Experimental study of the $^{18}\text{O}(d, p)^{19}\text{O}$ reaction and the ANC Method.

V. Burjan$^1$, Z. Hons$^1$, V. Kroha$^1$, J. Mrázek$^1$, Š. Piskoř$^1$, A. M. Mukhamedzhanov$^2$, L. Trache$^2$, R. E. Tribble$^2$, M. La Cognata$^3$, M. Gulino$^3,4$, L. Lamia$^3$, G. R. Pizzone$^3$, S. M. R. Puglia$^3$, G. G. Rapisarda$^3$, S. Romano$^3$, M. L. Sergi$^3$, R. Spartà$^3$, C. Spitaleri$^3$, A. Tumino$^3,4$

1 Nuclear Physics Institute of Czech Academy of Sciences, 250 68 Řež, Czech Republic
2 Cyclotron Institute, Texas A&M University, College Station, TX 77843
3 Università di Catania and INFN Laboratori Nazionali del Sud, Catania, Italy
4 Università degli Studi di Enna "KORE", Enna, Italy

E-mail: burjan@ujf.cas.cz

Abstract. The neutron capture rate $^{18}\text{O}(n, \gamma)^{19}\text{O}$ is important for analysis of nucleosynthesis in inhomogeneous Big Bang models and also for models of helium burning in massive red giant stars and AGB stars. Angular distributions of the $^{18}\text{O}(d, p)^{19}\text{O}$ reaction were measured at a deuteron energy of 16.3 MeV in NPI in Řež, Czech Republic, with the aim to determine Asymptotic Normalization Coefficients which can then be used for indirect determination of the direct contribution to the $^{18}\text{O}(n, \gamma)^{19}\text{O}$ process. In the experiment, the gas target with $^{18}\text{O}$ isotope of high purity 99.9% was used thus eliminating any contaminating reactions. Reaction products were measured by the set of 8 $\Delta E-E$ telescopes consisting of thin and thick silicon surface-barrier detectors. Angular distributions of proton transfers corresponding to 6 levels of $^{19}\text{O}$ up to the 4.1093 MeV excitation energy were determined. The analysis of angular distributions in the angular range from 6 to 64 degree including also the angular distribution of elastically scattered deuterons was carried out by means of ECIS and DWUCK codes. From the determined ANCs the direct contribution to the radiative capture $^{18}\text{O}(n, \gamma)^{19}\text{O}$ was deduced.

1. Introduction

The cross sections of radiative capture processes in the region of astrophysical energies are important for the knowledge of both stellar and Big Bang nucleosynthesis and also for understanding of other characteristics of astrophysical processes. Usually it is very difficult to measure directly the cross sections of the capture reactions with sufficient precision because they proceed at very low energies or with participation of short living isotopes. As one of the indirect methods of the determination of the cross sections of proton or alpha direct capture reactions the method of the so called Asymptotic Normalization Coefficients (ANC) was proposed [1]. This method uses peripheral transfer reactions for the determination of capture cross sections and has been later used in a number of cases (see e. g. [2, 3, 4, 5]). The ANC method can be also applied to direct radiative neutron capture reactions [6] though the neutron capture process could not be entirely peripheral and the contribution from the interior of a target nucleus can play a certain role. Here, we used the ANC method in the case of the $^{18}\text{O}(n, \gamma)^{19}\text{O}$ capture. In inhomogeneous Big Bang mod-
els in neutron rich environment, where nuclei with \( A > 12 \) can be formed in reaction sequences as \( ^7\text{Li}(n, \gamma)^{18}\text{Li}(\alpha, n)^{11}\text{B}(n, \gamma)^{12}\text{B}(\beta^-)^{12}\text{C}(n, \gamma)^{13}\text{C}(\alpha, \gamma)^{14}\text{C}(n, \gamma)^{18}\text{O}(n, \gamma)^{19}\text{O}(\beta^-)^{19}\text{F} \) [7], the reaction \( ^{18}\text{O}(n, \gamma)^{19}\text{O} \) enables the creation of elements with higher mass numbers.

The part of the same sequence can be replaced by alternative branch with reactions \( ^{14}\text{C}(n, \gamma)^{15}\text{C}(\beta^-)^{15}\text{N}(n, \gamma)^{16}\text{N}(\beta^-)^{16}\text{O}(n, \gamma)^{17}\text{O}(n, \gamma)^{18}\text{O}(n, \gamma)^{19}\text{O} \) [8]. The neutron radiative capture \( ^{18}\text{O}(n, \gamma)^{19}\text{O} \) has also significance for estimation of reaction rates of stellar helium burning in massive red stars and AGB stars. The radiative capture \( ^{18}\text{O}(n, \gamma)^{19}\text{O} \) was experimentally studied in the work of Vaughn et al. [9]. They measured the total cross section from 0.14 to 2.47 MeV by a transmission experiment using water enriched to 97% in \(^{18}\text{O} \) as the target. Rather extensive study was performed by Meissner et al. in the work [10], in which with a fast cyclic neutron activation technique the neutron capture cross section was measured at 5 laboratory energies: 25, 129, 152, 250 and 370 keV for transitions to the first three states of oxygen \(^{19}\text{O} \).

The target consisted of the mixture of Kr and 97% enriched \(^{18}\text{O} \). Windows of the gas chamber were covered by a 3 \( \mu \text{m} \) thick Ti foil at the back side and a 2 \( \mu \text{m} \) thick Te foil at the input in the gas chamber. The working pressure was kept at level of 150 mbar and was monitored by a gas control system, which registered the pressure and temperature of \(^{18}\text{O} \) gas inside the chamber. Reaction products were registered by eight \( \Delta\text{E-E} \) telescopes consisting of 250-\( \mu \text{m} \) and 5-mm thick Si(Li) surface barrier detectors. All telescopes were equipped with a pair of collimating slits of dimensions 2 x 3 mm\(^2 \) and 1 x 4 mm\(^2 \). The near 1 x 4 mm\(^2 \) and far 2 x 3 mm\(^2 \) slits were located 107 mm and 187 mm, respectively, from the center of the gas target chamber. The effective target thickness, different at different reaction angles, was determined for the given geometry by calculation. Three telescopes were fixed at the angles of 17\( ^\circ \), 27\( ^\circ \) and 37\( ^\circ \), respectively, as monitors and the remaining five were movable as a whole at different laboratory angles in the range between 6.5\( ^\circ \) and 64\( ^\circ \). All measured data including the charge from the Faraday cup were collected in an on-line computer for later processing. For the acquisition of data from preamplifiers and amplifiers ORTEC the VME system was used.

The estimation of uncertainties of measured data include several sources. Uncertainties due to the effective gas target thickness and detector solid angle were about 8\%. The charge of the beam was measured with the uncertainty about 3\%. These uncertainties together with statistical uncertainties, which were mostly better than 5\% for more intensive transitions at maxima of angular distributions, thus give the total uncertainty for forward angles less than 10\% in most of the cases.

### 2. Experimental Procedure

The experiment was performed on the isochronous cyclotron U-120M of the Nuclear Physics Institute of the Czech Academy of Sciences. A momentum analyzed 16.3 MeV deuteron beam was incident on a oxygen gas target. The target gas chamber contained the high purity \(^{18}\text{O} \) isotope (99.9\%). Windows of the gas chamber were covered by a 3 \( \mu \text{m} \) thick havar foil at the back side and a 2 \( \mu \text{m} \) thick Ti foil at the input in the gas chamber. The working pressure was kept at level of 150 mbar and was monitored by a gas control system, which registered the pressure and temperature of \(^{18}\text{O} \) gas inside the chamber. Reaction products were registered by eight \( \Delta\text{E-E} \) telescopes consisting of 250-\( \mu \text{m} \) and 5-mm thick Si(Li) surface barrier detectors. All telescopes were equipped with a pair of collimating slits of dimensions 2 x 3 mm\(^2 \) and 1 x 4 mm\(^2 \). The near 1 x 4 mm\(^2 \) and far 2 x 3 mm\(^2 \) slits were located 107 mm and 187 mm, respectively, from the center of the gas target chamber. The effective target thickness, different at different reaction angles, was determined for the given geometry by calculation. Three telescopes were fixed at the angles of 17\( ^\circ \), 27\( ^\circ \) and 37\( ^\circ \), respectively, as monitors and the remaining five were movable as a whole at different laboratory angles in the range between 6.5\( ^\circ \) and 64\( ^\circ \). All measured data including the charge from the Faraday cup were collected in an on-line computer for later processing. For the acquisition of data from preamplifiers and amplifiers ORTEC the VME system was used.

The estimation of uncertainties of measured data include several sources. Uncertainties due to the effective gas target thickness and detector solid angle were about 8\%. The charge of the beam was measured with the uncertainty about 3\%. These uncertainties together with statistical uncertainties, which were mostly better than 5\% for more intensive transitions at maxima of angular distributions, thus give the total uncertainty for forward angles less than 10\% in most of the cases.
3. Experimental results and analysis
Nine proton lines were identified from the $^{18}\text{O}(d,p)^{19}\text{O}$ reaction ($Q = 1.7311$ MeV) below the particle emission threshold of $^{19}\text{O}$ with a line corresponding to the neutron transfer populating the resonance state $4.1093$ MeV in $^{19}\text{O}$. A typical proton spectrum is shown in Fig. 1. We were interested in transitions to the ground state (1d5/2), to the $1.471$ MeV (2s1/2), $3.1535$ MeV (1d5/2), $3.2316$ (2p1/2), $3.9449$ MeV (2p3/2) states and corresponding neutron captures to them except the unbound state $4.1093$ MeV (1d3/2) which was evaluated as a check of experimental data.

![Spectrum of protons from the reaction $^{18}\text{O}(d,p)^{19}\text{O}$ at $\theta_{\text{lab}} = 16^\circ$.](image)

Figure 1. Spectrum of protons from the reaction $^{18}\text{O}(d,p)^{19}\text{O}$ at $\theta_{\text{lab}} = 16^\circ$.

To obtain ANCs of mentioned transitions, it is necessary to perform DWBA analysis of experimental angular distributions of the transfer reaction $^{18}\text{O}(d,p)^{19}\text{O}$. For the analysis of the angular distributions the phenomenological optical potential in general form [20] has been used

$$U(r) = V_c(r) - Vf(x_o) + \left( \frac{\hbar}{m_w c} \right)^2 V_{so}(\sigma, l) \frac{1}{r} \frac{d}{dr} f(x_{so}) - i \left[ Wf(x_w) - 4W_d \frac{d}{dr} f(x_d) \right],$$

where $f(x_i) = (1 + e^{x_i})^{-1}$ and $x_i = (r - r_i A^{1/3})/a_i$ represents the usual Woods-Saxon form factor. $V$, $W$, $W_d$, and $V_{so}$ are the real, imaginary volume, imaginary surface and spin-orbital potential depths respectively with appropriate radii $r_i$ and diffusenesses $a_i$. $V_c(r)$ is the Coulomb potential of a uniformly charged spherical nucleus of a radius $R_c = r_c A^{1/3}$.

Parameters of the optical model for the input channel were obtained from the fit of the measured angular distribution of elastically scattered deuterons. For this purpose the search code ECIS79 of Raynal [21] was used. At first we did some preliminary calculations with deuteron parameters of Strobel [17], Sen et al. [18] and Stephenson et al. [19]. They showed significantly worse agreement with experimental data than global parameters of Perey and Perey [20]. In Fig 2 the experimental elastic scattering $^{18}\text{O}(d,d)^{18}\text{O}$ is presented together with calculated distributions with global parameters of the optical model of Perey and Perey used as a seed for our fitted parameters (solid line) and also with parameters of Sen et al. [18]
Table 1. Fit of optical model parameters in input channel: d + \textsuperscript{18}O

| Pot          | V   | r   | a   | W   | r_w  | a_w  | W_d  | r_d  | a_d  | r_c  |
|--------------|-----|-----|-----|-----|------|------|------|------|------|------|
| seed Perey  | 83.5 | 1.15| 0.81| -   | -    | -    | 18.3 | 1.3  | 0.68 | 1.3  |
| our fit     | 83.4 | 1.15| 0.76| -   | -    | -    | 11.1 | 1.48 | 0.74 | 1.3  |

seed Perey: global parameter set from [20]
fit of our elastic scattering data

representing also the similar shape of calculations with data of Strobel [17] and Stephenson et al. [19]. Obtained parameters of the optical model for the deuteron channel are given in table 1. The seed parameters of Perey and Perey themselves described the experimental angular distribution of the deuteron elastic scattering very well and after the fitting the agreement of the new angular distribution with experimental data was still better. Surprisingly, the parameters of Strobel derived also from experimental data almost at the same energy as ours showed worse agreement especially at the second maxima around angles 50 degrees. Similarly, other data were not describing the elastic scattering very well and were not used as seed parameters.

Figure 2. The angular distribution of elastically scattered deuterons \textsuperscript{18}O at energy 16.3 MeV (black squares) compared with angular distributions calculated with global parameters of Perey and Perey [20] (dashed line), with parameters of Sen et al. [18] (dash-dot line) and with parameters obtained from the fit (solid line) of experimental data.

As optical model parameters for protons on \textsuperscript{19}O we have used 3 sets from the following
papers. They were global parameters of Perey and Perey [20], parameters of Duke [23] derived from elastic scattering of protons on the $^{16}$O nucleus and parameters of Watson et al. [24] used in the $^{17}$O(t, p)$^{19}$O reaction (global formula) (see table 2). The energy and mass dependences $V(E, A)$, $W(E, A)$, $r(E)$ and $a(E, A)$ given in these works were taken into account.

Table 2. Parameters of optical model parameters in output channel: p + $^{19}$O

| Pot          | $V$   | $r$   | $a$  | $W_d$ | $r_d$ | $a_d$ | $W_{so}$ | $r_{so}$ | $a_{so}$ | Refer. |
|--------------|-------|-------|------|-------|-------|-------|---------|---------|---------|-------|
| global       | $V(E, A)$ | 1.16  | 0.75 | $W(E, A)$ | 1.37  | $a(E, A)$ | 6.04 | 1.064 | 0.78     | [20]  |
| Duke         | 49.0  | 1.25  | 0.61 | 4.5   | 1.25  | 1.20  | 6.8    | 1.25   | 0.61    | [23]  |
| Watson       | $V(E, A)$ | $r(E)$ | 0.57 | $W(E, A)$ | $r(E)$ | 0.5   | 5.5    | $r(E)$ | 0.57    | [24]  |

$r_c = 1.3$ fm in all cases

We calculated the $^{18}$O(d, p)$^{19}$O angular distributions of the displayed experimental data (see Figs. 3 to 8) within the framework of DWBA theory using the DWUCK5 code of Kunz [22]. We used several combinations of sets of optical model parameters for deuteron and proton channels. The d-global and p-global sets in Figs 3 to 8 are global parameters of Perey and Perey [20] from table 1 and 2, respectively, and proton parameter sets of p-Duke and p-Watson are taken from table 2. The transitions to the ground ($5/2^+$) and 1.471 MeV($1/2^+$) states are described well by calculated curves especially at main maxima. The agreement for 3.15($5/2^+$) and 3.23 MeV($1/2^-$) [12] states is worse than for the ground and 1.471 MeV states. The state 3.23 MeV could be populated by 1p1/2 transfer being the part of the possibly fragmented inner shell 1p1/2 in $^{19}$O but here we considered it as the 2p1/2 transfer. A similar situation occurs for the 3.944 MeV($3/2^-$) state. But also here the transition 2p3/2 was adopted because the shell 1p3/2 should be fully occupied. The state 4.109 MeV($3/2^+$) is unbound and is analyzed only as a check of consistency of experimental data. Its angular distribution is in a relatively good agreement with the DWBA calculations (with simulated binding energy of 0.1 MeV).

In the Distorted Wave Born Approximation, the matrix element of the transitions of the direct cross section of the two-body reaction, if we assume the single step direct mechanism, contains two overlap integrals. In the expression for the A(d, p)B reaction one overlap integral corresponds to the decay of d → p + n (it is replaced by $C_{pn}^2 = 0.77$ fm$^{-1}$ in terms of the ANC method [25]) and the another overlap integral is that one which we want to determine from the experimental data. This overlap integral containing the wave function of the bound state of the transferred neutron can be given for peripheral reactions asymptotically by Hankel function (transferred neutral particle). When using the ANC method for the direct transfer reaction A(d, p)B the nuclear cross section can be expressed as [26]

$$\frac{d\sigma_{DW}}{d\Omega}(\theta) = \sum \frac{C_{Ai}^2 C_{Ai}^{(2)} C_{Bi}^{(2)} b_{Ai}^{(2)} b_{Bi}^{(2)} \sigma_{DW}^{(2)} b_{Ai}^{(2)} b_{Bi}^{(2)}}{b_{Ai}^{(2)} b_{Bi}^{(2)}}$$

In this equation, the $(C_{pn})^2$ and $(C_{An})^2$ stand for ANCs of the projectile and final nucleus, $j_i$, $l_i$ are the total and orbital angular momenta, respectively, of the transferred neutron in the nucleus B and in the deuteron, $b$'s are the single-particle ANCs defining the amplitude of the tail of the radial single-particle bound-state wave function. Thus it is possible to express the cross section of the direct neutron capture by the formula where the normalization factor $(C_{An})^2/(b_{An})^2$ is known from the transfer (d, p) reaction and the shape of the cross section for the radiative
Figure 3. The angular distribution from the $^{18}\text{O}(d,p)^{19}\text{O}$ reaction for the transition to the ground state.

Figure 4. The angular distribution for the transition to the 1.471 MeV state (2s1/2). Sets of optical model parameters are the same as in Fig. 3.

Figure 5. The angular distribution for the transition to the 3.153 MeV state (1d5/2).

Figure 6. The angular distribution for the transition to the 3.231 MeV state (2p1/2). Sets of optical model parameters are the same as in Fig. 5.

capture can be calculated e. g. by the potential model [27]. If the studied reaction is peripheral, then the ratio

$$R(b_{AnlBJB}, b_{pnldjd}) = \frac{\sigma_{DW(\text{max})}^{\text{B}}}{b_{AnlBJB}^{B}b_{pnldjd}^{d}}$$

where $\sigma_{DW(\text{max})}^{\text{B}}$ means the DWBA differential cross section calculated at the main maximum of the angular distribution, is independent of the single particle ANCs $b_{An}$ and $b_{pn}$ [26]. Hence this ratio is an important check of the peripherality of the transfer process. In fig. 9 it is demonstrated that the $R(b)$ dependence on the shape of the potential well of the captured neutron is the strongest for the transition to the ground state, for other transitions is very weak. For the application of the ANC method also the condition about the weak dependence of the
cross section on the cut-off radius of the reaction region should be fulfilled. We analyzed the
dependence of the cross section of (d, p) reaction on the cut-off radius for 4 values: without the
cut-off and with 1 fm-, 2 fm- and 3 fm- cut-offs, respectively. The change of the differential
cross-section at maximum of the angular distribution for the transfer to the ground state for the
case without cut-off to the case with the 3 fm cut-off was 13%, for other transitions the change
was negligible (2%).

![Figure 7](image1.png)
**Figure 7.** The angular distribution for the transition to the 3.944 MeV state(2p3/2).

![Figure 8](image2.png)
**Figure 8.** The angular distribution for the transition to the unbound 4.109 MeV state.
Sets of optical model parameters are the same as in Fig. 7.

![Figure 9](image3.png)
**Figure 9.** The ratio R for three transitions from the $^{18}$O(d,p)$^{19}$O reaction. The solid, dashed and
dash-dotted lines are for the transitions to the ground state and to the 1.4717 and 3.9449 MeV states,
respectively.

Resulting values $C_{l}^{2}$ for the transitions to 5 states of $^{19}$O are given in table 3. The values
for the ground state and 1.471 MeV state of $^{19}$O dominate. The uncertainties given here are only
standard deviations calculated from these tabulated values and do not include the experimental
uncertainties mentioned earlier. If we include the experimental uncertainties then the overall
uncertainties of ANCs are 22% at most.

The deduced values of ANCs can be then used for calculations of the direct contribution to
the neutron capture by $^{18}$O oxygen. The calculations were performed by the code FRESCO of
Thompson [27]. In fig. 10 the direct capture $(n, \gamma)$ to levels of $^{19}$O are shown. The captures of
Table 3. ANCs and spectroscopic factors $S_{ij}$ from the $^{18}\text{O}(d, p)^{19}\text{O}$ reaction

| $^{19}\text{O}$ state [MeV] | $j_{tr}$ | $b_{ij}$ | $S_{ij}$ | $\text{ANC}(C_{A_{ij}}^2)$ | $S_{ij}$ [18] |
|-----------------------------|---------|----------|---------|-----------------------------|-------------|
| $0 \left(5/2^+\right)$     | 1d5/2   | 0.8931   | 0.529   | $0.4223 \pm 0.0423$         | 0.57        |
| $1.4717 \left(1/2^+\right)$| 2s1/2   | 2.4882   | 0.849   | $5.2562 \pm 1.0871$         | 1.00        |
| $3.1535 \left(5/2^+\right)$| 1d5/2   | 0.2214   | 0.0228  | $(1.117 \pm 0.168)\times 10^{-3}$ | 0.06        |
| $3.2316 \left(1/2^-\right)$ | 2p1/2   | 0.5927   | 0.0179  | $(6.283 \pm 0.872)\times 10^{-3}$ | —           |
| $3.9449 \left(3/2^-\right)$ | 2p3/2   | 0.1053   | 0.0884  | $(9.814 \pm 1.214)\times 10^{-4}$ | 0.11        |

$^{18}\text{O}(n, \gamma)^{19}\text{O}$

Figure 10. The $(n \gamma)$ direct capture for 5 states with the normalization factor determined from the reaction $^{18}\text{O}(d, p)^{19}\text{O}$. The sum of all contributions is given by the solid black line.

$s$- and $p$-waves (dashed and solid lines respectively) are scaled by the deduced ANCs (tab 3). In all cases the E1 multipolarity of $\gamma$ radiation was assumed and the channel radius was taken as 3.3 fm. The main contribution to the total sum (black solid line) comes from transition to the 1.471 MeV state (2s1/2).

We compared our results with available experimental data (Fig. 11). Several points were measured by Meissner [10] and by Ohsaki et al. [11], usually for the transitions to the ground state and 1.471 MeV state. Vaughn et al. [9] measured in a larger interval (transitions to the g. s. and 1.471 MeV state). The direct part of their data is reproduced relatively well.

The ANC method gives in this case of the neutron rich nucleus of $^{18}\text{O}$ oxygen usable results. The main contribution comes from transition to the 1.471 MeV state (2s1/2).

4. Conclusion

We have determined ANCs for neutron captures by $^{18}\text{O}$ to the 5 final states of $^{19}\text{O}$. The transitions to the ground and 1.471 MeV states of $^{19}\text{O}$ give the main DC contributions to
Figure 11. The comparison of the cross section of the direct radiative neutron capture $^{18}\text{O}(n, \gamma)^{19}\text{O}$ determined by ANC method from the reaction $^{18}\text{O}(d, p)^{19}\text{O}$ with experimental data of Vaughn et al. [9], Meisner et al. [10] and Ohsaki et al. [11].

the total capture cross section. The inclusion of the neutron capture to higher considered states (3.1535 MeV - p wave, 3.2316 MeV - s wave and 3.9449 MeV - s wave) gives negligible contribution except at very low energies $\sim$ 10 keV (capture to the 3.9449 MeV state), where nevertheless the capture to the 1.4717 state prevails. Results are thus very near to the work of Huang et al. [13]. The reasonable agreement with experimental data of Vaughn et al. [9], Meissner et al. [10] and Ohsaki et al. [11] was achieved even at low energy region. It was shown, by comparing with the experimental data, that for the neutron-rich nucleus $^{18}\text{O}$ the neutron radiative capture even to the ground state can be taken as a peripheral process. The certain role is also played by the fact that the transferred neutron to the ground and 1.471 MeV states is captured as the p-wave in relative motion with regard to the $^{18}\text{O}$ nucleus and the process proceeds farther from the target nucleus than in the case of the s-wave.

Acknowledgments
This work was partially supported by Grant No. M10480902 of the Czech Academy of Sciences, Grant No. LH11001 of the AMVIS Project (Czech - American S & T Cooperation), GACR Project No. P203/10/310 and Grant No. RBFR082838 (FIRB2008) of the Italian Ministry of University and Research.

References
[1] Xu H M, Gagliardi C A, Tribble R E, Mukhamedzhanov A M and Timofeyuk N K Phys. Rev. Lett. 1994 73 2027
[2] Gagliardi C A, et al Phys. Rev. 1999 C59 1149
[3] Azhari A, et al Phys.Rev. 1999 C60 055803
[4] Titus L J, Capel P and Nunes F M Phys. Rev. 2011 C84 035805
[5] Guimarães V Braz. J. Phys. 2004 34 1012
[6] Imai N, et al 2001 Nucl. Phys. 2001 A688 281c
[7] Rauscher T, Applegate J H, Cowan J J, Thielemann F K and Wiescher M Ap. J. 1994 **429** 499-530
[8] Wiescher M, Görres J and Thielemann F K Ap. J. 1990 **363** 340-343
[9] Vaughn F J, Grench H A, Imhof W L, Rowland J H and Walt M Nucl. Phys. 1965 **64** 336
[10] Meissner J, Schatz H, Görres J, Herndl H, Wiescher M, Beer H and Käppeler F Phys. Rev. 1996 **C53** 459
[11] Ohsaki T, Igashira M, Nagay Y, Segawa M and Muto K Phys. Rev. 2008 **C77** 051303(R)
[12] Nagai Y, Segawa M, Ohsaki T, Matsue H and Muto K Phys. Rev. 2007 **C76** 051301(R)
[13] Huang J T, Bertulani C A and Guimarães V At. Data and Nucl. Data Tables 2010 **96** 824
[14] Herndl H, Hofinger R, Jank J, Oberhummer H, Görres J, Wiescher M, Thielemann F K and Brown B A Phys. Rev. 1999 **C60** 064614
[15] Moreh R and Daniels T Nucl. Phys. 1965 **74** 403
[16] Wiza J L and Middleton R Phys. Rev. 1966 **143** 676
[17] Strobel G L Phys. Rev. 1967 **154** 941
[18] Sen S, Darden S E, Hiddleston H R and Yoh W A Nucl. Phys. 1974 **A219** 489
[19] Stephenson E J, Hichwa B P and Hutton J D Nucl. Phys. 1979 **A331** 269
[20] Perey C M and Perey F G At. Data Nucl. Data Tables 1976 **17** 1-101
[21] Raynal J, code ECIS79 (unpublished)
[22] Kunz P D, code DWUCK5 (unpublished)
[23] Duke C B Phys. Rev. 1963 **129** 681
[24] Watson B A, Singh P P and Segel R E Phys. Rev. 1969 **182** 977
[25] Mukhamedzhanov A M, et al Phys. Rev. 2011 **C84** 024616
[26] Mukhamedzhanov A M, Clark H L, Gagliardi C A, Lui Y-W, Trache L, Xu H M, Zhou X G, Burjan V, Cejpek J, Kroha V and Carstoiu F, Phys. Rev. 1997 **C56** 1302
[27] Thompson I J Comp. Phys. Rep. 1988 **7** 167