EXPERIMENTAL METHODS AND PROCESSING OF DATA

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KINEMATIC MODEL OF SEQUENTIAL TWO-PART DECAY IN THE $^{12}C(\gamma,np)^{10}B$ REACTION

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For the reaction $^{12}C(\gamma,np)^{10}B$, a kinematic model was developed assuming a sequential two-particle decay with the formation of an intermediate excited nucleus. The possibility of decay through two channels – ($n+^{11}C^*$) or ($p+^{11}B^*$) – was created. In the system of the center of mass of a two-particle reaction, the kinematics is determined by the fact that, regardless of the specific type of interaction, the reaction products scatter at an angle of 180^0 and have equal modulus momentum, and their energies in the same system depend only on the masses of the particles and the total energy of the system. To visualize model calculations in the Python programming language, a graphical application was created with the possibility to interact with experimental data on the $^{12}C(\gamma,np)^{10}B$ reaction. Comparison of kinematic calculations with experimental results allowed us to identify certain limitations for the selection of experimental events corresponding to the channel of sequential two-particle decay.

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INTRODUCTION

Experimental studies of nuclear reactions on light nuclei are usually accompanied by a mathematical model of the process under investigation [1, 2]. However, various mechanisms of interaction between the γ-quantum and the nucleus are possible in these reactions. Thus, in works [3, 4], where reactions (γ,np) on nuclei ^4He, ^{12}C, ^{14}N and ^{16}O were studied, it was concluded that within the framework of the quasi-deuteron model, two mechanisms are possible – a pole diagram, when nucleons after the splitting of a quasi-deuteron do not interact with the spectator, and a triangular diagram, when in the final state one of the nucleons may interact with the spectator. In the reactions $^{12}C(\gamma,np)^{10}B$, $^{14}N(\gamma,np)^{12}C$ and $^{16}O(\gamma,np)^{14}N$, in the case of a triangular diagram, the formation of an intermediate excited nucleus is possible [5].

This paper develops a kinematic model assuming two-particle decay with the formation of an intermediate excited state (Fig. 1) within the framework of the triangular diagram of the quasi-deuteron model.

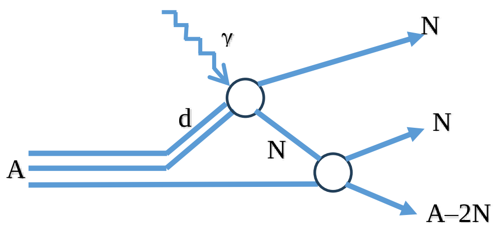

Fig. 1. Schematic representation of the interaction mechanism between a γ-quantum and the nucleus in the assumption of sequential two-particle decay.

In the system of the center of mass (s.c.m.) of a two-particle reaction, the kinematics is determined by the fact that, regardless of the specific type of interaction, the reaction products scatter at an angle of 180^0 and have equal modulus momentum, and their energies in the same system depend only on the masses of the particles and the total energy of the system.

To visualize the calculations, a graphical application was created in the Python programming language [6] on the Tkinter graphical library platform using additional NumPy and SciPY modules, which have a set of high-level mathematical functions for working with large multidimensional arrays. The Matplotlib library was used to visualize the data.

DESCRIPTION OF PROCEDURES FOR KINEMATIC MODELING OF THE $^{12}C(\gamma,np)^{10}B$ REACTION

We will show the kinematic model diagram in detail using the example of the $^{12}C(\gamma,np)^{10}B$ reaction. Decay is possible through two channels:

$$\gamma + {}^{12}C \rightarrow n + {}^{11}C^* \rightarrow n + p + {}^{10}B \qquad \text{(i)}$$

or

$$\gamma + {}^{12}C \rightarrow p + {}^{11}B^* \rightarrow n + p + {}^{10}B. \qquad \text{(ii)}$$

The mathematical calculation is based on the literature data on the parameters of the levels of ^{11}C and ^{11}B nuclei [7] and the corresponding assumptions about the angular distributions in the system of the reaction center of the particle that first left the ^{12}C nucleus and the particles in the intermediate state resting state. Each decay mode is reduced to three two-particle systems:

- ✓ ($\gamma+^{12}C$) – initial,
- ✓ ($n+^{11}C^*$) or ($p+^{11}B^*$) – intermediate,
- ✓ ($p+^{10}B$) or ($n+^{10}B$) – final.

To generate random values, a set of functions of the standard random library of the Python programming language was used. Several excited states of ^{11}C and ^{11}B nuclei can contribute to the reaction. A scheme was created that allows you to select both the relative contribution for each channel (i) or (ii) and the contribution of a separate level in each channel. To do this, we used the *random.randint(0,100)* function, which creates random, uncorrelated numbers evenly distributed in the range from 0 to 100. For the initial system, the numerical function of the distribution of the number of events on the energy of quanta $N(E_\gamma)$ was taken from a real experiment, and random values of E_γ were generated by the *random.choice()* function.

The excitation curves $f(E_x)$ of the ^{11}C and ^{11}B states of the nuclei were taken as Gaussian functions with a maximum position E_0 and half-width at half-height (σ) from a compilation of spectroscopic data [7]. The energy threshold for the decay of $^{11}C \to p + {}^{10}B$ is 8.69 MeV, and for the decay of $^{11}B \to p + {}^{10}B$ it is 11.46 MeV. Therefore, the first levels above the threshold were selected – for the ^{11}C nucleus, E_0 = 10.58 MeV and σ = 1.96 MeV were taken, and for the ^{11}B nucleus, E_0 = 12.67 MeV and σ = 1.64 MeV were taken. Random values were generated by the function *random.gauss(E_0,σ)*.

In the non-relativistic approximation, in the system of the center of mass of the two-particle reaction $\gamma + {}^{12}C \to N + ({}^{12}C\text{-}N)^*$, the law of energy conservation is [8]:

$$E_\gamma = T_N + T_{12C\text{-}N} + E_x({}^{12}C\text{-}N) + Q, \qquad (1)$$

where T is the kinetic energy of particles N and (^{12}C-N), $E_x(^{12}C\text{-}N)$ is the excitation energy of the intermediate particle (^{12}C-N), and Q is the energy threshold of the $\gamma + {}^{12}C \to N + ({}^{12}C\text{-}N)$ reaction.

Using the two-particle channel and the unambiguous connection between T_N and $T_{12C\text{-}N}$ in the system of the center of mass, we obtain:

$$T_N = \frac{M_{12C\text{-}N}}{M_N + M_{12C\text{-}N}}(E_\gamma - Q - E_x(M_{12C\text{-}N})) \cdot \qquad (2)$$

After the procedures for generating E_γ and $E_x(^{12}C\text{-}N)$, T_N and, accordingly, the particle momentum p_N was determined.

The distributions over the polar angle Θ_N for particle N were taken in form:

$$f(\Theta)=c_1\sin^2\Theta+c_2\sin^2\Theta\cos\Theta+c_3\sin^2\Theta\cos^2\Theta+c_4, \qquad (3)$$

where $c_{1\text{-}4}$ are coefficients containing information about the reaction mechanism and wave functions of the nuclei. Parameters $c_{1\text{-}4}$ were determined from the quantum values of the intermediate excited nucleus [8].

The distribution in the azimuthal angle φ_N is isotropic and was generated by multiplying the random number *random.randint(0,1)* by 2π.

The polar (Θ_N) and azimuthal (φ_N) angles were generated and the longitudinal and transverse projections of the momentum of particle N were determined.

The values of the projections and the total momentum of nucleus (^{12}C-N) were calculated from the two-particle process.

A similar procedure was carried out for the final system, provided that the energy of the system is the excitation energy of the particle (^{12}C-N). The kinematic parameters of the particles were transferred from the s.c.m. reaction to the laboratory reference frame. The laws of conservation of energy and momentum for the kinematic parameters of the particles were checked. An event was considered formed if it satisfied the conservation laws.

In Fig. 2, a solid histogram with a step of 1 MeV shows the dependence of the number of events on the energy of γ-quanta (data taken from the current experiment). The points are placed in the middle of the step. The dotted histogram shows the distribution of E_γ values obtained by modeling 10^6 events. The histogram step is the same – 1 MeV. Normalization was performed for the area under the experimental distribution.

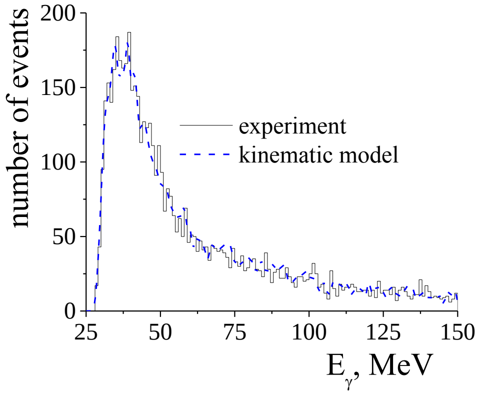

Fig. 2. Dependence of the number of events on the energy of γ-quanta. Solid histogram – experimental data, dotted histogram – simulation results

The simulation results agree with the experimental distribution. This allows us to conclude that the simulation is performed correctly.

In Fig. 3,a, histograms with a step of 15 MeV show the dependence of the number of events on the momentum of the final particles. The data were taken from the current experiment for a qualitative comparison with the simulation results. Note that in the experimental distribution for ^{10}B, a structure with two maxima is observed.

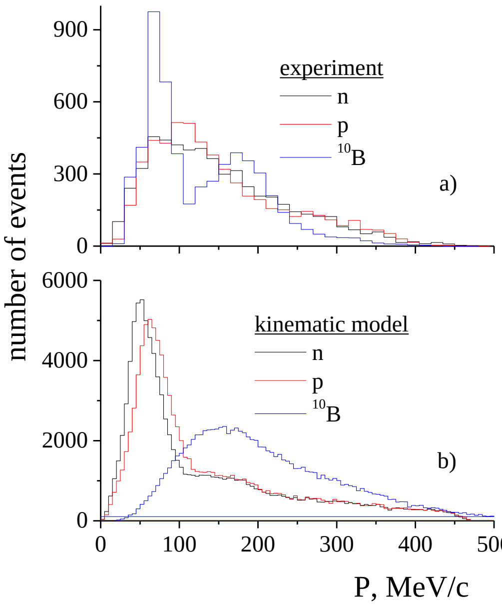

Fig. 3. Dependence of the number of events on the momentum of final particles in the $^{12}C(\gamma,np)^{10}B$ reaction: experimental data (a); results of kinematic modeling (b)

In Fig. 3,b, histograms with a step of 5 MeV show the dependence of the number of events on the momentum of the final particles, but now obtained using kinematic modeling. A total of 10^6 events were simulated. The probability of channels (i) and (ii) is the same – 50%.

It should be noted that the distribution of events for ^{10}B does not show a structure with two maxima.

However, the distribution qualitatively agrees with the second maximum in the experiment (see Fig. 3,a). Recall that the first maximum in the experiment was explained by the mechanism of interaction of the γ-quantum with the quasi-deuteron.

However, in the distribution of the number of events for nucleons in Fig. 3,b (kinematic modeling), a sharp change in the decay rate is observed at P ~ 100 MeV/c.

To identify the cause of this change, it was proposed to divide the nucleons into first and second ones within the process $\gamma + {}^{12}C \rightarrow N_1 + ({}^{12}C - N)^* \rightarrow N_1 + N_2 + ({}^{12}C - 2N)$. The kinematic model allows this to be done unambiguously.

Fig. 4 shows the dependence of the number of events on the momentum of nucleons N_1 (black histogram) and N_2 (red histogram). The histogram step is 5 MeV.

The figure shows that the contribution to the maximum at P < 100 MeV/c is mainly due to the nucleon that arises from the decay of the intermediate excited nucleus $({}^{12}C - N)^*$, so it should be expected that the distribution for N_1 will not change depending on the energy of the γ-quantum.

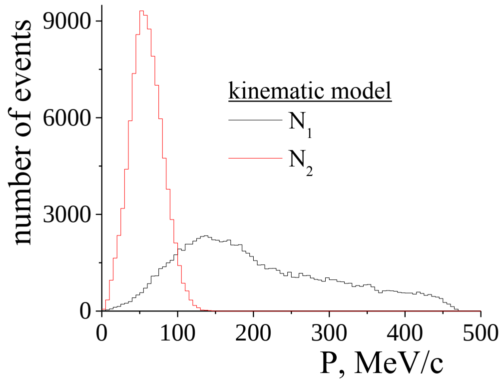

Fig. 4. Dependence of the number of events on pulses N_1 and N_2 within the framework of modeling a sequential two-particle process

One of the important physical parameters in studying (γ,np) reactions on ${}^{12}C$, ${}^{14}N$, and ${}^{16}O$ nuclei is the relative energy of the nucleon pair η_{np}. It was previously determined [5] that the maximum found at ηnp above 0.85 can be explained within the framework of the pole diagram of the quasi-deuteron model, when nucleons after the splitting of the quasi-deuteron do not interact with the spectator. It was also determined that there is a certain dependence of η_{np} on the momentum distribution of a multi-charge particle (${}^{10}B$, ${}^{12}C$, or ${}^{14}N$), in which a structure with two maxima is manifested. P^{lim}, the boundary between these maxima, was determined.

In Fig. 5, histograms show the dependence of the number of events on the relative energy of the nucleon pair η_{np} for the reaction ${}^{12}C(\gamma,np){}^{10}B$. The solid blue histogram corresponds to $P({}^{10}B) > P^{lim}$, and the dotted red histogram corresponds to $P({}^{10}B) < P^{lim}$.

For comparison, the results of kinematic modeling are plotted as a solid black curve. The figure shows that the experimental data at $P({}^{10}B) > P^{lim}$ can be qualitatively explained within the framework of a two-particle decay mechanism with the formation of an intermediate excited state. Therefore, events at $\eta_{np} < 0.85$ may correspond to sequential two-particle decay.

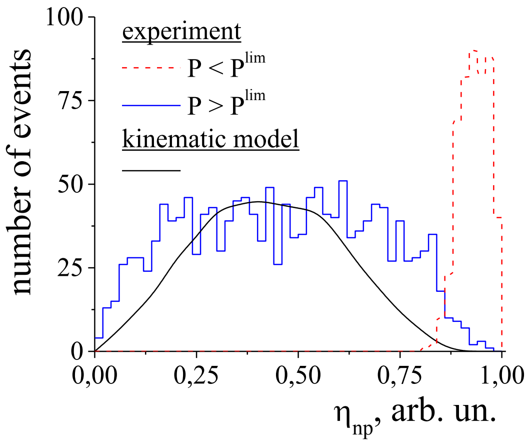

Fig. 5. Dependence of the number of events on the relative energy of the nucleon pair: histograms – experimental data; solid curve – kinematic modeling

To understand the need for such a division, let us give an example of determining one of the main characteristics of a reaction – the differential cross section. For a three-particle reaction, determining the differential cross section has always been somewhat complicated and uncertain due to the indistinguishability of the final particles because of the possible ways in which they arise. For example, within the framework of the pole diagram of the quasi-deuteron model, both nucleons arise simultaneously after the decay of a virtual quasi-deuteron. The isolation of the two-particle decay channel with the formation of an intermediate excited state provides unambiguous information about the first nucleon and, therefore, allows the differential cross section to be calculated in the experiment.

CONCLUSIONS

For the reaction ${}^{12}C(\gamma,np){}^{10}B$, assuming a two-particle decay with the formation of an intermediate excited state, an algorithm with a set of mathematical procedures for kinetic modeling is proposed. Two channels with possible decay paths have been selected: $\gamma + {}^{12}C \rightarrow (n + {}^{11}C^*)$ or $(p + {}^{11}B^*) \rightarrow n + p + {}^{10}B$ with the possibility of varying the relative contribution for each channel.

A graphical application has been created in the Python programming language with a scripted interaction cycle – when certain parameters are selected, data is automatically calculated and visualized in the form of graphs or numerical values. Specialized mathematical modules (NumPy, SciPY) were used for kinematic calculations, which simplify working with large data arrays.

A comparison of the results of kinematic modeling with experimental data on the ${}^{12}C(\gamma,np){}^{10}B$ reaction was performed. Criteria for energy and angular restrictions were proposed for the selection of experimental events that may correspond to sequential two-body decay. Such information will enable the identification of particles at each stage of decay and the correct calculation of, for example, differential cross sections.

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КІНЕМАТИЧНА МОДЕЛЬ ПОСЛІДОВНОГО ДВОЧАСТИНКОВОГО РОЗПАДУ В РЕАКЦІЇ $^{12}C(\gamma,np)^{10}B$

С.М. Афанасьєв

Для реакції $^{12}C(\gamma,np)^{10}B$ розроблено кінематичну модель у припущенні послідовного двочастинкового каналу розпаду з утворенням проміжного збудженого ядра. Створено можливість розпаду двома каналами – ($n+^{11}C^*$) або ($p+^{11}B^*$). У системі центру мас таких двочастинкових каналів кінематика визначається тим, що незалежно від конкретного типу взаємодії продукти реакції розлітаються під кутом 180^0 і мають рівний за модулем імпульс, а їх енергії в тій же системі залежать тільки від мас часток і повної енергії системи. Для візуалізації модельних розрахунків на мові програмування Python створено графічний застосунок із можливістю інтерактивної взаємодії з експериментальними даними за реакцією $^{12}C(\gamma,np)^{10}B$. Порівняння кінематичних розрахунків із результатами експерименту дозволило визначити певні обмеження для виділення експериментальних подій, що відповідають каналу послідовного двочастинкового розпаду.