Cumhuriyet Science Journal
CSJ

e-ISSN: 2587-246X
ISSN: 2587-2680

Cumhuriyet Sci. J., Vol.38-4, Supplement (2017) 98-104

Investigation of the Nuclear Structure Properties of ^{60}Co via Phenomenological Approach

Ozan ARTUN

Faculty of Arts and Sciences, Department of Physics, Bülent Ecevit University, Zonguldak / TURKEY

Received: 12.09.2017; Accepted: 01.11.2017 *http://dx.doi.org/10.17776/csj.363311*

Abstract: In the present paper, the nuclear structure properties of ^{60}Co were investigated by using the Hartree-Fock method with Skyrme forces, such as the binding energy per particle, the root-mean-square (rms) nuclear charge, proton, neutron radii and charge, proton, neutron density distributions as a function of radius via HAFOMN code. The bulk and surface contributions to neutron skin thickness were analyzed by results obtained from proton and neutron density distributions. The calculated results were compared with the experimental results in the literature. Additionally, proton, neutron, deuteron, triton, he-3 and alpha separation energies of ^{60}Co were determined by Talys code. Because, these separation energies can be used for nuclear reaction, r-process and skin behavior of nuclei.

***Keywords*:** Nuclear structure, Skyrme force, Neutron skin thickness, Separation energy.

^{60}Co'ın Nükleer Yapı Özelliklerinin Fenemojiksel Yaklaşımlarla İncelenmesi

Özet: Bu çalışmada, ^{60}Co'ın nükleer yapı özellikleri olan parçacık başına bağlanma enerjileri, kare ortalama karekök (rms) yük, proton ve nötron yarıçapları, proton, nötron ve yük yoğunluk dağılımları yarıçapın bir fonksiyonu olarak HAFOMN kodu vasıtasıyla, Skyrme kuvvetli Hartree-Fock methodu kullanılarak araştırılmıştır. Nötron yüzey kalınlığına hacim ve yüzey katkıları, proton ve nötron yoğunluk dağılımlarından elde edilen sonuçlardan analiz edilmiştir. Hesaplanan sonuçlar literatürdeki deneysel sonuçlar ile karşılaştırılmıştır. İlaveten, ^{60}Co'ın proton, nötron, döteron, triton, he-3 ve alfa ayırma enerjileri Talys kodu ile belirlenmiştir. Çünkü, bu ayırma enerjileri çekirdeklerin yüzey davranışları, r-process ve nükleer reaksiyonlarda kullanılabilir.

Anahtar Kelimeler: Nükleer yapı, Skyrme kuvveti, Nötron yüzey kalınlığı, Ayırma enerjisi.

1. INTRODUCTION

The structure of the nucleus constitutes one of the fundamental aims of research in nuclear physics since the atomic nucleus is the building block of matter in the universe [1]. There are several phenomenological approaches for describing the ground-state properties of nuclei such as Hartree-Fock, which is one of the most important approaches used in nuclear structure calculations. The Hartree-Fock approach has been put forward to adjust many body problems as it figures out the many-electron problem via the one-electron problem with an effective potential between all the electrons [2]. The Hartree-Fock with Skyrme interaction approach, which is an effective density-dependent nucleon-nucleon force, enables the appropriate microscopic description of nuclear structure properties of nuclei such as binding

* Corresponding author. *Email address:* *ozanartun@yahoo.com*
http://dergipark.gov.tr/csj ©2016 Faculty of Science, Cumhuriyet University

energy of nucleus, the root mean square (rms) charge, proton and neutron radii, and density distribution of nucleus. In order to calculate these nuclear properties, there are various force parameters, S3, SKM, SKM*, SLy4, SLy5, SLy6, SLy7 and T3 in the literature [3-7]. These force parameters have certain input parameters based on the Skyrme formalization and the values of force parameters are widely given in Table 1 [3-5].

Table 1. Numerical values of Skyrme force parameters.

Parameters	Skyrme Forces							
	S3	SKM	SKM*	SLy4	SLy5	SLy6	SLy7	T3
t_0 (MeVfm^3)	-1128.75	-2645.00	-2645.00	-2488.91	-2483.45	-2479.5	-2482.41	-1791.80
t_1 (MeVfm^5)	395.00	385.00	410.00	486.82	484.23	462.18	457.97	298.50
t_2 (MeVfm^5)	-95.00	-120.00	-135.00	-546.39	-556.69	-448.61	-419.85	-99.50
t_3 (MeVfm^3)	14000	15595	15595	13777	13757	13673	13677	12794
t_4 (MeVfm^5)	120	130	130	123	125	122	126	126
x_0	0.450	0.09	0.090	0.834	0.834	0.825	0.846	0.138
x_1	0.000	0.000	0.000	-0.344	-0.317	-0.465	-0.511	-1.000
x_2	0.00	0.00	0.00	-1.00	-1.00	-1.00	-1.00	1.00
x_3	1.000	0.000	0.000	1.354	1.263	1.355	1.391	0.075
α	1	1/6	1/6	1/6	1/6	1/6	1/6	1/3

The major goal of this paper is to investigate nuclear structure calculations of ^{60}Co with different Skyrme force parameters. Since ^{60}Co is effectively used in radiotherapy as a gamma source in nuclear medicine [8-11], it has a potential in radioisotope power systems (RPS) [12-14] as a beta energy source (β^-_{max} =0.318 MeV) [15,16] with suitable shielding [16]. However, in the literature, there is a lack of studies on the theoretical and experimental nuclear structure properties of ^{60}Co. We, therefore, used the Hartree-Fock method with Skyrme S3, SKM, SKM*, SLy4, SLy5, SLy6, SLy7 and T3 forces via HAFOMN code [17] to widely provide nuclear data of ^{60}Co. For this purpose, the binding energy per particle, the rms charge, proton, neutron radii, the charge, proton and neutron density distributions, the neutron skin thickness and the separation energies of ^{60}Co have been calculated for each Skyrme force.

2. THEORY

To determine the nuclear structure properties of ^{60}Co, we have utilized HAFOMN code using harmonic oscillator wave function for different Skyrme forces: S3, SKM, SKM*, SLy4, SLy5, SLy6, SLy7 and T3. These phenomenological Skyrme forces mainly make up two-body and three-body term dependent on momentum and density, respectively. However, for the three-body, Skyrme force is hypothesized to be a zero range:

$$V_{Skyrme} = \sum_{i<j} V_{ij}^{(2)} + \sum_{i<j<k} V_{ijk}^{(3)} \quad (1)$$

$$V_{ijk}^{(3)} \cong V_{ij} = \frac{1}{6} t_3 (1 + x_3 P_\sigma) \delta(\vec{r}_i - \vec{r}_j) \rho^\alpha \left(\frac{\vec{r}_i + \vec{r}_j}{2} \right) \quad (2)$$

Based on the parameters, the two-body and three-body terms as a single form are given by [18-21]

$$V_{Skyrme} = \sum_{i<j} V_{ij} = t_0(1+x_0P_\sigma)\delta(\vec{r_i}-\vec{r_j}) + \frac{1}{2}t_1(1+x_1P_\sigma)\left\{\delta(\vec{r_i}-\vec{r_j})\vec{k}^2 + \vec{k_i}'^2\delta(\vec{r_i}-\vec{r_j})\right\} + t_2(1+x_2P_\sigma)\vec{k}'\delta(\vec{r_i}-\vec{r_j})\vec{k} + it_4(\vec{\sigma_i}+\vec{\sigma_j}).\vec{k}' \times (\vec{r_i}-\vec{r_j})\vec{k} + \frac{1}{6}t_3(1+x_3P_\sigma)\delta(\vec{r_i}-\vec{r_j})\rho^\alpha \quad (3)$$

The values of force parameters in Eqs. (1), (2) and (3) are clearly given in Table 1. P_σ, $\vec{k}$, ρ, σ and $\delta(r)$ represent the space exchange operator, relative momentum, density, vector of Pauli spin matrices, and delta function, respectively.

In order to calculate the nuclear structure properties of ^{60}Co, the density formulas are given by

$$r_q = \langle r_q^2 \rangle^{1/2} = \left[\frac{\int \vec{r}^2\rho_q(\vec{r})d^3\vec{r}}{\int \rho_q(\vec{r})d^3\vec{r}}\right]^{1/2} \quad (4)$$

where, q represents proton, neutron or charge. ρ_q is density, but the neutron or proton densities are different from the charge density due to nucleons having an intrinsic electromagnetic structure.

i) For the proton and neutron densities:

$$\rho_q(\vec{r}) = \sum_{\beta\epsilon q} \omega_\beta \varphi_\beta^+(\vec{r})\varphi_\beta(\vec{r}) \quad (5)$$

ii) For the charge density:

$$\rho_q(\vec{r}) = \frac{1}{2\pi^2}\int k^2 j_0(kr)\, F_{ch}(k)dk \quad (6)$$

where, $\varphi(\vec{r})$ is the wave function, ω represents occupation probability, $F_{ch}(k)$ is the charge form factor, and j represents the spherical Bessel function [22-24]. The neutron skin thickness (NST) having another nuclear structure property via the bulk and surface contributions can be calculated by the following equation [25]:

$$\Delta r_{np} = \Delta r_{np}^{bulk} + \Delta r_{np}^{surf} \quad (7)$$

The bulk contribution to NST can be written as

$$\Delta r_{np}^{bulk} \cong \sqrt{\frac{3}{5}}\left[(C_n - C_p) + \frac{\pi^2}{3}\left(\frac{a_n^2}{C_n} - \frac{a_p^2}{C_p}\right)\right]. \quad (8)$$

The surface contribution of NST:

$$\Delta r_{np}^{surf} \cong \sqrt{\frac{3}{5}}\frac{5\pi^2}{6}\left(\frac{a_n^2}{C_n} - \frac{a_p^2}{C_p}\right) \quad (9)$$

where, a and C parameters are the half-density radius and the surface diffuseness. We have determined C_n, C_p, a_n and a_p parameters from proton and neutron distributions given in Figure 1 for each force parameter.

Furthermore, for the neutron (S_n), proton (S_p), deuteron (S_d), triton (S_t), he-3 (S_{He-3}) and alpha (S_α), the separation energies of nuclei are also quite important in halo and skin behaviors of nuclei, and in r-process [6, 26-28]. Therefore, we calculated separation energies of ^{60}Co by Talys code [29].

3. RESULTS AND DISCUSSION

The calculated binding energies per particle, neutron skin thickness, the rms charge, proton and neutron density radii for S3, SKM, SKM*, SLy4, SLy5, SLy6, SLy7 and T3 force parameters are presented in Table 2 and the calculated binding energies are compared with the experimental value. However, for the experimental radii in literature, there is a lack of nuclear structure properties of ^{60}Co nucleus used in RPS technology as an energy source and in cancer therapy as radiation source. The calculated results of binding energies per particle of ^{60}Co are in the energy range of 8.5570 - 8.8054 MeV. The findings for the SLy6 parameter are consistent with the experimental result. SKM and SLy7 parameters are close to experimental results [30] relative to other parameters. If the charge density radii are taken into account, S3 force parameter has the highest charge, proton, neutron density radii, however, it is the contrary for the SKM parameter. Besides, in the S3 parameter, the

neutron skin thickness is less compared to that of the other parameters. The surface and bulk contributions to NST analyzed for all force parameters are given in Table 2. It is clear that NST values generally lie between 0.32 fm and 0.39 fm, except for S3 and SLy4. It is known that the surface contributions to NST for all force parameters are bigger than the bulk contributions.

Table 2. Calculated some nuclear properties of ^{60}Co.

Forces	Binding energies per particle (MeV)	Rms charge density radii (fm)	Rms proton density radii (fm)	Rms neutron density radii (fm)	Bulk contribution to NST (fm)	Surface contribution to NST (fm)	Neutron skin thickness (NST) (fm)
S3	8.5570	3.845	3.756	3.825	0.0665	0.1081	0.1746
SKM	8.7996	3.788	3.700	3.792	0.0417	0.3193	0.3610
SKM*	8.6283	3.810	3.721	3.812	0.0373	0.3527	0.3900
SLy4	8.6350	3.817	3.728	3.819	0.0659	0.3798	0.4457
SLy5	8.6094	3.801	3.713	3.825	0.0462	0.2975	0.3437
SLy6	8.7464	3.805	3.717	3.807	0.0386	0.2844	0.3230
SLy7	8.8054	3.803	3.714	3.804	0.0308	0.3230	0.3538
T3	8.6528	3.790	3.701	3.797	0.0994	0.2484	0.3478
Exp.	8.7470	-	-	-	-	-	-

The proton, neutron and charge density distributions are calculated by S3, T3, SKM, SKM*, SLy4, SLy5, SLy6 and SLy7 force parameters in the Hartree-Fock method (Figure 1). It is obvious that the neutron density distributions are generally higher than the charge and proton density values between r=0 fm and r=3 fm. In addition, in the region of r=0-3 fm, the density distributions are in the form of hump. After this region, the densities decrease up to r=6 fm, and the proton, neutron and charge densities approach to zero between r=6.5 fm and r=7 fm. SLy5 and SLy4 parameters for the proton and charge densities at the center (r=0) have the highest density values of ρ_p =0.0905 fm^{-3} (SLy5), ρ_c =0.0844 fm^{-3}(SLy5), and ρ_p =0.0913 fm^{-3} (SLy4), ρ_c =0.0842 fm^{-3}(SLy4), compared to the other parameters. However, in neutron density, SLy5 parameter together with S3 parameter at r=0 fm have lower values (ρ_n =0.0849 fm^{-3} and ρ_n =0.0838 fm^{-3}). All the Skyrme force parameters for the densities of proton, neutron and charge are consistent with each other beyond r=3.7 fm. On the other hand, S3 parameter has the lowest value for the proton (ρ_p =0.75 fm^{-3}), neutron (ρ_n = 0.84 fm^{-3}) and charge (ρ_c =0.72 fm^{-3}) density values.

Moreover, the neutron, proton, deuteron, triton, he-3 and alpha separation energies of ^{60}Co are calculated by the Talys code and are presented in Figure 2 as bars. It is clearly shown that while the S_{he-3} and S_t have the highest separation energies, i.e., 19.09479 (MeV) and 16.41833 (MeV), respectively, the minimum separation energies are determined for S_α and S_n as 7.16379 MeV and 7.49192 MeV.

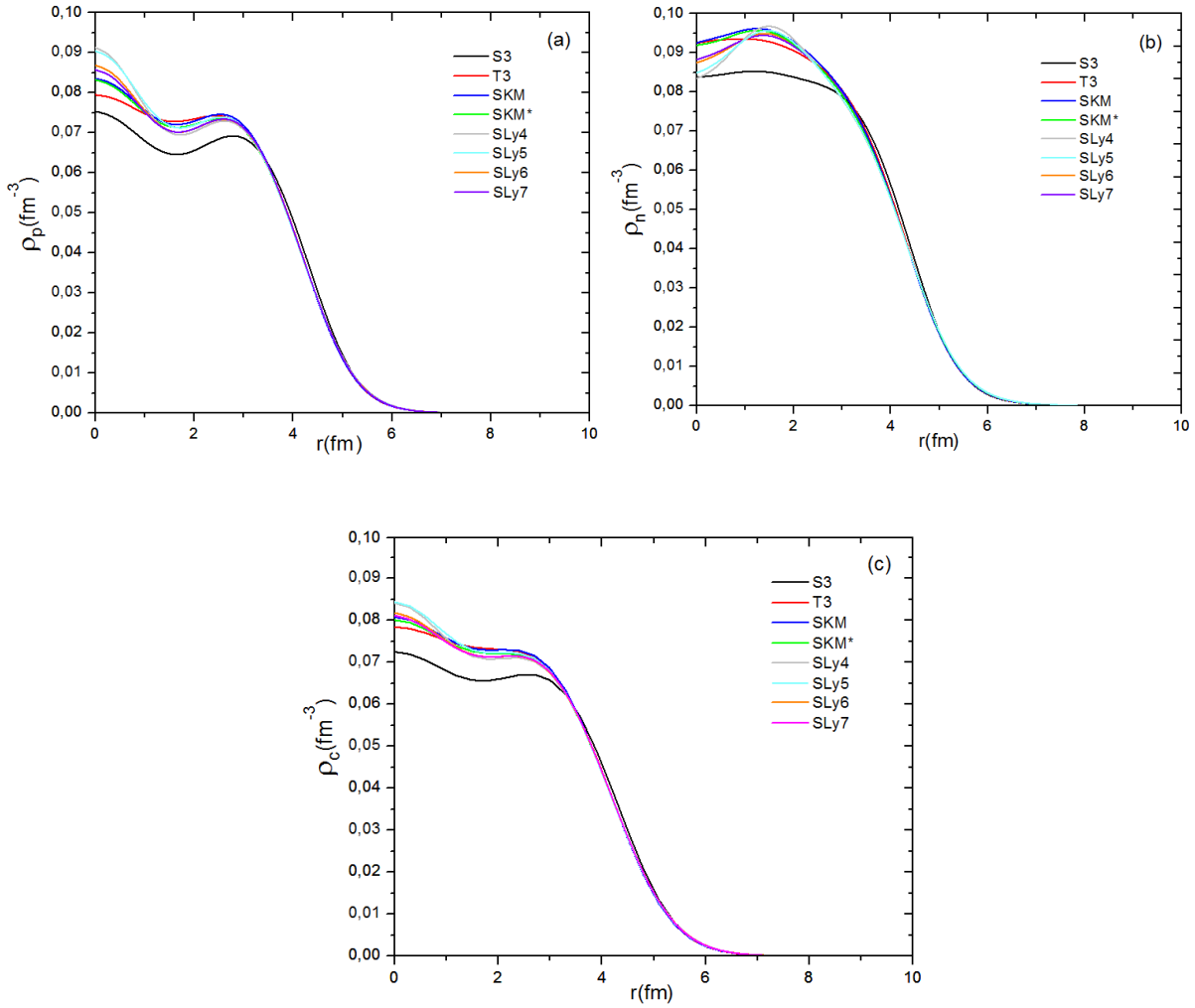

Figure 1. Calculated proton, neutron and charge density distributions for cobalt-60 with Skyrme force parameters.

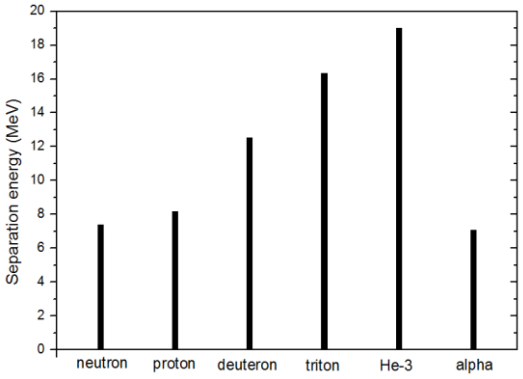

Figure 2. Neutron, proton, deuteron, triton, he-3 and alpha separation energies of cobalt-60.

4. CONCLUSIONS

The binding energy per particle, the rms proton, neutron and charge radii, neutron, proton and charge density distributions, bulk and surface contributions to NST have been calculated for ^{60}Co nucleus, which is important in nuclear medicine as a gamma source and in RPS as a beta source. The Hartree-Fock method was used for the calculations along with an effective Skyrme force with S3, SKM, SKM*, SLy4, SLy5, SLy6, SLy7 and T3 parameter to extend nuclear data of ^{60}Co.

NST values have been severally determined by the proton and neutron density distributions for the

bulk and the surface contributions. The main contribution to NST comes from the part of surface, and the average NST value is determined as 0.342 fm. The bulk and surface parts of NST can be used for better understanding the skin structure of ^{60}Co nucleus because it is known that deviations of the NST from the average trend are indications of the nuclear deformation and there is a lack of sufficient literature for ^{60}Co. To overcome these deficiencies, the best S_n, S_p, S_d, S_t, S_{he-3} and S_α separation energy values used in nuclear reactions, skin behavior of nuclei and r-process in literature have been analyzed by Talys code.

REFERENCES

[1]. Asai M., Heßberger F.P., Martensd A.L. Nuclear structure of elements with 100≤Z≤10 from alpha spectroscopy. Nucl Phys A 2015; 944: 308-32.

[2]. Sheikh J.A., Ring P. Symmetry-projected Hartree-Fock-Bogoliubov equations. Nucl Phys A 2000; 665(1): 71-91.

[3]. Reinhard P.G., Flocard H. Nuclear effective forces and isotope shifts. Nucl Phys A 1995; 584: 467-88.

[4]. Chabanat E., Bonche P., Haensel P., Meyer J., Schaeffer R. A Skyrme parametrization from subnuclear to neutron star densities. Nucl Phys A 1997; 627: 710-46.

[5]. Chabanat E., Bonche P., Haensel P., Meyer J., Schaeffer R. A Skyrme parametrization from subnuclear to neutron star densities Part II. Nuclei far from stabilities. Nucl Phys A 1998; 635: 231-56.

[6]. Artun O., Aytekin C., Aytekin H. An investigation of nuclear properties ofeven even natural 92–100Mo isotopes. Mod Phys Lett A 2014; 29(39): 1450208-11

[7]. Aytekin H., Artun O. An investigation of the nuclear structures of even-even neutron-rich Sr, Zr and Mo isotopes. Mod Phys Lett A 2013; 28(5): 1350007-11.

[8]. Wooten H.O., Rodriguez V., Green O., Kashani R., Santanam L., Tanderup K., Mutic S., Li H.H. Radiother Oncol 2015; 114(3): 402-5.

[9]. Hung T.V., Khac T.A. Dose mapping using MCNP code and experiment for SVST-Co-60/B irradiator in Vietnam. Appl Radiat Isot 2010; 68: 1104-7.

[10]. Mutic S., Dempsey J.F. The ViewRay system: magnetic resonance-guided and controlled radiotherapy. Semin Radiat Oncol 2014; 24: 196-9.

[11]. Yong J.S., Ung N.M., Jamalludin Z., Malik R.A., Wong J.H.D., Liew Y.M., Ng K.H. Dosimetric impact of applicator displacement during high dose rate (HDR) Cobalt-60 brachytherapy for cervical cancer: A planning study. Radiat Phys and Chem 2016; 119: 264-71.

[12]. Lange R.G., Carroll W.P. Review of recent advances of radioisotope power systems. Energy Convers Manage 2008; 49(3): 393-01.

[13]. Bennett G.L. Mission interplanetary: Using radioisotope power to explore the solar system. Energy Convers Manage 2008; 49: 382-92.

[14]. National Research Council Radioisotope Power Systems. Radioisotope Power Systems: An Imperative for Maintaining U.S. Leadership in Space Exploration. Washington, DC: The National Academies Press., USA, 2009.

[15]. Prelas M.A., Weaver C.L., Watermann M.L., Lukosi E.D., Schott R.J., Wisniewski D.A. A review of nuclear batteries. Prog Nucl Energy 2014; 75: 117-48.

[16]. Doherty B.J. Design of a cobalt-60 fueled thermionic power supply. Department of Physics, Massachusetts Institute of Technology, Master Thesis, Massachusetts, USA, 1969; 1-80. Adres: https://calhoun.nps.edu/handle/10945/11956

[17]. Aytekin H., Baldik R., Tel E. Calculation of the Ground State Properties of Even–Even Sn Isotopes. Phys Atomic Nucl 2010; 73(6): 922-6.

[18]. Skyrme T.H.R. The nuclear surface. Philos Mag 1956; 1: 1043-54.

[19]. Skryme T.H.R. The effective nuclear potential. Nucl Phys 1959; 9: 615-34.

[20].Lingxiao G., Yizhong Z., Nörenberg W. Temperature-dependent optical potential and mean free path based on skyrme interactions. Nucl Phys A 1986; 459: 77-92.

[21].Vautherin D., Brink D.M. Hartree-Fock Calculations with Skyrme's Interaction. I. Spherical Nuclei. Phys Rev C 1972; 5: 626-47.

[22].Bennaceur K., Dobaczewski J. Coordinate-space solution of the Skyrme–Hartree–Fock–Bogolyubov equations within spherical symmetry. The program HFBRAD (v1.00). Comput Phys Commun 2005; 168: 96-122.

[23].Reinhard P.G., Grummer F., Goeke K.Z. A comparative study of mass parameters and linear response in three-dimensional grids. Z. Phys A 1984; 317(3): 339-46.

[24].Dreher B., Friedrich J., Merle K., Rothhaas H., Lührs G. The determination of the nuclear ground state and transition charge density from measured electron scattering data. Nucl Phys A 1974; 235: 219-48.

[25].Warda M., Centelles M., Viñas X., Maza X. R. Influence of the single-particle structure on the nuclear surface and the neutron skin. Phys Rew C 2014; 89(6): 064302

[26].Artun O. Investigation of the production of promethium-147 via particle accelerator. Indian J Phys 2017; 91(8): 909-914.

[27].Artun O. A study of nuclear structure for 244Cm, 241Am, 238Pu, 210Po, 147Pm, 137Cs, 90Sr and 63Ni nuclei used in nuclear battery. Mod Phys Lett A 2017; 32: 1750117.

[28].Artun O. Estimation of the production of medical Ac-225 on thorium material viaproton accelerator. Appl Radiat Isot 2017; 127: 166-72.

[29].Koning A., Hilaire S., Goriely S. Talys 1.8, User Manual, 2015. Adres: http://www.talys.eu/fileadmin/talys/user/docs/talys1.8.pdf

[30].Audi G., Wapstra A.H., Thibault C. The Ame2003 atomic mass evaluation: (II). Tables, graphs and references. Nucl Phys A 2003; 729: 337-676.