition, the never-come-back approximation is adopted.

The emission rate \(w_k\) for ejectile \(k\) with spin \(s_k\) is given by

\[
w_k(p_\pi, h_\pi, p_\nu, h_\nu, E_k) = \frac{2s_k + 1}{\pi^2 h^3} \mu_k E_k \sigma_{k,\text{inv}}(E_k) \frac{\omega(p_\pi - Z_k, h_\pi, p_\nu - N_k, h_\nu, E_x)}{\omega(p_\pi, h_\pi, p_\nu, h_\nu, E_{\text{tot}})},
\] (2)

where \(\sigma_{k,\text{inv}}(E_k)\) is the inverse reaction cross section as calculated from the optical model, and \(\omega\) is the two-component particle-hole state density. The full reaction dynamics that leads to Eq. (1) is described in Refs. \[32, 33\]. We here restrict ourselves to the formulae given above since they contain the model- and parameter-dependent quantities. The expression for \(S_{pre}\) contains the adjustable transition matrix element \(M^2\) for each possible transition between neutron-proton exciton configurations. A proton-neutron ratio of 1.6 for the squared internal transition matrix elements was adopted to give the best overall agreement with experiment, i.e., \(M_{\pi\nu}^2 = M_{\nu\pi}^2 = 1.6 M_{\pi\pi}^2 = 1.6M_{\nu\nu}^2 = 1.6M^2\). For \(^{16}\text{O}\), we use the following expression for the matrix element \[32\],

\[
M^2 = \frac{0.6}{A^3} \left[ 6.8 + \frac{4.2 \times 10^5}{(E_{\text{inv}}^\text{ext} / n + 10.7)^3} \right],
\] (3)

where \(n\) is the exciton number. Partial level density parameters \(g_\pi = Z / 17\) and \(g_\nu = N / 17\) were used in the equidistant spacing model for the partial level densities. Finally, an effective surface interaction well depth \(V = 12\) MeV \[32\] was used.

At incident energies above several tens of MeV, the residual nuclides formed after binary emission may have so large excitation energy that the presence of additional fast particles inside the nucleus becomes possible. The
latter can be imagined as strongly excited particle-hole pairs resulting from
the first binary interaction with the projectile. The residual system is then
clearly non-equilibrated and the excited particle that is high in the contin-
umum may, in addition to the first emitted particle, also be emitted on a short
time scale. This so-called multiple pre-equilibrium emission forms an alter-
native theoretical picture of the intra-nuclear cascade process, whereby the
exact location and momentum of the particles are not followed, but instead
the total energy of the system and the number of particle-hole excitations
(exciton number). In actual calculations, the particle-hole configuration of
the residual nucleus after emission of the ejectile, is re-entered as initial con-
dition in Eq. 1. When looping over all possible residual configurations, the
multiple pre-equilibrium contribution is obtained. In TALYS, multiple pre-
equilibrium emission is followed up to arbitrary order, though for 96 MeV
only secondary pre-equilibrium emission is significant.

It is well-known that semi-classical models, such as the exciton model,
have always had some problems to describe angular distributions (essentially
because it is based on a compound-like concept instead of a direct one).
Therefore, as mentioned previously, the double-differential cross sections are
obtained from the calculated energy spectra using the Kalbach systemat-
ics 28.

To account for the evaporation peaks in the charged-particle spectra,
multiple compound emission was treated with the Hauser-Feshbach model.
In this scheme, all reaction chains are followed until all emission channels are
closed. The Ignatyuk model 34 has been adopted for the total level density
to account for the damping of shell effects at high excitation energies.

For pre-equilibrium reactions involving deuterons, tritons, $^3$He and alpha
particles, a contribution from the exciton model is automatically calculated
with the formalism described above. It is, however, well known that for
nuclear reactions involving projectiles and ejectiles with different particle
numbers, mechanisms like stripping, pick-up and knock-out play an impor-
tant role and these direct-like reactions are not covered by the exciton model.
Therefore, Kalbach has developed a phenomenological contribution for these
mechanisms 35, which is included in TALYS. It has recently been shown (see
Table I of Ref. 36) that this method gives a considerable improvement over
the older methods. The latter seemed to consistently underpredict neutron-
induced reaction cross sections involving pick-up of one or a few nucleons.
5 Results and discussion

5.1 Experimental results

Double-differential cross sections of $^{16}$O($n$,xlc$p$) reactions, where lcp stands for light charged particle, at laboratory angles of 20°, 40°, 100° and 140° for protons, deuterons, tritons, $^3$He and alpha particles are shown in Figs. 1–5 respectively, all angles plotted with the same cross section scale for each emitted particle to facilitate comparison of magnitudes. The choice of energy bin width is a compromise between the energy resolution in the experiment, the width of the inverse response functions and acceptable statistics in each energy bin. The error bars in Figs. 1–5 represent statistical uncertainties only.

The overall relative statistical uncertainties of individual points in the double-differential energy spectra at 20° are typically 8 % for protons, 13 % for deuterons, 20 % for tritons, 15 % for $^3$He and 12 % for alpha particles. As the angular distributions are forward-peaked, these values increase with angle. The systematic uncertainty contributions are due to thick target correction (1 – 20 %), collimator solid angle (1 – 5 %), beam monitoring (2 – 3 %), the number of oxygen nuclei (0.1 %), CsI(Tl) intrinsic efficiency (1 %), particle identification (1 %) and dead time (< 0.1 %). The uncertainty in the absolute cross section is about 5 %, which is due to uncertainties in the $np$ scattering angle, the contribution from the low-energy continuum of the $^7$Li($p$,n) spectrum to the $np$ scattering proton peak (3 %), the reference $np$ cross sections (2 %) [21], statistics in the $np$ scattering proton peak (2 %), the carbon contribution (0.1 %) and the number of hydrogen nuclei (0.1 %).

From Figs. 1–5 it is obvious that the charged-particle emission at forward angles from 96 MeV neutron irradiation of oxygen is dominated by proton, deuteron and alpha particle channels. The yield of deuterons is about a factor of 3 lower than for protons and the spectra of the two other particle types studied in this work (tritons and $^3$He) are more than an order of magnitude weaker. All the spectra have more or less pronounced peaks at low energies (below 10 – 15 MeV), the angular distributions of which are not too far from isotropy except for alpha particles, where the yield at backward angles is about four times weaker than at 20°. The low-energy peak is not fully observed in the $^3$He spectra due to the 8 MeV low-energy cutoff discussed in Sec. 3.

All the particle spectra at forward angles show relatively large yields at medium-to-high energies. The emission of high-energy particles is strongly forward-peaked and hardly visible in the backward hemisphere. It is a sign of particle emission before statistical equilibrium has been reached in the
reaction process. In addition to this broad distribution of emitted particles, the deuteron spectra at forward angles show narrow peaks corresponding to transitions to the ground state and low-lying states in the final nucleus, $^{15}$N. These transitions are most likely due to pick-up of weakly bound protons in the target nucleus, $^{16}$O. A similar but less pronounced effect is observed in the proton spectra at forward angles. The structure observed in this case is due to transitions to Gamow-Teller states and other low-lying states with considerable single-particle strength [1].

5.2 Comparison with theoretical model calculations

In Figs. 1–5 the experimental results are presented together with theoretical model calculations. The GNASH calculations of Ref. [27] have been done for protons, deuterons and alpha particles, whereas the TALYS calculations discussed in Sec. 4 have been performed for all five particle types. The TALYS calculations include a transformation of the calculated cross sections to the lab system. Also in the GNASH code a similar transformation from the c.m. to the lab system is performed using the kinematics of one-particle emission. Differences between data given in the lab and c.m. systems are particularly significant in this case, because oxygen is such a light nucleus.

Fig. 1 shows the comparison between the double-differential $(n,px)$ experimental spectra and the calculations based on the TALYS and GNASH models. For protons above 25 MeV, both calculations give a reasonably good description of the spectra, although the calculated $20^\circ$ cross sections, in particular the TALYS ones, fall below the experimental data. The low-energy statistical peak below 15 MeV in the spectra is considerably overpredicted by the two codes. The overestimate is particularly strong at backward angles for TALYS and at forward angles for GNASH.

The situation is quite different for the deuteron spectra (Fig. 2). None of the calculations do account very well for the data, although the GNASH code gives a reasonable description of the angular dependence of the cross section. For the TALYS code deviations between data and calculations of a factor of two or more are present. At forward angles the high-energy part is strongly overestimated, in particular by the TALYS code, indicating problems in the hole-strength treatment. It is obvious, however, that efforts have been spent in these calculations to include individual hole-state strengths. Such strengths are not included in the GNASH calculations, but in spite of this the average behavior of the cross section at high energies is in fair agreement with the data. Like for the proton spectra, the statistical peak is overpredicted by the TALYS calculations essentially at all angles, whereas the GNASH calculations seem to do a slightly better job in this case.
For tritons (Fig. 3), the TALYS calculation gives a fairly good description of the experimental data, except that it fails to account for an intensity bump around 15 MeV observed at forward angles.

The general trends of the forward-angle $^3$He data (Fig. 4) are reasonably well described in the TALYS calculations although the cross sections are underestimated by a large factor. At backward angles the yield is very small and it is difficult to make quantitative comparisons.

The overall shapes of the alpha particle spectra (Fig. 5) are reasonably well described by the two models. The GNASH calculations, however, overpredict the cross sections at forward angles and underpredict them at large angles, whereas the TALYS calculations do the opposite, i.e., underpredict at small angles and overpredict at large angles.

The ability of the models to account for the low-energy peak caused by evaporation processes (and for $\alpha$ particles also $\alpha$ breakup of $^{12}$C) is not impressive. In general, the models tend to overpredict the cross sections. It should, however, be kept in mind that the peak maximum is close to (for $^3$He below) the low-energy cutoff, which complicates the comparison. Another complication in this context is that the GNASH cross sections although given in the lab system, are calculated using the kinematics of one-particle emission [24, 25] for the c.m.-to-lab transformation, which obviously is an approximation.

### 5.3 Integrated spectra

For each energy bin of the light-ion spectra, the experimental angular distribution is fitted by a simple two-parameter functional form, $a \exp(b \cos \theta)$ [28]. This allows extrapolation of double-differential cross sections to very forward and very backward angles. In this way coverage of the full angular range is obtained. By integration of the angular distribution, energy-differential cross sections ($d\sigma/dE$) are obtained for each ejectile. These are shown in Fig. 6 together with theoretical calculations. For all ejectiles both calculations give a fair description of the energy dependence. Both calculations are in good agreement with the proton experimental data over the whole energy range. Concerning the deuteron spectra, the GNASH calculations are in good agreement with the data, whereas the TALYS code gives cross sections a factor of two or more larger than the experimental ones at energies above 30 MeV. In the case of alpha particles, the GNASH calculation tends to overpredict the high-energy part of the spectrum, and the TALYS calculations fall below the data from an alpha particle energy of 25 MeV. The energy dependence of the triton and $^3$He spectra are well described by the TALYS code, but in both cases the calculation falls below the data from about 25 MeV.
The production cross sections are deduced by integration of the energy-differential spectra (see Table 1). To be compared with the calculated cross sections, the experimental values in Table 1 have to be corrected for the undetected particles below the low-energy cutoff. This is particularly important for $^3$He because of the high cutoff energy. The corrections obtained with TALYS seem to be too small in some cases, in particular for the (n,xα) production cross section. This is illustrated in Fig. 6 bottom panel, where the TALYS curve falls well below the experimental $dσ/dE$ data in the 4–7 MeV region.

The proton, deuteron, triton, and alpha particle production cross sections are compared with previous data at lower energies [5] in Fig. 7. There seems to be general agreement between the trends of the previous data and the present data points. The curves in this figure are based on a GNASH calculation [27].

6 Conclusions and outlook

In the present paper, we report an experimental data set on light-ion production in oxygen induced by 96 MeV neutrons. Experimental double-differential cross sections ($d^2σ/dΩdE$) are measured at eight angles between 20° and 160°. Energy-differential ($dσ/dE$) and production cross sections are obtained for the five types of outgoing particles. Theoretical calculations based on nuclear reaction codes including direct, pre-equilibrium and statistical models give generally a good account of the magnitude of the experimental cross sections. For proton emission, the shape of the spectra for the double-differential and energy-differential cross sections are well described. The calculated and the experimental alpha-particle spectra are also in fair agreement with the exception of the high energy part, where one model predicts higher yield and another model lower yield than experimentally observed. For the other complex ejectiles (deuteron, triton and $^3$He) there are important differences between theory and experiment in what concerns the shape of the spectra at various angles, whereas the magnitude of the angle-integrated cross sections is reasonably well accounted for.

For the further development of the field, data at even higher energies are requested. The results suggest that the MEDLEY facility, which was used in the present work, should be upgraded to work also at 180 MeV, i.e., the maximum energy of the TSL neutron beam facility. At present, a new neutron beam facility is under commissioning at TSL [37], covering the same energy range, but with a projected intensity increase of a factor five. This will facilitate measurements at energies higher than in the present work.
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References


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Figure captions

1. Experimental double-differential cross sections (filled circles) of the O(n,px) reaction at 96 MeV at four laboratory angles. The curves indicate theoretical calculations based on GNASH [27] (dotted) and TALYS (solid).

2. Experimental double-differential cross sections (filled circles) of the O(n,dx) reaction at 96 MeV at four laboratory angles. The curves indicate theoretical calculations based on GNASH [27] (dotted) and TALYS (solid).

3. Experimental double-differential cross sections (filled circles) of the O(n,tx) reaction at 96 MeV at four laboratory angles. The curve indicates theoretical calculations based on TALYS.

4. Experimental double-differential cross sections (filled circles) of the O(n,3He) reaction at 96 MeV at four laboratory angles. The curve indicates theoretical calculations based on TALYS.

5. Experimental double-differential cross sections (filled circles) of the O(n,αx) reaction at 96 MeV at four laboratory angles. The curves indicate theoretical calculations based on GNASH [27] (dotted) and TALYS (solid).

6. Experimental energy-differential cross sections (filled circles) for neutron-induced p, d, t, 3He and α production at 96 MeV. The curves indicate theoretical calculations based on GNASH [27] (dotted) and TALYS (solid).

7. Neutron-induced a) proton, b) deuteron, c) triton, and d) alpha particle production cross section as a function of neutron energy. The full circles are from the present work, whereas the open circles are from previous work [5]. The curves are based on a GNASH calculation [27]. The data as well as the calculations correspond to cutoff energies of 6 MeV for protons and deuterons and 12 MeV for tritons and alpha particles. Note that the cutoff energies are different from those in Table 1.
Table 1: Experimental production cross sections for protons, deuterons, tritons, $^3$He and alpha particles from the present work. Theoretical values resulting from GNASH and TALYS calculations are given as well. The experimental data in the second column have been obtained with cutoff energies of 2.5, 3.0, 3.5, 8.0 and 4.0 MeV for p, d, t, $^3$He and alpha particles, respectively. The third column shows data corrected for these cutoffs, using the TALYS calculations of the present work.

<table>
<thead>
<tr>
<th>$\sigma_{\text{prod}}$</th>
<th>Experiment (mb)</th>
<th>Experiment (cutoff corr.)</th>
<th>GNASH (Ref. [27])</th>
<th>TALYS (present work)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(n,px)</td>
<td>226±12</td>
<td>233</td>
<td>259.9</td>
<td>221.7</td>
</tr>
<tr>
<td>(n,dx)</td>
<td>71±4</td>
<td>72</td>
<td>73.4</td>
<td>131.3</td>
</tr>
<tr>
<td>(n,tx)</td>
<td>20±1</td>
<td>20.2</td>
<td>–</td>
<td>10.6</td>
</tr>
<tr>
<td>(n,$^3$He)</td>
<td>6.6±0.6</td>
<td>8.4</td>
<td>–</td>
<td>8.2</td>
</tr>
<tr>
<td>(n,αx)</td>
<td>114±7</td>
<td>114</td>
<td>224.7</td>
<td>88.4</td>
</tr>
</tbody>
</table>
Proton Energy [MeV]

$\frac{d^2\sigma}{d\Omega dE}$ [mb/(sr × MeV)]
$d^2\sigma/d\Omega dE \ [\text{mb/(sr}\times\text{MeV})]$
\[ \frac{d^2 \sigma}{d \Omega dE} \] [mb/(sr × MeV)]

\[ q = 20^\circ \quad q = 40^\circ \quad q = 100^\circ \quad q = 140^\circ \]

Triton Energy [MeV]
\[ d^2 \sigma / d\Omega dE \left[ \text{mb/(sr} \times \text{MeV)} \right] \]

\[ q = 20^\circ \]
\[ q = 40^\circ \]
\[ q = 100^\circ \]
\[ q = 140^\circ \]
\[ \frac{d^2 \sigma}{d\Omega dE} \text{ [mb/(sr $\times$ MeV)]} \]

\[ q = 20 \]
\[ q = 40 \]
\[ q = 100 \]
\[ q = 140 \]
$d\sigma/dE$ [mb/MeV] vs. Energy [MeV]

- Proton
- Deuteron
- Triton
- $^3$He
- $\alpha$
Neutron Energy [MeV]

\[ \sigma_{\text{prod}}(n, \text{lcpx}) \] [mb]

Proton (a)

Deuteron (b)

Triton (c)

\( \alpha \) (d)