EPJ Web of Conferences 66, 05014 (2014)
DOI: 10.1051/epjconf/20146605014

Parity and time-reversal violation in A=2-4 nuclei

R. Lazauskas[1,a], Y.H. Song[2], and V. Gudkov[3]

[1] IPHC, IN2P3-CNRS/Université de Strasbourg, 23 rue du Loess, 67037 Strasbourg, France
[2] RISP, Institute for basic science, Daejeon, S. Korea
[3] Department of Physics and Astronomy, University of South Carolina, Columbia, South Carolina, 29208, USA

Abstract. Parity and time-reversal symmetry violating components of the nucleon-nucleon interaction play an important role in understanding the main features of the Standard model. These symmetries have been rather intensively studied during the last decade. Moreover, new spallation neutron facilities, such as the SNS at the Oak Ridge National Laboratory and the J-SNS at J-PARC, may provide new data of very high accuracy.

In this presentation, we review the current status of the theoretical calculations of parity-violating and time reversal invariance-violating observables in few-nucleon systems. In particular, we concentrate on the low energy nucleon scattering on mass A=1-3 targets, as well as on nuclear EDM calculations for A=2-3 nuclei.

1 Introduction

In the late 1950s, Lee and Yang revealed that the parity might be violated in the weak interaction [1]. There were well-known violations of C-symmetry as well. Some years later, CP-violation in the neutral kaon system has been observed [2]. In 1967, Andrei Sakharov pointed out that CP-symmetries should be violated during the baryon creation phase in the early Universe, as one of the three necessary conditions to produce matter and antimatter at different rates [3]. On the other hand, Lorentz-invariance, as has been proved by by G.Lüders, W.Pauli, and J.Bell in the framework of local Lagrangian field theory, implies CPT-invariance [4]. The search for the combinations of charge, parity, and time reversal symmetry violations is, therefore, crucial in understanding properties of matter and the universe, as well as for a detailed study of the Standard model. This also can be a way to search for the possible manifestations of new physics which are not incorporated in the Standard Model.

During the last six decades, a great deal of theoretical work has been performed, with the goal of understanding the patterns of observation of the possible combinations of C-, P-, and T- violations that emerged from the experiments. In this relation, there are a number of advantages to search for these weak interaction driven symmetry violations in nuclear processes. The main advantage relies on the fact that in some nuclei, the symmetry breaking observables might be enhanced by many orders of a magnitude due to the complex nuclear structure (for the case of T-violation see, i.e. paper [5] and references therein). Another advantage is the richness of the nuclear chart, which permits one to perform extensive search and acquire enough observations against possible "accidental" cancellation of

[a] e-mail: rimantas.lazauskas@iphc.cnrs.fr

symmetry violating effects due to uncertain structural factors related to the strong interaction. Finally, with the emergence of new spallation neutron facilities, such as the SNS at the Oak Ridge National Laboratory and the J-SNS at J-PARC, there is hope to obtain a new experimental data of P- and/or T-violation in nuclei with very high accuracy.

In hadronic systems, the most explored symmetry violating effects are parity-violating (PV) ones, because they are much stronger than the effects involving time-reversal invariance violation (time-reversal invariance violating (TV) or time-reversal and parity (TPV) processes). Still, the natural strength of the parity violation is only of the order of $G_F F_\pi^2 \sim 10^{-7}$ as compared to the dominant strong interaction, and thus these effects are very small. Therefore, it requires exceptional effort to observe these effects in experiments in order to accumulate sufficient counts and to control systematics that could yield false signals. One should be very careful in choosing the system and processes, which may lead to non-null observation of these tiny effects. The presence of the Electric Dipole Moments (EDMs) is due to simultaneous breaking of time reversal and parity and thus is commonly accepted as the smoking gun of the TPV interactions. However, PV, TV, or TPV effects might also be observed as tiny asymmetries in the dynamical processes, like nuclear collisions or radiative capture/desintegration reactions. P- and/or T symmetry breaking could be traced in observing specific asymmetries in the reaction cross sections involving polarized projectile-target system, or otherwise, polarized reaction products. In particular, the transmission of a low-energy polarized neutron beam through the matter is intriguing, since in this case, PV, TV, and TPV effects might be explored at very low (thermal or resonance) neutron energies. The beam of neutrons may scatter coherently, whereas the presence of PV, TV, or TPV terms in neutron-nucleus interaction will lead to overall neutron spin rotation by the angle proportional to the thickness of target material. Moreover, PV, TV, and TPV effects evolve differently as neutron-target polarization or beam energy change, see fig. 1. Therefore, one may distinguish between these effects by varying neutron-target setup and determining the correlation pattern of the symmetry breaking observable with three experimental setup parameters: neutron spin ($\vec{\sigma_n}$), target spin ($\vec{I}$), and the direction of the beam ($\hat{p_n}$). Similar, the study can be also performed by analyzing the asymmetries in the total reaction cross section, as well as for charged projectiles (protons); however, in the last case, higher energy beams should be involved.

It has been mentioned above that some heavy nuclei are very favorable to observe symmetry breaking-effects. However, the ultimate goal is to pin down the Standard model ingredients from the experimental data. To this aim, reliable theoretical tools are required to relate experimental observables with the constants of the bare nucleon-nucleon interaction. Unfortunately, heavy nuclei remain beyond the reach of the ab-initio methods and, therefore, in general, one is not able to derive these relations reliably. To resolve this issue and eliminate theoretical uncertainties, it is necessary to focus on few-body systems, where calculations of nuclear related effects can be done with high precision. In this contribution, we will discuss recent progress in describing parity and time-reversal violation in the lightest nuclei, with A≤4.

2 Theory ingredients

P- and/or T- symmetry violating interactions are weak and thus might be treated as a perturbation when calculating matrix elements related with the symmetry violating effects. Two main components enter the calculation: hadronic wave functions, which are due to strong Hamiltonian only, and symmetry violating potentials.

The last two decades have witnessed decisive progress in nuclear physics by ab-initio calculations. First enormous progress has been achieved in the description of the strong nuclear interaction by developing realistic nucleon-nucleon (NN) potentials based either on phenomenological or

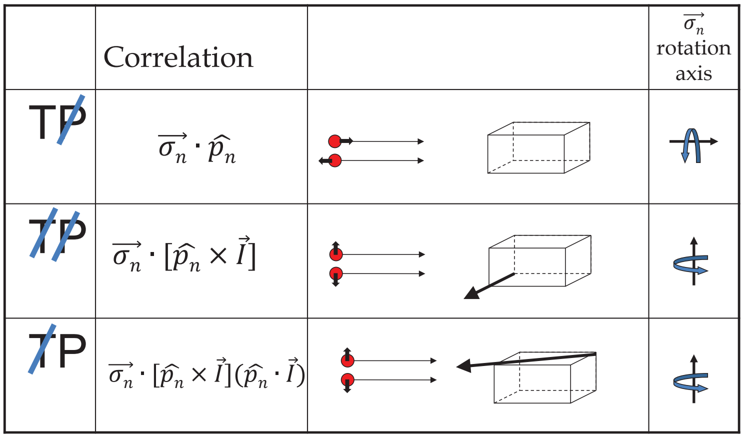

Figure 1. Schematic demonstration of the lowest order correlations, which may reveal parity violating ($T\not{P}$), time-reversal and parity violating($\not{T}\not{P}$) or time-reversal violating($\not{T}P$) effects respectively, in low energy neutron scattering on the target with polarization $\vec{I}$. Eventual neutron-spin rotation axis is pointed out in the last column.

meson-exchange models. During the first decade of the 21st century, nuclear forces based on chiral effective field theory emerged, which enabled one to derive nucleon-nucleon forces in a more systematic way at the same time providing the error-estimate [7]. In parallel, very powerful methods for nuclear bound-state calculations have been developed, which have reached a degree of sophistication allowing the accurate description of the nuclei up to several nucleons. The most advanced of those are Green's function Monte Carlo [8], No-core shell [6], and Coupled-cluster [9] methods. Sizable progress has been also achieved in handling problems of nuclear reactions: rigorous methods for nucleus-nucleus collisions have been extended from A=3 to A=4 case; the long-standing problem of including Coulomb interaction has been also resolved. Finally, Lorentz integral transform method has been developed to treat hadronic reactions induced by the weak perturbation and recently applied for $A = 16$ nucleus [10].

The general structure of the symmetry violating nucleon-nucleon potential is determined by the symmetry. Thus, the nucleon-nucleon interaction can be expanded in terms of a set of $O_{ij}^{(k)}$ operators [23] as

$$V_{ij} = \sum_k \hat{O}_{ij}^k(\hat{p}_{ij}, \vec{l}_i j, \vec{s}_i j, \vec{\tau}_i, \vec{\tau}_j, ...) f_k(p_{ij}, p'_{ij}). \tag{1}$$

Here, the operators $\hat{O}_{ij}^k(\hat{p}_{ij}, \vec{l}_i j, \vec{s}_i j, \vec{\tau}_i, \vec{\tau}_j, ...)$, span the most general structure consistent with a given symmetry breaking. The exact number of operators and form of form-factors $f_k(p_{ij}, p'_{ij})$ depends on the assumption on the origin of symmetry violation and truncation scheme for the infinite possible operators. Then, weak hadronic potentials might be classified into two groups, the meson exchange type and the effective field theory (EFT) type, according to the strategy used to determine the most important terms entering this expansion and to provide the respective form-factors $f_k(p_{ij}, p'_{ij})$. Further, we can think of two kinds of EFT type potentials, pionless and pionic, depending on the inclusion of explicit pion degrees of freedom.

Meson-exchange models. The structure of the potential is determined based on the meson exchange mechanism of nucleon-nucleon interactions. The operator structure of the generated meson fields

Table 1. The most general form of the parity-violating nucleon-nucleon potential in the first order of relative nucleon-nucleon momentum. In the first column of the table, the lightest meson generating fields of a given symmetry in meson-exchange models are provided. A shorthand notation $X_{ij,\pm} \equiv [\mathbf{p}_i - \mathbf{p}_j, f(r_{ij})]_\pm$, where $f(r_{ij})$ represents specific functional form for each operator, is used in this table.

Contributing mesons	Isospin	Spin-orbital structure
ω,ρ	1	$(\sigma_i \times \sigma_j) \cdot X_{ij,-}$
π,ω,ρ	$(\tau_i \times \tau_j)^z$	$(\sigma_i + \sigma_j) \cdot X_{ij,-}$
ω,ρ	$(\tau_i + \tau_j)^z$	$(\sigma_i - \sigma_j) \cdot X_{ij,+}$
ρ	$\mathcal{T}_{ij}^z$	$(\sigma_i - \sigma_j) \cdot X_{ij,+}$
ρ	$\mathcal{T}_{ij}^z$	$(\sigma_i \times \sigma_j) \cdot X_{ij,-}$

Table 2. The same as in the previous table, only for Time reversal symmetry violating potential.

Contributing mesons	Isospin	Spin-orbital structure
	$1, (\tau_i + \tau_j)^z, \mathcal{T}_{ij}^z$	$\hat{r} \cdot \bar{p}$
h_1	$1, (\tau_i + \tau_j)^z, \mathcal{T}_{ij}^z$	$\sigma_i \cdot \sigma_j \hat{r} \cdot \bar{p}$
h_1	$1, (\tau_i + \tau_j)^z, \mathcal{T}_{ij}^z$	$\hat{r} \cdot \sigma_i \bar{p} \cdot \sigma_j + \bar{p} \cdot \sigma_i \hat{r} \cdot \sigma_j - \frac{2}{3} \bar{p} \cdot \hat{r} \sigma_i \cdot \sigma_j$
	$1, (\tau_i + \tau_j)^z, \mathcal{T}_{ij}^z$	$\hat{r} \cdot \sigma_i \hat{r} \cdot \sigma_j \hat{r} \cdot \bar{p} - \frac{1}{3} \bar{p} \cdot \hat{r} \sigma_i \cdot \sigma_j$
	$(\tau_i + \tau_j)^z$	$\hat{r} \cdot [(\sigma_i \times \sigma_j) \times \bar{p}]$
ρ	$(\tau_i \times \tau_j)^z$	$\hat{r} \cdot [(\sigma_i - \sigma_j) \times \bar{p}]$

depends on the internal symmetry of the exchanged mesons (their spin, isospin, parity,...); the resulting form factors have the range moderated by the mass of exchanged meson. Nevertheless, these models do not provide systematic expansion scheme for eq.(1).

Pionless Effective Field theory (EFT) uses the most general operator structure of the interactions, which corresponds to the given order of the power counting (determined by the powers of momenta or their derivatives entering the expression), without explicit pion degrees of freedom. Note, that in the EFT approach, the only constraint on the form-factors $f_k(p_{ij}, p'_{ij})$ is that they should be localized, like delta function or its derivative.

Pionic EFT models retain the long range interactions due to one-pion exchange, middle range interactions due to two-pion exchange, as well as short range interactions due to nucleon contact terms inline with pionless EFT case. Though the pionless EFT and pionic EFT are supposed to be equivalent at very low energy scale, they can have different range of convergence.

The most general structure of the nucleon-nucleon potentials up to the first order in relative momentum is presented in the tables 1, 3, and 2 – respectively for parity violation, for the parity plus time-reversal violation, and for the time-reversal violation cases. In the first column of these tables, the lightest meson generating fields of a given symmetry within meson-exchange theory are provided.

In order to trace the origin of the weak nucleon-nucleon interaction to the standard model components, it is important to use consistent theory for strong and weak interaction. However, at the current stage of the phenomenological investigation of the weak hadronic interactions, there are no practical advantages for using one combination of the weak plus strong interaction model over the other. It is expected that the short-range details of the interaction can be integrated out by leaving only minimal information representing symmetry constrains (low energy constants). Thus, the low-energy observables should not depend on the shape of the short-range interaction terms as long as these interactions are symmetry equivalent and the respective low energy constants are accurately fixed to

Table 3. The same as in the previous table, only for T- reversal symmetry and Parity violating potential. Note, that the first two lines correspond to the static potential, where momentum dependence is not involved. Non-static meson exchange is not considered here.

Contributing mesons	Isospin	Spin-orbital structure
π, η, ω, ρ	$1, (\tau_i+\tau_j)^z, \mathcal{T}_{ij}^z$	$(\sigma_i-\sigma_j)\cdot\hat{r}$
π, η, ω, ρ	$(\tau_i-\tau_j)^z$	$(\sigma_i+\sigma_j)\cdot\hat{r}$
	$1, (\tau_i+\tau_j)^z, \mathcal{T}_{ij}^z$	$(\sigma_i\times\sigma_j)\cdot\bar{p}$
	$1, (\tau_i+\tau_j)^z, \mathcal{T}_{ij}^z$	$\hat{r}\cdot(\sigma_i\times\sigma_j)\hat{r}\cdot\bar{p}-\frac{1}{3}(\sigma_i\times\sigma_j)\cdot\bar{p}$
	$(\tau_i-\tau_j)^z$	$\hat{r}\cdot\sigma_i\hat{r}\cdot[\sigma_j\times\bar{p}]+\hat{r}\cdot\sigma_j\hat{r}\cdot[\sigma_i\times\bar{p}]$
	$(\tau_i\times\tau_j)^z$	$(\sigma_i+\sigma_j)\cdot\bar{p}$
	$(\tau_i\times\tau_j)^z$	$\hat{r}\cdot(\sigma_i+\sigma_j)\hat{r}\cdot\bar{p}-\frac{1}{3}(\sigma_i+\sigma_j)\cdot\bar{p}$

reproduce the relevant low energy data. The last feature has been clearly demonstrated when studying electromagnetic (EM) processes [12–15].

On the other hand, the exact values of the low energy constants entering the description of the weak interaction, and in particular those related with the short-range (high-momentum) operators, are strongly model dependent. Values of the coupling constants are associated with a given combination of the strong/weak interaction models and may not be employed with a different combination of the Hamiltonians. Let us briefly explain that. The realistic strong nucleon-nucleon interaction models are usually fitted to nucleon-nucleon scattering phaseshifts, providing excellent description of the two-nucleon experimental observables. Experimental nucleon-nucleon data fixes so called on-shell (momentum conserving) parts of the nucleon-nucleon interaction, and thus different realistic models are fully equivalent on-shell. Nevertheless, off-shell (momentum non-conserving) parts of the realistic nucleon-nucleon potentials differ. As pointed out by Polyzou and Glöckle [11], the different strong nuclear Hamiltonians are connected by the unitary transformation, which does not affect on-shell physics. Thus, let us consider two phase-equivalent strong nuclear Hamiltonians $\hat{H'}_s = \hat{U}^\dagger \hat{H}_s \hat{U}$, related by the unitary operator $\hat{U}$. Respective weak interaction Hamiltonians should be also related by the same unitary transformation $\hat{H'}_w = \hat{U}^\dagger \hat{H}_w \hat{U}$. Such a transformation will not affect any weak-interaction observable; however, it will modify coupling constants $C'_k \neq C_k$.

3 Summary of the performed calculations

In terms of symmetry violation, parity-violation is by far the most explored in nuclear few-body calculations. Using meson-exchange theory, Desplanques et al. derived [16] DDH potential, which includes estimated meson-nucleon coupling constants for π, ρ and ω mesons, see table 1. Pionless and pionic EFT potentials have been developed by Zhu [17, 18].

There have also been many phenomenological calculations related to hadronic parity violation, see a recent review [19]. In particular, recently extensive analysis of the parity violation in the neutron-proton system [20] and for the longitudinal asymmetry in proton-proton elastic scattering has been performed by Schiavilla et al. [22] and very recently by de Vries et al. [21]. In these papers, different realistic strong interaction Hamiltonians have been employed in conjunction with the parity-violating DDH potential. These calculations have been extended to the neutron-deuteron elastic scattering case in [23]. Parity violating effects, including neutron spin rotation and the longitudinal asymmetry, for n-p and n-d elastic scattering have been also carried out using hybrid model, i.e. combining realistic strong interaction Hamiltonians with pionless and pionic EFT weak currents in [24]. Lately, parity violation has also been explored for the case of neutron-deuteron radiative capture [25]. Parity-violation has also been studied in the four nucleon system, namely in the charge-exchange reaction $^3He(\vec{n},p)^3H$ at vanishing incident neutron energies by Viviani et al. [26]. In the last paper, a hybrid approach has also been employed; it used both a phenomenological and a chiral (two- and three-nucleon) strong-interaction potentials in combination with either the DDH or pionless EFT model for the weak-interaction potentials. It has been observed the dominance of the one-pion exchange for parity-violating observables in elastic neutron scattering on protons and deuterons. The matrix elements related to one-pion exchange contribution turned out to be independent on the strong nuclear Hamiltonian employed in calculating nuclear wave functions. Nevertheless, parity-violation in $^3He(\vec{n},p)^3H$, as well as in the radiative capture processes $p(n,\vec{\gamma})d$, $d(n,\vec{\gamma})^3H$, turned out to be much more sensitive to short-range part of the weak interactions and thus resulted in a sizeable model dependence of the corresponding matrix elements. It has been observed that the PV effects turn out to be of the same order of magnitude in 2, 3 and 4-nucleon systems.

Parity violation has been also studied in the neutron-proton system consistently using pionless EFT for strong and weak interaction potentials [27]. In the later papers of Griesshammer [28] and Vanasse [29], these calculations have been extended for the n-d elastic scattering case at very low incident neutron energies. The obtained results turned out to be consistent with the aforementioned phenomenological and hybrid approaches.

The general structure of the Time-reversal and parity violating two-nucleon interaction has been derived by Herczeg [30]. Realizing the importance of TPV interactions in generating nuclear Electric Dipole Moments (EDMs), several calculations have been performed for estimating matrix elements related to EDMs of deuteron [31–33, 35–37], triton, and ^3He [32, 35, 36]. Mostly hybrid approach has been employed, combining the realistic strong-interaction potentials with either the phenomenological weak-interaction potentials or potentials based on chiral-EFT [35, 36]. Nuclear EDMs, induced by the two-nucleon interactions, are in general of the same order of magnitude in three-nucleon system and in deuteron (except certain operators whose contribution for the deuteron is suppressed by the symmetry). The strong model dependence has also been observed for nuclear matrix elements which are related to pion-exchange contributions to nuclear EDMs [36].

The effects due to TPV weak interactions have also been studied for polarized neutron scattering on the polarized deuteron target [38]. In this case, TPV might be explored by analyzing either difference of the total neutron cross sections for the neutron spins (σ_n) elongated parallel and antiparallel to $\vec{p}_n \times \vec{I}$ axis, or the σ_n rotation angle around the $\vec{p}_n \times \vec{I}$ axis (see fig. 1).

The general structure of the parity conserving but time-reversal violating two-nucleon interaction has been derived in [30]. The TV effects related with this interaction have been calculated for low-energy neutron scattering on deuterons with tensor polarization by Song et al. [39]. In this case, either difference of the total cross section for the neutron spins elongated parallel and antiparallel to $\vec{p}_n \times \vec{I}(\vec{p}_n \cdot \vec{I})$ axis or the neutron spin rotation angle around the same axis should be analyzed (see fig. 1). It has been found that the TV effects turn out to be kinematically suppressed for thermal neutrons as compared to either PV or TPV ones, and kinematically enhanced for keV neutron energy region.

This extensive analysis of symmetry violations in few nucleon systems shows that different systems are sensitive to different mechanisms of fundamental symmetries violations. Therefore, they can be used as a test laboratory to study the Standard model and to search for new physics.

Acknowledgments: This work was supported by the DOE grants no. DE-FG02-09ER41621. This work was granted access to the HPC resources of IDRIS under the allocation 2009-i2009056006 made by GENCI (Grand Equipement National de Calcul Intensif). We thank the staff members of the IDRIS for their constant help.

References

[1] T. D. Lee et al., Phys. Rev. **104**, 822 (1956).
[2] J. H. Christenson et al., Phys. Rev. Lett. **13**, 138 (1964).
[3] A. D. Sakharov, JETP Lett **5** 32 (1967)
[4] G. Lüders, Math. Fysik. Medd. Kgl. Danske Akad. Ved. Vol. **28**, 5 (1954); J. S. Bell, Birmingham University thesis (1954).
[5] V. P. Gudkov, Phys. Rept. **212**, 77 (1992).
[6] B. R. Barrett et al., Prog. Part. Nucl. Phys. **69**, 131 (2013).
[7] E. Epelbaum et al., Rev. Mod. Phys. **81**, 1773 (2009).
[8] S. C. Pieper et al., Phys. Rev. **C 66**, 044310 (2002).
[9] G. Hagen et al., Phys. Rev. **C 82**, 034330 (2010).
[10] S. Bacca et al., arXiv1303.7446 (2013).
[11] W. N. Polyzou et al, Few-Body Systems **9**, 97 (1990).
[12] S. Kölling et. Phys. Rev. **C 80**, 045502 (2009).
[13] S. Pastore et al., Phys. Rev. **C 80**,034004 (2009).
[14] L. Girlanda, Phys. Rev. Lett. **105**, 232502 (2010).
[15] R. Lazauskas et al.,Phys. Rev. **C 83**, 034006 (2011).
[16] B. Desplanques et al.:, Ann. Phys. (N.Y.) **124**, 449 (1980).
[17] S.-L. Zhu, et al.:, Nucl. Phys. **A 748**, 435 (2005),
[18] L. Girlanda et al., Phys. Rev. **C 77**, 067001 (2008).
[19] W. C. Haxton and B. R. Holstein, Prog. Part. Nucl. Phys. **71**, 185 (2013).
[20] R. Schiavilla et al., Phys. Rev. **C 70**, 044007 (2004).
[21] J. de Vries et al., arXiv:1309.4711.
[22] J. Carlson et al., Phys. Rev. **C 65**, 035502 (2002).
[23] R. Schiavilla et al., Phys. Rev. **C78**, 014002 (2008); Erratum-ibid. **C83**, 029902 (2011).
[24] Y. H. Song et al., Phys. Rev. **C 83**, 015501 (2011).
[25] Y. H. Song et al, Phys. Rev. **C 86**, 045502 (2012).
[26] M. Viviani et al., Phys. Rev.**C 82**, 044001 (2010).
[27] D. R. Phillips et al., Nucl. Phys. **A 822** 1 (2009); M. R. Schindler et al., Nucl. Phys. **A 846**, 51 (2010); J.W. Shin et al., PRC 81 (2010) 055501;
[28] H. Griesshammer et al., Eur. Phys. Jour. **A 48**, 7 (2012).
[29] J. Vanasse, Phys. Rev.**C 86**, 014001 (2012).
[30] P. Herczeg, Nucl. Phys. **75**, 655 (1966).
[31] C. P. Liu et al., Phys. Rev. **C 70**, 055501 (2004).
[32] I. Stetcu et al., Phys. Lett. **B 665** , 168 (2008)
[33] I. R. Afnan et al., Phys. Rev. C 82 , 064002 (2010).
[34] C. Maekawa et al., Nucl. Phys. **A 872** , 117 (2011).
[35] J. de Vries et al., Phys. Rev. **C 84** , 065501 (2011).
[36] Y.H. Song et al., Phys. Rev. **C 87**, 015501 (2013).
[37] J. Bsaisou et al., Eur. Phys. Jour **A 9**, 31 (2013).
[38] Y.H. Song et al., Phys. Rev. **C 83**, 065503 (2011).
[39] Y.H. Song et al., Phys. Rev. **C 84**, 025501 (2011).