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THE ASYMPTOTIC NORMALIZATION COEFFICIENTS FOR $^{24}\mathrm{Mg} + p \to {}^{25}\mathrm{Al}$ FROM THE $^{24}\mathrm{Mg}(^3\mathrm{He}, d)^{25}\mathrm{Al}$ REACTION DATA

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Abstract. The main goal of this work is to determine the values of the asymptotic normalization coefficients for $^{24}\mathrm{Mg} + p \to {}^{25}\mathrm{Al}$. For this purpose the analysis of differential cross section for the proton transfer $^{24}\mathrm{Mg}(^3\mathrm{He}, d)^{25}\mathrm{Al}$ reaction at the energies $E_p = 16$, 18, 20, 25, 33.3 and 38.5 MeV was carried out within the Modified Distorted Wave Born Approximation method. New values of the asymptotic normalization coefficients for the $^{24}\mathrm{Mg} + p \to {}^{25}\mathrm{Al}$ configuration were obtained.

Key words: differential cross section, Modified Distorted Wave Born Approximation, asymptotic normalization coefficient, astrophysical $S-$factor

I. INTRODUCTION

The actual experimental task at present is to obtain the accuracy data on the cross sections ($S-$factors) and rates of different reactions occurring in the stellar medium. In particular, the proton radiative capture $^{24}\mathrm{Mg}(p,\gamma)^{25}\mathrm{Al}$ reaction is one of the important hydrogen burning processes at various stages of stellar nucleosynthesis. In astrophysical scenarios, it is assumed that the enrichment in $^{24-26}\mathrm{Mg}$ and $^{27}\mathrm{Al}$ nuclei is blocked near their solar enrichment during the second, proton-enriched period of explosive carbon burning. During this period, the $^{24-26}\mathrm{Mg}$ nuclei burn out by the reactions of the radiative proton capture $^{24-26}\mathrm{Mg}(p,\gamma)^{25-27}\mathrm{Al}$ with the final formation of $^{27}\mathrm{Al}$ nuclei. The temperature interval for the explosive carbon burning is $1.8 < \mathrm{T9} < 2.2$ ($0.50 < E_p^{\mathrm{c.m.}} < 1.59$ MeV). Excessive enrichment with the $^{26}\mathrm{Mg}$ isotope found in the Allende 2 meteorite [1, 2] required clarification of the ways of production of the $^{26}\mathrm{Al}$ isotope [3]. Besides to the explosive carbon burning, the MgAl cycle of hydrogen burning is possible, including the sequence $^{24}\mathrm{Mg}(p,\gamma)^{25}\mathrm{Al}(\beta^+ + \nu)^{25}\mathrm{Mg}(p,\gamma)^{26}\mathrm{Al}$ in the process of explosive or hydrostatic nucleosynthesis. Therefore, the rates of the above reactions must be known in a wide range of stellar temperatures [4].

Data on resonances in the systematics of levels $^{25}\mathrm{Al}^* = \{^{24}\mathrm{Mg} + p\}$ for the energy range $0.2 - 5.7$ MeV have been studied in sufficient detail. The systematics of these data required for calculations is given in [5]. However, experimental data on the radiative capture $^{24}\mathrm{Mg}(p,\gamma)^{25}\mathrm{Al}$ in the low-energy region are very scarce and are practically presented only in Ref [6]. The authors limited the lower energy of the incident protons to ~ 600 keV, and the resonance structure of the cross section is not revealed due to the large energy step. The experimental errors are quite large (up to 40% or more), preventing accurate calculation of the reaction rate at stellar temperatures. Therefore, in addition to direct measurement of the astrophysical $S-$factors of these processes in the laboratory available energy range, it is important to use correct extrapolation methods of calculations. However, the contribution of direct proton capture at astrophysically relevant energies can be correctly calculated using the "ANC method" (see [7] and references therein), which requires precisely determined "experimental" values of the ANC of proton-bound states in $^{25-26}\mathrm{Al}$ nuclei. These values can be obtained from the analysis of the direct peripheral proton transfer reactions at relatively high energies, where measurements of the differential cross sections (DCSs) can be carried out with high precision.

In this context, of interest are the nucleon transfer reactions in the energy range significantly above the Coulomb barrier, but this requires reactions with a dominance of the peripheral process of nucleon transfer. The most convenient reaction in this regard is the $(^3\mathrm{He}, d)$ reaction in the energy range of incident $^3\mathrm{He}$ ions of $15 - 50$ MeV. Firstly, in the $^3\mathrm{He}$ nucleus the proton

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is relatively weakly bound (the proton binding energy, $\varepsilon_p = 5.4935$ MeV, is noticeably less than the average binding energy of nucleons in nuclei), and the proton transfer is usually preferential. Another advantage is the well-known ANC value of the proton separation, which has been calculated ab initio in such few-nucleon system [8] and carefully measured in a number of experimental studies [9]. This reaction is currently widely used to obtain proton-separation ANC values, which is extremely valuable in problems of nucleosynthesis in light nuclei [10–12]. To date, there is only one study that provides the values of the proton separation ANC in the ground and three lowest states of the ^{25}Al ($= {}^{24}\mathrm{Mg} + p$) nucleus [13], extracted from the analysis of the experimental DCS of the $^{24}\mathrm{Mg}(^3\mathrm{He}, d)^{25}\mathrm{Al}$ reaction at the energy $E_{^3\mathrm{He}} = 38.5$ MeV [14]. However, there are several experimental studies on this reaction, carried out at various energies before 2000. Analysis of these data allows one to assess the dominance of the single-step reaction mechanism and can significantly refine the ANC values for ($^{24}\mathrm{Mg} + p$) bound states in the ^{25}Al nucleus. Such analysis, in turn, will help assess the need for additional research of reactions involving proton transfer to these states to refine the ANCs.

In this work, within the framework of the Modified Distorted Wave Born Approximation method (MDWBA), a reanalysis of the literature experimental data on the reaction $^{24}\mathrm{Mg}(^3\mathrm{He}, d)^{25}\mathrm{Al}$ was performed. At that, the values of ANC for $^{24}\mathrm{Mg} + p \to {}^{25}\mathrm{Al}$ have been obtained from the analysis of DCS of the proton transfer $^{24}\mathrm{Mg}(^3\mathrm{He}, d)^{25}\mathrm{Al}$ reaction at several energies of the ^{3}He projectiles. These data are necessary to clarify the structure of light nuclei and, as shown before, important for estimation of the astrophysical $S-$factor for radiative capture of a proton by the ^{24}Mg nucleus.

II. RESULTS AND DISCUSSION

In the MDWBA the calculated DCS in the region of the main peak of the angular distribution for the peripheral nuclear one-particle (a) transfer reaction $x + \mathrm{A} \to y + \mathrm{B}$ (here $x = y + a$ and $\mathrm{B} = \mathrm{A} + a$) is parameterized in terms of the product of squares ANC and has the form of [15, 16]

$$\frac{d\sigma}{d\Omega} = C^2_{a\mathrm{A};l_\mathrm{B}j_\mathrm{B}} \times R(E_i, \theta; b_{ya;l_xj_x}, b_{a\mathrm{A};l_\mathrm{B}j_\mathrm{B}}) \tag{1}$$

$$R(E_i, \theta; b_{ya;l_xj_x}, b_{a\mathrm{A};l_\mathrm{B}j_\mathrm{B}}) = N^{NBCE} \times \left(\frac{C^2_{ya;l_xj_x}}{b^2_{ya;l_xj_x}}\right) \times \frac{\sigma^{\mathrm{DWBA}}_{l_xl_\mathrm{B}j_\mathrm{B}}(E_i, \theta; b_{ya;l_xj_x}, b_{a\mathrm{A};l_\mathrm{B}j_\mathrm{B}})}{b^2_{a\mathrm{A};l_\mathrm{B}j_\mathrm{B}}} \tag{2}$$

where $\sigma^{\mathrm{DWBA}}_{l_xl_\mathrm{B}j_\mathrm{B}}$ is the single-particle DWBA cross section; $b_{ya;l_xj_x}$ and $b_{a\mathrm{A};l_\mathrm{B}j_\mathrm{B}}$ are the single-particle ANCs which determine the amplitudes of the tails of the shell model wave functions corresponding to bound states ($x = y + a$ and $\mathrm{B} = \mathrm{A} + a$); $C_{a\mathrm{A};l_\mathrm{B}j_\mathrm{B}}$ ($C_{ya;l_xj_x}$) is ANC for $\mathrm{A} + a \to \mathrm{B}$ ($y + a \to x$) which determine the amplitudes of the tail of the corresponding "model-less" radial overlap functions [8]; N^{NBCE} is the Coulomb renormalization factor arising due to correct taking into account the three-body Coulomb dynamics in the transfer mechanism [17, 18]; l_x and l_B are the orbital moments of particle a in the nuclei x and B respectively. j_x and j_B are the total angular momentum of the transferred particle a in nuclei x and B respectively.

The peripheral character of the considered reaction in the region of the main peak of the angular distribution can be evaluated by the condition [18, 19]

$$R(E_i, \theta; b_{ya;l_xj_x}, b_{a\mathrm{A};l_\mathrm{B}j_\mathrm{B}}) = f(E_i, \theta) \tag{3}$$

as a function of free parameters $b_{ya;l_xj_x} = b_{ya;l_xj_x}(r_0, a)$ and $b_{a\mathrm{A};l_\mathrm{B}j_\mathrm{B}} = b_{a\mathrm{A};l_\mathrm{B}j_\mathrm{B}}(r_0, a)$ which in turn are functions of the geometric parameters of the radius and diffusion for the Woods–Saxon (W-S) potential for all scattering angles θ and a fixed value of the energy E_i. If expression (3) does not change or changes only slightly when the arguments $b_{ya;l_xj_x}$, $b_{a\mathrm{A};l_\mathrm{B}j_\mathrm{B}}$ are varied within physical reasonable limits and angle θ is within the main maximum of the angular distribution of the DCS, then the transfer of particle a occurs at the periphery of the nuclei. Then the value of ANC for $\mathrm{A} + a \to \mathrm{B}$ can be determined from the condition

$$C^2_{a\mathrm{A};l_\mathrm{B}j_\mathrm{B}} = \frac{(\frac{d\sigma}{d\Omega}^{\mathrm{expr}})_{\theta=\theta_{\mathrm{peak}}}}{R(E_i, \theta; b_{ya;l_xj_x}, b_{a\mathrm{A};l_\mathrm{B}j_\mathrm{B}})} = const \tag{4}$$

which must be satisfied for each energy E_i of the incident particles, where the dominance of a simple one-step reaction mechanism is assumed, as well as for scattering angle θ and the corresponding function $R_{l_xj_xl_\mathrm{B}j_\mathrm{B}}$ from Eq. (3).

The fulfillment of the conditions (3) and (4) (or their slight violation within the experimental errors of the DCS) makes it possible to obtain indirectly determined ANC values for $\mathrm{A} + a \to \mathrm{B}$ using the experimental DCS $\frac{d\sigma}{d\Omega}^{\mathrm{expr}}$ in the main peak. For

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determining the values of the ANC squares the analysis of the DCS of the $^{24}\mathrm{Mg}(^{3}\mathrm{He},d)^{25}\mathrm{Al}$ reaction which was measured at $E_p = 16, 18, 20$ MeV [20], 25 MeV [21], 33.3 MeV [22] and at 38.5 MeV [14] have been carried out within the framework of the MDWBA. The calculations were carried out using our modified version [23] of the DWUCK5 code [24] which permits one to test the reaction peripherality and extract directly the ANC squares.

A detailed procedure for analyzing the DCSs of the $^{24}\mathrm{Mg}(^{3}\mathrm{He},d)^{25}\mathrm{Al}$ reaction is presented here for experimental data at $E_{^3\mathrm{He}} = 25$ [21] and 33 MeV [22], which are representative of the entire energy range under consideration. Data at other energies were analyzed similarly. The OP parameters for the entrance and exit channels of reactions at all cases were taken from the same publications where the experimental data were obtained, or global OPs were used (see tables I and II with references). Note that at local OPs, the cited authors usually used the parameters of the $^{25}\mathrm{Mg}$ nucleus instead of the unstable $^{25}\mathrm{Al}$ nucleus. The value of ANC for $p + d \to {}^{3}\mathrm{He}$ equal to $C^2_{pd} = 4.32 \pm 0.3\ \mathrm{fm}^{-1}$, is taken as the average between the results obtained in [9] and [25].

	channel	V	r_0	a_0	$W_{V/D}$	$r_{V/D}$	$a_{V/D}$	V_{SO}	r_{SO}	a_{SO}	r_C	ref
SetA	$^{24}\mathrm{Mg} + {}^{3}\mathrm{He}$	220.2	1.15	0.672	$20.1V$	$1.529V$	$0.988V$				1.4	[21]
	$^{25}\mathrm{Al} + d$	87.212	1.17	0.743	$0.5V$ $12.221D$	$1.325V$ $1.325D$	$1.325V$ $0.734D$	6.75	1.07	0.66	1.3	[26]
SetB	$^{24}\mathrm{Mg} + {}^{3}\mathrm{He}$	109.454	1.15	0.77	$20.96D$	$1.289D$	$0.8D$				1.4	[27]
	$^{25}\mathrm{Al} + d$	89.64	1.129	0.756	$10.202V$ $2.381D$	$1.386V$ $1.34D$	$0.712V$ $0.562D$	3.557	0.972	1.011	1.303	[28]
SetC	$^{24}\mathrm{Mg} + {}^{3}\mathrm{He}$	109.454	1.15	0.77	$20.96D$	$1.289D$	$0.8D$				1.4	[27]
	$^{25}\mathrm{Al} + d$	84.864	1.174	0.809	$21.073V$ $4.581D$	$1.328V$ $1.563D$	$0.456V$ $0.7D$	3.703	1.234	0.813	1.698	[29]

TABLE I: Sets of OPs used in calculations at the energy $E_{^3\mathrm{He}} = 25$ MeV. The letters V and D in columns $6-8$ denote the volume and surface form of the potential.

	channel	V	r_0	a_0	$W_{V/D}$	r_D	a_D	V_{SO}	r_{SO}	a_{SO}	r_C	ref
Set1	$^{24}\mathrm{Mg} + {}^{3}\mathrm{He}$	171.564	1.096	0.729	$20.511D$	1.173	0.913	3.375	1.255	0.211	1.25	[22]
	$^{25}\mathrm{Al} + d$	94.2	1.053	0.814	$10.77D$	1.36	0.726	7	1.053	0.814	1.25	[14]
Set2	$^{24}\mathrm{Mg} + {}^{3}\mathrm{He}$	191.644	1	0.744	$18.27V$	1.682	0.944	3.815	1.053	0.278	1.25	[22]
	$^{25}\mathrm{Al} + d$	94.2	1.053	0.814	$10.77D$	1.36	0.726	7	1.053	0.814	1.25	[14]
Set3	$^{24}\mathrm{Mg} + {}^{3}\mathrm{He}$	178.5	1.104	0.722	$42V$	1.295	0.852	2.5	1.2	0.72	1.25	[14]
	$^{25}\mathrm{Al} + d$	94.2	1.053	0.814	$10.77D$	1.36	0.726	7	1.053	0.814	1.25	[14]

TABLE II: Sets of OPs used in calculations at the energy $E_{^3\mathrm{He}} = 33$ MeV.

For testing the dominance of the periphery of the proton stripping in the considered reactions the parameters r_0 and a of the W–S potential for the proton binding in the $^{25}\mathrm{Al}$ nucleus were varied in the intervals $1.10 \le r_0 \le 1.40$ fm and $0.50 \le a \le 0.80$ fm. This variation changes the single-particle ANC $b_{p^{24}\mathrm{Mg}}$ in the range of $2.698 \le b_{p^{24}\mathrm{Mg}} \le 5.679$. The single-particle DWBA cross section $\sigma^{\mathrm{DWBA}}_{12\frac{5}{2}}(E_i,\theta)$ ($\theta \approx \theta_{\mathrm{peak}}$) is a rapidly changing function of the variable $b_{p^{24}\mathrm{Mg}}$. Nevertheless the calculated values of $R(E_i,\theta;b_{ya;l_xj_x},b_{a\mathrm{A};l_{\mathrm{B}}j_{\mathrm{B}}})$ at a fixed value of $b_{p^{24}\mathrm{Mg}}$ as a function of the free parameter $b_{p^{24}\mathrm{Mg}}$ practically does not change within the mentioned intervals practically for all cases under consideration. As an example, the results of the calculation of the $R(E_i,\theta;b_{ya;l_xj_x},b_{a\mathrm{A};l_{\mathrm{B}}j_{\mathrm{B}}})$ function and the ANC $C^2_{p^{24}\mathrm{Mg}}$ of $^{25}\mathrm{Al}$ nucleus in the $(^{24}\mathrm{Mg}+p)-$ channel at the energy $E_{^3\mathrm{He}} = 25$ and 33 MeV with the formation of the $^{24}\mathrm{Mg}$ nucleus in the ground state are shown in Fig. 1. As seen from the figure the condition (3) is satisfied with an accuracy not exceeding the relative experimental errors of the analyzed DCSs.

The DCSs and their comparison with the experimental data from Refs. [21] and [22] are shown in Fig. 2. As can be seen from the figure the calculated cross sections within the framework of the MDWBA reproduce well the experimental data in the region of the main maximum of the angular distribution.

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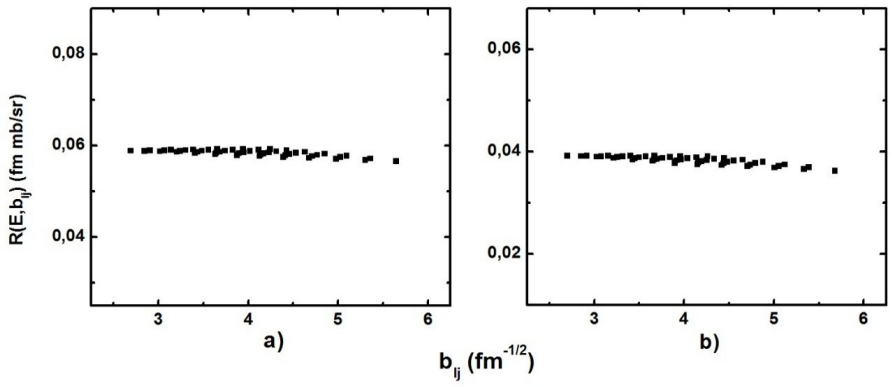


FIG. 1: Ranges of the $R(b)$ functions in the regions of the main maxima of the DCS at energies of 25 MeV (a) and 33 MeV.

The ANC squared values for $^{24}\mathrm{Mg} + p \to {}^{25}\mathrm{Al}$, extracted from the normalization of the calculated DCS to the experiment for each set of OPs and averaged with weights equal to the inverse of the corresponding standard deviations, are presented in Table III for each energy. The errors are the mean square errors associated with the ranges of the values of the functions $R(E_i, \theta; b_{dp;l_{^3\mathrm{He}} j_{^3\mathrm{He}}}, b_{p^{24}\mathrm{Mg};l_{^{25}\mathrm{Al}} j_{^{25}\mathrm{Al}}}) = R(b_{p^{24}\mathrm{Mg}})$, the ambiguities of the OP parameters at each projectile energy, the errors of the experimental DCSs and the C^2_{pd} value.

E^*, MeV	$I^\pi(l_p, j_p)$	E_p, MeV	C^2, fm^{-1}
0.0	$5/2^+$ $(2, 5/2)$	16	3.49 ± 0.49
		18	4.56 ± 0.73
		20	3.96 ± 0.55
		25	5.44 ± 0.76
		33.3	3.92 ± 0.19
		38.5	4.69 ± 0.84
0.452	$1/2^+$ $(0, 1/2)$	16	130.6 ± 19.6
		18	162.7 ± 20.3
		25	189.0 ± 26.4
		33.3	138.6 ± 19.4
		38.5	129.1 ± 22.5
0.945	$3/2^+$ $(2, 3/2)$	16	2.0 ± 0.3
		18	2.68 ± 0.48
		20	2.41 ± 0.32
		25	3.66 ± 0.55
		33.3	2.25 ± 0.24

TABLE III: The ANC squares $C^2_{p^{24}\mathrm{Mg}}$ obtained for the lowest states of the $^{25}\mathrm{Al}$ nucleus at different energies of the $^3\mathrm{He}$ projectiles.

The Table IV presents the averaged energy values of the ANC squares and the average deviations from the mean. From the Table III we can see that the ANC values obtained from the analysis of data at an energy of 25 MeV [21] are significantly higher than the average. Assuming that the experimental DCS values in this study are overestimated and the Table IV shows the energy averaging results in parentheses without including these data. The average deviations from the average are significantly reduced, although the average squared ANC values decrease by only 5%.

Ratio (3) for $R(b_{p^{24}\mathrm{Mg}})$ is satisfied with an accuracy not exceeding the relative experimental errors of the analyzed DCSs,

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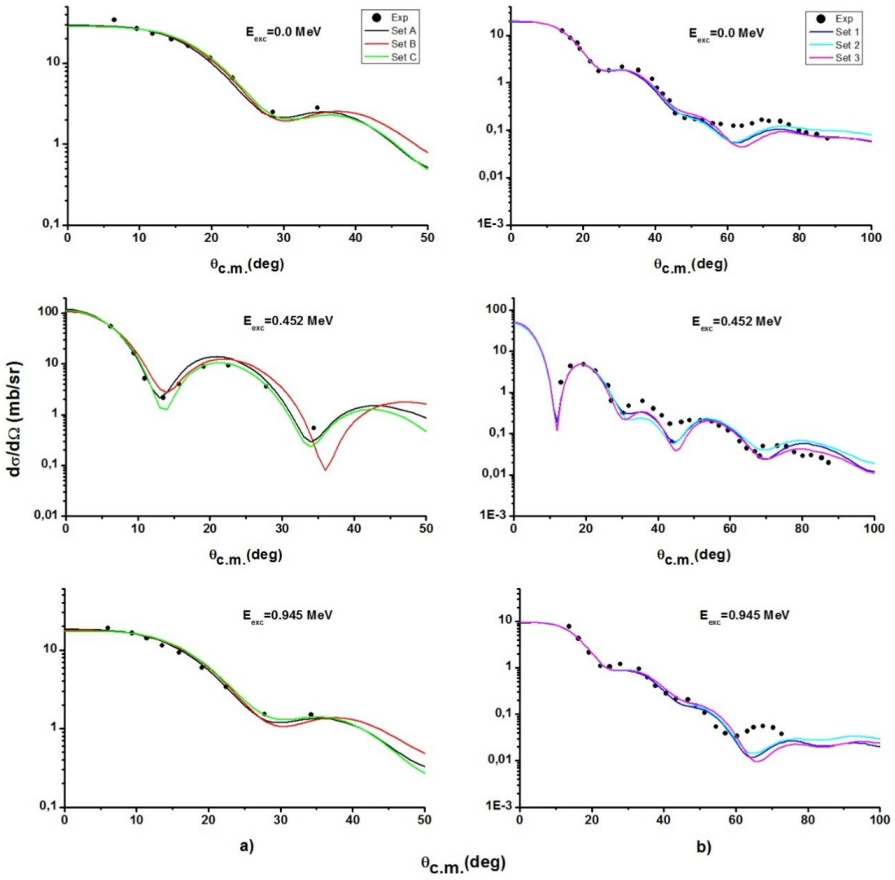


FIG. 2: Angular distribution of the $^{24}\mathrm{Mg}(^{3}\mathrm{He}, d)^{25}\mathrm{Al}$ reaction at energies 25 MeV (left panel) and 33.3 MeV. The experimental DCSs are taken from the [21] and [22], correspondingly. The solid lines are the calculated DCS using different OP sets.

$C^2_{p^{24}\mathrm{Mg};2\frac{5}{2}}$ [fm^{-1}]	$C^2_{p^{24}\mathrm{Mg};0\frac{1}{2}}$ [fm^{-1}]	$C^2_{p^{24}\mathrm{Mg};2\frac{3}{2}}$ [fm^{-1}]	Ref
4.34 ± 0.55	150.0 ± 20.8	2.60 ± 0.42	This work
(4.12 ± 0.39)	(140.3 ± 16.1)	(2.34 ± 0.31)	
5.37	128	2; 2.3	[17]

TABLE IV: Resulting values of the ANC squares for the $^{25}\mathrm{Al} \to {}^{24}\mathrm{Mg} + p$ configurations. Also the corresponding values from the Ref [17] are presented.

which allows us to consider the proton transfer in the reaction as peripheral. But in some cases, the ratio (4) for $C^2_{p^{24}\mathrm{Mg}}$ is not satisfied as the deviations of the ANC values from the energy-averaged value exceed the error limits found. In principle, this may be due to the contribution of more complex mechanisms than simple proton stripping. However, the contribution of the compound nucleus mechanism can be excluded, since the angular distribution of the DCS does not demonstrate its increasing at angles close to 180° at lower energies in the range under consideration (18 MeV, [30]). Also, the extracted values of the ANC as a function of energy (see Table III) do not contain an explicit energy dependence, which could indicate a significant contribution from multistep processes and coupling of reaction channels. We also note that the available literary estimates of the ANC values are in satisfactory agreement with the values we obtained.

Overall, the deviations from the energy-averaged values are unsystematic, and the energy-averaged ANC squared values from Table III and Table IV can be adopted as the recommended values for this paper.

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III. CONCLUSION

Within the framework of MDWBA, an analysis of the experimental DCS of proton transfer $^{24}\mathrm{Mg}(^{3}\mathrm{He},d)^{25}\mathrm{Al}$ reaction at $E_p = 16$, 18, 20, 25, 33.3 and 38.5 MeV was carried out. It was shown that the proton transfer to the low-lying states of the $^{25}\mathrm{Al}$ nucleus is peripheral in the region of the main peak of the angular distribution and the one-step mechanism dominates at all cases.

It has been established that the analyzed experimental data permit to determine in a model-independent way the ANC values for the $^{25}\mathrm{Al}$ nucleus in the $(^{24}\mathrm{Mg}+p)$ configuration and a new values of ANC squires were obtained for the ground and several excited states of the $^{25}\mathrm{Al}$ nucleus.

The obtained ANC values are planned to be used to calculate astrophysical $S-$factors of radiative capture reactions $^{24}\mathrm{Mg}(p,\gamma)^{25}\mathrm{Al}$.

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REFERENCES

[1] T. Lee, *et al*., Astrophys. J. Lett. **211** (1977) L107.
[2] T. Lee, *et al*., Astrophys. J. Lett. **220** (1978) L21.
[3] W.A. Richter *et al*., Phys. Rev. C **83** (2011) 065803.
[4] J. Keinonen and S. Brandenburg, Nucl. Phys. A **341** (1980) 345.
[5] G.R. Caughlan and W.A. Fowler, At. Data Nucl. Data Tables **40** (1988) 283.
[6] H.P. Trautvetter and C. Rolfs, Nucl.Phys. A **242** (1975) 519.
[7] A.M. Mukhamedzhanov, L. D. Blokhintsev, Eur. Phys. J. A **58** (2022) 29.
[8] L.D. Blokhintsev *et al*., Sov. J. Part. Nucl. **8** (1977) 485.
[9] S.V. Artemov *et al*., Bull. Russ. Acad. Sci.: Phys. **73** (2009) 165.
[10] M. Ayguna *et al*., Act. Phys. Pol. B **54** (2023) 5-A1.
[11] V. Burjan *et al*., Eur. Phys. J. A **55** (2019) 114.
[12] E.T. Ruziev *et al*., Int. J. Mod. Phys. E **33** (2024) 2450024.
[13] S.V. Artemov *et al*., Int. Jour. Mod. Phys. E **19** (2010) 1102.
[14] R.J. Peterson and R.A. Ristinen, Nucl. Phys. A **246** (1975) 402.
[15] S.V. Artemov *et al*., Phys. At. Nucl. **59** (1996) 428.
[16] A.M. Mukhamedzhanov *et al*., Phys. Rev. C **56** (1997) 1302.
[17] Sh.S. Kajumov *et al*., Z. Phys A **336** (1990) 297.
[18] R. Yarmukhamedov *et al*., Int. J. Mod. Phys.: Conf. Ser. **49** (2019) 1960016.
[19] G. Kiss *et al*., Phys. Lett. B **807** (2020) 135606.
[20] B. Mertens *et al*., Nucl. Phys. A **158** (1970) 97.
[21] J. Vernotte *et al*., Nucl. Phys. A **571** (1994) 1.
[22] F. Entezami *et al*., Nucl. Phys. A **366** (1981) 1.
[23] Artemov S.V. *et al*., Svidetelstvo ob ofitsialnoy registratsii programmi dlya elektronno-vichislitelnix mashin **№ DGU 02401** "Programma avtomaticheskogo chteniya i prosmotra dvumernix matris Win_EDE" (in russian).
[24] Kunz P D, "Computer code DWUCK5", `http://spot.colorado.edu/~kunz/DWBA.html`.
[25] S.V. Artemov *et al*., Phys. At. Nucl. **71** (2008) 998.
[26] W.W. Daehnick *et al*., Phys. Rev. C **21** (1980) 2253.
[27] J. Trost *et al*., Nucl. Phys. A **462** (1987) 333.
[28] Haixia An *et al*., Phys. Rev. C **73** (2006) 054605.
[29] Yinlu Han *et al*., Phys. Rev. C **74** (2006) 044615.
[30] B.Mertens *et al*., Nucl. Phys. A **158** (1970) 97.

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