LIST OF PUBLICATIONS 2019 – 2023

ARTICLES

1. M. Thürauf, **Ch. STOYANOV**, M. Scheck, M. Jentschel, C. Bernards, A. Blanc, N. Cooper, G. De France, E. T. Gregor, C. Henrich, S. F. Hicks, J. Jolie, O. Kaleja, U. Köster, T. Kröll, R. Leguillon, P. Mutti, D. O Donnell, C. M. Petrache, G. S. Simpson, J. F. Smith, T. Soldner, M. Tezgel, W. Urban, J. Vanhoy, M. Werner, V. Werner, K. O. Zell, and T. Zerrouki

Low-lying octupole isovector excitation in 144Nd

PHYSICAL REVIEW C 99, 011304(R) (2019)

PHYSICAL REVIEW C 99, 011304(R) (2019)

Rapid Communications

Low-lying octupole isovector excitation in ^{144}Nd

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The nature of low-lying 3^- levels in ^{144}Nd was investigated in the ^{143}Nd$(n,\gamma\gamma)$ cold neutron-capture reaction. The combination of the high neutron flux from the research reactor at the Institut Laue-Langevin and the high γ-ray detection efficiency of the EXILL setup allowed the recording of $\gamma\gamma$ coincidences. From the coincidence data precise branching ratios were extracted. Furthermore, the octagonal symmetry of the setup allowed angular-distribution measurements to determine multipole-mixing ratios. Additionally, in a second measurement the ultra-high resolution spectrometer GAMS6 was employed to conduct lifetime measurements using the gamma-ray induced Doppler-shift technique (GRID). The confirmed strong $M1$ component in the $3^-_5 \rightarrow 3^-_1$ decay strongly supports the assignment of the 3^-_5 level at 2779 keV as low-lying isovector octupole excitation. Microscopic calculations within the quasiparticle phonon model confirm an isovector component in the wave function of the 3^-_5 level, firmly establishing this fundamental mode of nuclear excitation in near-spherical nuclei.

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Recently, with the observations of strong $B(E3, 0^+ \rightarrow 3^-)$ reduced transition probabilities for ^{220}Rn, but in particular for ^{224}Ra [1], the nuclear octupole degree of freedom has experienced a renaissance. The observed strong $B(E3)$ value for ^{224}Ra suggests octupole correlations in the ground state, which are in interplay with the quadrupole deformation predicted to enhance a possible *CP*-violating nuclear Schiff moment (e.g., see Refs. [2,3] and references therein). In order to predict this enhancement and the subsequent gain of sensitivity of experiments using strongly octupole-correlated nuclei in the search for *CP* violation, a complete understanding of the octupole degree of freedom is mandatory.

At present, for the octupole degree of freedom one of the missing pieces of information is the strength of the isovector coupling constant (ICC) for the proton-neutron part of the octupole-octupole residual interaction. In the nucleus, proton and neutron excitations are distinguished by the isospin degree of freedom. Properties of collective levels with an isovector character, for which in the complex wave function of the collective excitation at least one component of a subsystem is out of phase relative to the other components, are very sensitive to the strength of the residual proton-neutron interaction [4,5]. In the ideal case of equal proton and neutron components, the isoscalar wave function is symmetric under the exchange of protons and neutrons, while the isovector wave function is antisymmetric. Due to the general attractive nature of the proton-neutron interaction, the isovector level is found at higher energy, while the isoscalar excitation is lowered in energy. The isoscalar excitation, for which all components of the wave function are in phase, is usually the lowest-lying state for a given spin and parity. However, in order to reliably fit the ICC, a systematic identification of the isovector levels in several nuclei is mandatory.

Examples of well-established, low-lying isovector excitations are the 1^+ nuclear scissors mode in deformed or the 2^+ quadrupole mixed-symmetry state in near-spherical nuclei. Since its original discovery in 1984 in ^{156}Gd [6], the scissors mode [5] continues to be the subject of intense research

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2. Alan A. Dzhioev A. I. Vdovin, and **Ch. STOYANOV**

Thermal quasiparticle random-phase approximation calculations of stellar electron capture rates with the Skyrme effective interaction

PHYSICAL REVIEW C 100, 025801 (2019)

PHYSICAL REVIEW C **100**, 025801 (2019)

Thermal quasiparticle random-phase approximation calculations of stellar electron capture rates with the Skyrme effective interaction

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A microscopic thermodynamically consistent approach is applied to compute electron capture (EC) rates and cross sections on nuclei in hot stellar environments. The cross-section calculations are based on the Donnelly-Walecka multipole expansion method for treatment of semileptonic processes in nuclei. To take into account thermal effects, we express the electron capture cross section in terms of temperature- and momentum-dependent spectral functions for respective multipole charge-changing operators. The spectral functions are computed by employing the self-consistent thermal quasiparticle random-phase approximation (TQRPA) with the Skyrme effective interaction. Three different Skyrme parametrizations (SkM*, SGII, and SLy4) are used to investigate thermal effects on EC for ^{56}Fe and ^{78}Ni. For ^{56}Fe, the impact of thermally unblocked Gamow-Teller GT$_+$ transitions on EC is discussed and the results are compared with those from shell-model calculations. In particular, it is shown that for some temperature and density regimes the TQRPA rates exceed the shell-model rates due to violation of the Brink-Axel hypothesis within the TQRPA. For neutron-rich ^{78}Ni, the full momentum dependence of multipole transition operators is considered and it is found that not only thermally unblocked allowed 1^+ transitions but also thermally unblocked first-forbidden 1^- and 2^- transitions favor EC.

DOI: 10.1103/PhysRevC.100.025801

I. INTRODUCTION

The knowledge of low-energy nuclear weak-interaction-mediated processes is crucial for understanding the late stage of massive stars' evolution [1,2]. Among them, electron capture strongly influences the precollapse stage as well as the gravitational collapse of the iron core, leading to the supernova explosion. The collapse starts when the core exceeds the Chandrasekhar limit and electrons begin to be captured by iron-group nuclei. As electrons dominate the matter pressure, the depletion of the electron population due to capture by nuclei is a crucial factor determining the initial collapse phase. Until the core reaches densities of $\rho \approx 10^{11}$ g cm^{-3}, neutrinos produced by these reactions leave the star practically unhindered, cooling the core and reducing its entropy. Moreover, the electron capture (EC) rates strongly determine the electron-to-baryon ratio Y_e in a way that directly influences the collapse dynamics and the fate of the shock wave formed by the supernova explosion. So, the nuclear electron capture is one of the most essential ingredients involved in the complex dynamics of core-collapse supernova, and reliable estimates of EC rates are crucial for better understanding of the explosion mechanism.

The determination of stellar EC rates is a challenging nuclear structure problem. First of all, because of the low entropy in the core and the neutron-rich conditions, very neutron-rich nuclei may be produced with abundance several orders of magnitude larger than that of free protons. Usually, only theoretical weak interaction rates for such nuclei are available. Additionally, in high-temperature stellar environments, the total EC rate is given by a sum of individual contributions λ_i from thermally excited states:

$$\lambda(T) = \sum_i p_i(T)\lambda_i, \qquad (1)$$

where $p_i(T)$ is the Boltzmann population factor for a parent state with energy E_i at temperature T. The contributions from excited states remove the reaction threshold and at high temperatures they dominate the EC rate. However, the calculation of specific contributions λ_i is a problem whose complexity grows considerably with temperature and for $T \approx 1$ MeV the state-by-state evolution of individual contributions becomes computationally infeasible because of too many thermally populated states.

The first set of EC rates in stellar matter has been computed and published for *sd*- and *pf*-shell nuclei by Fuller *et al.* [3–6], employing the independent particle model. The calculations were based on the idea by Bethe *et al.* [7], who first recognized the key role played by the Gamow-Teller (GT) resonance in stellar weak processes. With the improvement of nuclear structure models and computer algorithms, large-scale shell-model (LSSM) calculations have become possible for *pf*-shell nuclei. Their results on GT strength distributions for iron-group nuclei agreed quite well with experimental data [8]. In Refs. [9,10], detailed shell-model calculations of the

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3. Alan A. Dzhioev , K. Langanke, G. Martínez-Pinedo, A. I. Vdovin, and **Ch. STOYANOV**

Unblocking of stellar electron capture for neutron-rich N = 50 nuclei at finite temperature

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PHYSICAL REVIEW C **101**, 025805 (2020)

Unblocking of stellar electron capture for neutron-rich $N = 50$ nuclei at finite temperature

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We have calculated electron-capture rates for neutron-rich $N = 50$ nuclei (^{78}Ni, ^{82}Ge, ^{86}Kr, ^{88}Sr) within the thermal quasiparticle random-phase approximation approach at temperatures $T = 0$, corresponding to capture on the ground state, and at $T = 10$ GK (0.86 MeV), which is a typical temperature at which the $N = 50$ nuclei are abundant during a supernova collapse. In agreement with recent experiments, we find no Gamow-Teller (GT$_+$) strength at low excitation energies, $E < 7$ MeV, caused by Pauli blocking induced by the $N = 50$ shell gap. At the astrophysically relevant temperatures, this Pauli blocking of the GT$_+$ strength is overcome by thermal excitations across the $Z = 40$ proton and $N = 50$ neutron shell gaps, leading to a sizable GT contribution to the electron capture. At the high densities, at which the $N = 50$ nuclei are important for stellar electron capture, forbidden transitions contribute noticeably to the capture rate. Our results indicate that the neutron-rich $N = 50$ nuclei do not serve as an obstacle of electron capture during supernova collapse.

DOI: 10.1103/PhysRevC.101.025805

I. INTRODUCTION

Electron captures on nuclei play an essential role during the collapse of a massive star leading to a type-II or core-collapse supernova [1–4]. It reduces the electron-to-baryon ratio Y_e and hence the pressure which the relativistic degenerate electron gas can stem against the gravitational collapse. As the neutrinos produced by the capture process can leave the star, carrying away energy, it is also an effective cooling mechanism, resulting in the fact that heavy nuclei survive during the collapse [1]. The temperature in the collapsing core is sufficiently high that nuclei exist in nuclear statistical equilibrium (NSE) [5]. However, due to the decrease of Y_e by continuous electron capture, the abundance distribution of nuclei is shifted to more neutron-rich and heavier nuclei during the collapse.

Due to the electron energies involved, electron captures are dominated by allowed Gamow-Teller (GT$_+$) transitions (in which a proton is changed to a neutron) at the early stage of the collapse. However, forbidden transitions become increasingly important with growing electron energies and contribute significantly to the capture rates in the later collapse phases [6,7]. For core densities, $\rho \lesssim 10^{10}$ g cm^{-3} and the respective temperatures the core composition of nuclei is given by *pf* shell nuclei in the iron-nickel mass region. For these nuclei, electron capture rates can be calculated on the basis of large-scale shell-model diagonalization calculations [8–10]. The calculations reproduce the GT$_+$ distributions experimentally determined by charge-exchange reactions [11,12] quite well [13–15]. These rates are significantly smaller than the pioneering rates by Fuller *et al.* [16], resulting in a slower deleptonization in the early collapse phase [17,18].

As noted by Fuller [19], the continuous shift of the NSE abundance distribution to heavier and more neutron-rich nuclei can lead to a potential blocking of the GT$_+$ strength, once nuclei with proton numbers $Z < 40$ and neutron numbers $N > 40$ dominate the core composition. For such nuclei, GT$_+$ transitions are completely Pauli blocked within the simple independent-particle model. Based on this observation, Bruenn derived stellar capture rates which predicted vanishing capture rates for nuclei with $N > 38$ [20]. These capture rates have been the standard in supernova simulations for many years and led to the conclusion that electron capture proceeds on free protons in the advanced collapse phases (see, e.g., Ref. [2]). Cooperstein and Wambach pointed out that the Pauli blocking might be overcome by thermal excitations, but which would only happen at core densities in excess of 10^{11} g cm^{-3} [6]. However, the $N = 40$ shell closure is overcome by cross-shell correlations which move neutrons and protons into the $g_{9/2}$ orbital and hence open up GT$_+$ transitions. Experimentally this is observed for ^{76}Se ($Z = 34$, $N = 42$) which has a nonvanishing GT$_+$ strength distribution (required for the double-beta decay of ^{76}Ge [12,21]), made possible by a sizable neutron-hole structure in the *pf* shell as determined from transfer reactions [22]. The experimental GT$_+$ distribution is well described by shell-model diagonalization studies [23] confirming that cross-shell correlations require multiparticle-multihole correlations [24,25]. For stellar electron-capture rates, these correlations have been considered within a hybrid

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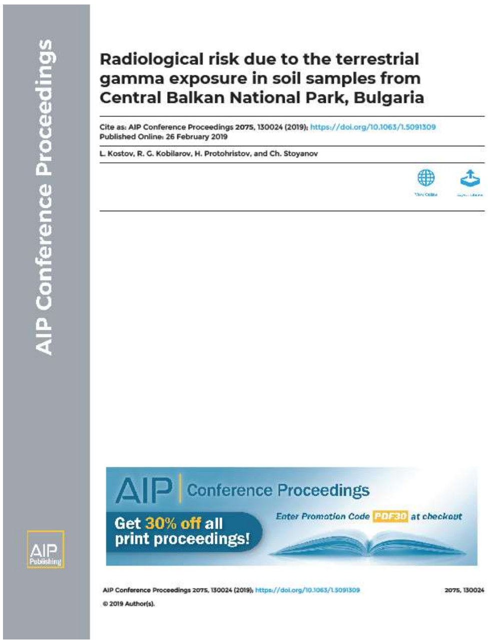
INVITED TALKS ON THE INTERNATIONAL MEETINGS AND SCHOOLS

1. L. Kostov, R. G. Kobilarov, H. Protohristov, and **STOYANOV, Ch.**

Radiological Risk Due to the Terrestrial Gamma Exposure in Soil Samples from Central Balkan National Park, Bulgaria.

AIP Conference Proceedings 2075, 130024 (2019);
https://doi.org/10.1063/1.5091309

10th Jubilee International Conference of the Balkan Physical Union



AIP Conference Proceedings

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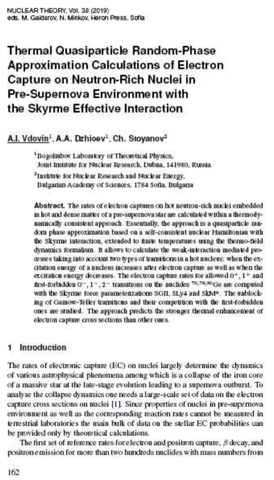
AIP Conference Proceedings 2075, 130024 (2019); https://doi.org/10.1063/1.5091309 2075, 130024

2. A.I. Vdovin, A.A. Dzhioev, **STOYANOV, Ch**

Thermal Quasiparticle Random-Phase Approximation Calculations of Electron Capture on Neutron-Rich Nuclei in Pre-Supernova Environment with the Skyrme Effective Interaction.

NUCLEAR THEORY, Vol. 38 (2019)pp 162 - 171
eds. M. Gaidarov, N. Minkov, Heron Press, Sofia



NUCLEAR THEORY, Vol. 38 (2019)
eds. M. Gaidarov, N. Minkov, Heron Press, Sofia

Thermal Quasiparticle Random-Phase Approximation Calculations of Electron Capture on Neutron-Rich Nuclei in Pre-Supernova Environment with the Skyrme Effective Interaction

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Abstract. The rates of electron captures on hot neutron-rich nuclei embedded in hot and dense matter of a pre-supernova star are calculated within a thermodynamically consistent approach. Essentially, the approach is a quasiparticle random phase approximation based on a self-consistent nuclear Hamiltonian with the Skyrme interaction, extended to finite temperatures using the thermo-field dynamics formalism. It allows to calculate the weak-interaction mediated processes taking into account two types of transitions in a hot nucleus: when the excitation energy of a nucleus increases after electron capture as well as when the excitation energy decreases. The electron capture rates for allowed 0^+, 1^+ and first-forbidden 0^-, 1^-, 2^- transitions on the nuclides ^{76,78,80}Ge are computed with the Skyrme force parameterizations SGII, SLy4 and SkM*. The unblocking of Gamow-Teller transitions and their competition with the first-forbidden ones are studied. The approach predicts the stronger thermal enhancement of electron capture cross sections than other ones.

1 Introduction

The rates of electronic capture (EC) on nuclei largely determine the dynamics of various astrophysical phenomena among which is a collapse of the iron core of a massive star at the late-stage evolution leading to a supernova outburst. To analyse the collapse dynamics one needs a large-scale set of data on the electron capture cross sections on nuclei [1]. Since properties of nuclei in pre-supernova environment as well as the corresponding reaction rates cannot be measured in terrestrial laboratories the main bulk of data on the stellar EC probabilities can be provided only by theoretical calculations.

The first set of reference rates for electron and positron capture, β decay, and positron emission for more than two hundreds nuclides with mass numbers from

3. P.K. Zhivkov, **STOYANOV, Ch**, S.I. Tyutyunnikov

Neutron induced reactions in massive spallation targets

Journal of Physics: Conference Series 1555 (2020) 012034 IOP Publishing

Journal of Physics: Conference Series

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Neutron induced reactions in massive spallation targets

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Papers in scientific journals for large audience

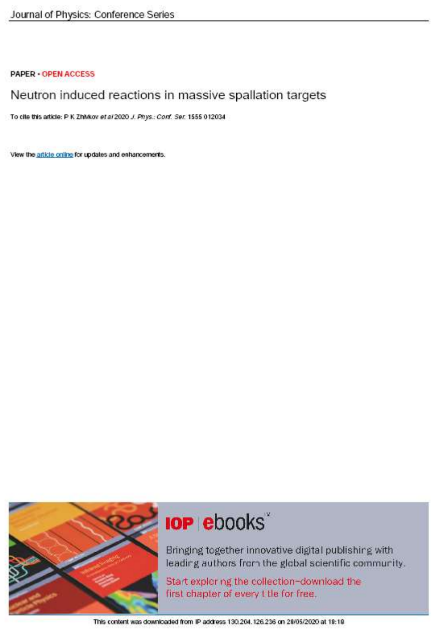
i. Nauka (SCIENCE) Journal of the Union of Scientists in Bulgaria

1. **Chavdar Stoyanov**, Hristo Protohristov

Nuclear Physics at BAS   Results and Perspectives

Nauka 4, (2019) pp 88-95

ISSN 0861 3362, ISSN 2603-3623



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Neutron induced reactions in massive spallation targets

To cite this article: P K Zhivkov *et al* 2020 *J. Phys.: Conf. Ser.* 1555 012034

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2. Lachezar Kostov, **Chavdar Stoyanov**

THE JOINT INSTITUTE FOR NUCLEAR RESEARCH (JINR) IN DUBNA - 65TH ANNIVERSARY OF THE FOUNDATION

Nauka 6, (2021) pp 72-76

2021: the Year
of Bulgaria in JINR

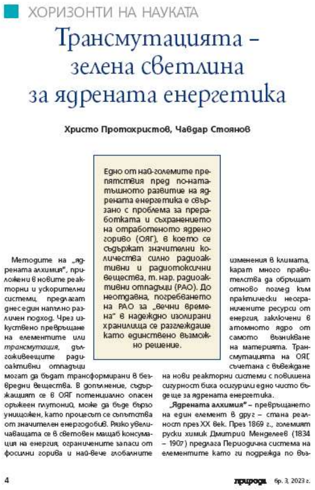
65 години
Обединен институт за ядрени изследвания – Дубна
Ч. Стоянов, Л. Костов
Институт за ядрени изследвания и ядрена енергетика - БАН

ii. Priroda (BAS)

3. H. Protohristov, **Ch. STOYANOV**

TRANSMUTATION - GREEN LIGHT FOR NUCLEAR ENERGY (HORISONT OF THE SCIENCE)

Priroda (BAS) 3, (2023), pp 4 - 16



ХОРИЗОНТИ НА НАУКАТА

Трансмутацията – зелена светлина за ядрената енергетика

Христо Протохристов, Чавдар Стоянов

Едно от най-големите препятствия пред по-нататъшното развитие на ядрената енергетика е свързано с проблема за преработката и съхранението на отработеното ядрено гориво (ОЯГ), в което се съдържат значителни количества силно радиоактивни и радиотоксични вещества, т. нар. радиоактивни отпадъци (РАО). До неотдавна, погребването на РАО за „вечни времена" в надеждно изолирани хранилища се разглеждаше като единствено възможно решение.

Методите на „ядрената алхимия", приложени в новите реакторни и ускорителни системи, предлагат днес един напълно различен подход. Чрез изкуствено превръщане на елементите или *трансмутация*, дългоживеещите радиоактивни отпадъци могат да бъдат трансформирани в безвредни вещества. В допълнение, съдържащият се в ОЯГ потенциално опасен оръжеен плутоний, може да бъде бързо унищожен, като процесът се съпътства от значителен енергодобив. Рязко увеличаващата се в световен мащаб консумация на енергия, ограничените запаси от фосилни горива и най-вече глобалните изменения в климата, карат много правителства да обръщат отново поглед към практически неограничените ресурси от енергия, заключени в атомното ядро от самото възникване на материята. Трансмутацията на ОЯГ, съчетана с въвеждане на нови реакторни системи с повишена сигурност биха осигурили едно чисто бъдеще за ядрената енергетика.

„Ядрената алхимия" – превръщането на един елемент в друг – стана реалност през XX век. През 1869 г., големият руски химик Дмитрий Менделеев (1834 – 1907) предлага Периодична система на елементите като ги подрежда по въз-

4 природа бр. 3, 2023 г.

iii. Journal of the Bulgarian Academy of Sciences, (Spisanie na BAN)

4. **Ch. Stoyanov**, L. Kostov

65 years of Joint Institute for Nuclear Research - Dubna

Journal of the Bulgarian Academy of Sciences, (Spisanie na BAN) 5, (2021) pp 3-6

2021: the Year
of Bulgaria in JINR

65 години
Обединен институт за ядрени изследвания – Дубна
Ч. Стоянов, Л. Костов
Институт за ядрени изследвания и ядрена енергетика - БАН

5. D. Dinev, **Ch. Stoyanov**

The new projects of the Laboratory for Nuclear Reactions of JINR-Dubna in the field of super heavy element and exotic nuclei

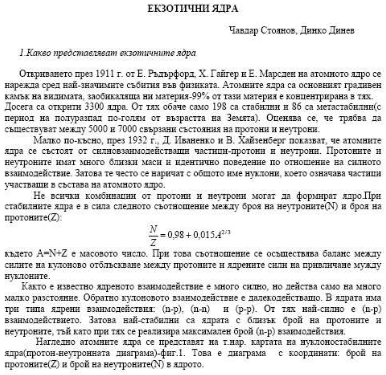
Journal of the Bulgarian Academy of Sciences, (Spisanie na BAN) 5, (2021) pp 29-34

iv. **The World of Physics, (Svetat na fizikata)**

6. **Ch. STOYA**NOV, D. Dinev

Exotic Nuclei

The World of Physics, (Svetat na fizikata) 2, (2020) pp 99-113



ЕКЗОТИЧНИ ЯДРА

Чавдар Стоянов, Динко Динев

1.Какво представляват екзотичните ядра

Откриването през 1911 г. от Е. Ръдърфорд, Х. Гайгер и Е. Марсден на атомното ядро се нарежда сред най-значимите събития във физиката. Атомните ядра са основният градивен камък на видимата, заобикаляща ни материя-99% от тази материя е концентрирана в тях. Досега са открити 3300 ядра. От тях обаче само 198 са стабилни и 86 са метастабилни(с период на полуразпад по-голям от възрастта на Земята). Оценява се, че трябва да съществуват между 5000 и 7000 свързани състояния на протони и неутрони.

Малко по-късно, през 1932 г., Д. Иваненко и В. Хайзенберг показват, че атомните ядра се състоят от силновзаимодействащи частици-протони и неутрони. Протоните и неутроните имат много близки маси и идентично поведение по отношение на силното взаимодействие. Затова те често се наричат с общото име нуклони, което означава частици участващи в състава на атомното ядро.

Не всички комбинации от протони и неутрони могат да формират ядро.При стабилните ядра е в сила следното съотношение между броя на неутроните(N) и броя на протоните(Z):

$$\frac{N}{Z} = 0{,}98 + 0{,}015A^{2/3}$$

където A=N+Z е масовото число. При това съотношение се осъществява баланс между силите на кулоново отблъскване между протоните и ядрените сили на привличане мужду нуклоните.

Както е известно ядреното взаимодействие е много силно, но действа само на много малко разстояние. Обратно кулоновото взаимодействие е далекодействащо. В ядрата има три типа ядрени взаимодействия: (n-p), (n-n) и (p-p). От тях най-силно е (n-p) взаимодействието. Затова най-стабилни са ядрата с близък брой на протоните и неутроните, тъй като при тях се реализира максимален брой (n-p) взаимодействия.

Нагледно атомните ядра се представят на т.нар. картата на нуклоностабилните ядра(протон-неутронната диаграма)-фиг.1. Това е диаграма с координати: брой на протоните(Z) и брой на неутроните(N) в ядрото.

7. **Chavdar Stoyanov**, Lachezar Kostov

Participation of Bulgarian physicists in the scientific program of JINR

The World of Physics, (Svetat na fizikata) 4, (2021) pp 310-317

2021: the Year of Bulgaria in JINR

Участие на български физици в научната програма на ОИЯИ

Ч. Стоянов, Л. Костов

8. **Ch. STOYANOV**, H. Protohristov, D. Dinev

BOOK

Nuclear physics in everyday life - translation from NuPECC

The World of Physics, (Svetat na fizikata) (2023) pp 1-147

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