THE METHOD OF BRANCHING RATIO MEASUREMENTS FOR NUCLEAR UNBOUND STATES PRODUCED BY THREE PARTICLE REACTIONS

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The direct method of decay branching ratio determination for nuclear unbound states is proposed. The method is based on the complex study of three particle reactions in kinematically complete and incomplete experiments. The resonance decay probability is defined as a ratio of experimentally observed magnitudes, namely the differential cross sections corresponding to the processes of resonance excitation and their decay. The most favourable conditions for such measurements have unbound states with the excitation energy near the decay threshold into the one of the possible channels. The peculiarities and some applications of the proposed method are discussed.

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1. INTRODUCTION

The main data about nuclear unbound states properties were obtained at study of binary reactions like

$$i+j \to R \to \begin{cases} \to i+j, & (1a) \\ \to m+n, & (1b) \end{cases}$$

in which these states are produced as intermediate resonance systems R decaying into $i+j$ and $m+n$ channels. Such researches involve laborious measurements of reaction cross sections with a small energy step of bombarding nuclei. In most cases the resonance parameters are obtained from the analysis of experimental data using **R**-matrix theory, which foundations were laid in work [1]. The important parameters of this and other more contemporary theories (e.g. [2]) are reduced widths γ_{ij}^2, γ_{mn}^2 of the channels (1a), (1b) which are energetically independent and characterize the structure of resonance R. The resonance branches ratio data may be received from the values of partial widths Γ_{ij}, Γ_{mn} ($\Gamma_{ij}+\Gamma_{mn}=\Gamma$, where Γ is a total level width). The radiation width Γ_γ may be neglected in comparison with the particle ($m\neq 0$) decay widths. The magnitudes Γ_{ij}, Γ_{mn}, Γ are energetically dependent as $\Gamma_{ij}=2P_{ij}(E_{ij})\gamma_{ij}^2$, $\Gamma_{mn}=2P_{mn}(E_{mn})\gamma_{mn}^2$, $P_{ij}(E_{ij})$ and $P_{mn}(E_{mn})$ being penetrability of the Coulomb and centrifugal barriers in corresponding decay channels, E_{ij} , E_{mn} are the relative energies of decay products. The values of Γ_{ij}, Γ_{mn} are usually presented at the resonance energy E_r. Accordingly the Γ_{ij}/Γ and Γ_{mn}/Γ ratios correspond to the decay branches ratio only at $E = E_r$ energy.

Despite the detailed studies that have been carrying out for tens of years, there still are significant discrepancies of resonance parameters obtained for a number of nuclei. The intensively studied "thermonuclear resonance" ^{5}He*(16.75 MeV) may serve as an example. This resonance was observed at the precision measurements of energy dependences of cross sections for the reactions (e.g. [3,4])

$$d+t \to {}^5He^* \to \alpha+n, \quad (2)$$

as well as of the total cross sections of elastic neutron scattering by ^{4}He nuclei [5]. The different values of partial widths for ^{5}He* decay into the channels $d+t$ and $\alpha+n$ were obtained by different authors, for example Γ_{dt}=33.07 keV, $\Gamma_{\alpha n}$=38.83 keV in [3] and Γ_{dt}=25.77 keV, $\Gamma_{\alpha n}$=48.39 keV in [4]. The detailed analysis of various approaches for determination of widhts Γ_{dt} and $\Gamma_{\alpha n}$ in binary reactions like (2) was carried out in [6].

Note must be taken that the branches ratios data for nuclear unbound states produced in many-particle reactions are almost absent till now. The direct method of the resonance decay probability measurements at the fixed energy in the input channel of three particle reactions is proposed in the given work. The method is based on the complex study of these reactions in inclusive and exclusive experiments.

2. DETERMINATION OF RESONANCE EXCITATION PROBABILITY IN INCLUSIVE EXPERIMENTS

It is known that in reactions

$$p+T \to k+R \quad (3)$$

the excitation of recoil nuclei R is provided in the energy range from 0 to E^*_{max} at the fixed energy of incident particles E_p (the value of E^*_{max} depends on the type of particles in the input and exit reaction channels and energy E_p). If the nucleus R excitation energy in reactions (3) exceeds the decay threshold on the $i+j$ and $m+n$ channels, the three particles are produced in the exit channels:

$$p+T \to k+R \to \begin{cases} \to k+i+j, & (4a) \\ \to k+m+n. & (4b) \end{cases}$$

The complete definition of reaction kinematics is provided by the measurement of two product's momentums, for example, particles k and i or k and m [7,8]. In kinematically incomplete experiments the momentum of only one final particle is measured. The structure of

inclusive spectrum of particles k (or differential reactions cross sections

$$\frac{d^2\sigma}{d\Omega_k dE_k} \quad (5)$$

of reaction (4)) measured in such experiments are defined in a great extent by the excitation processes of recoil nuclei R. By integrating the cross section (5) measured at the Θ_k, φ_k angles over the k particle energy in the range that corresponds to the excitation of analysed nucleus R the following cross section is obtained:

$$\frac{d\sigma_{exc}}{d\Omega_k}. \quad (6)$$

This cross section characterizes the excitation probability of nucleus R which centre of mass according to the kinematics of reaction (4) must move in the direction that is determined by the angles Θ_R, $\varphi_R=\varphi_k$ -180° (see Fig. 1).

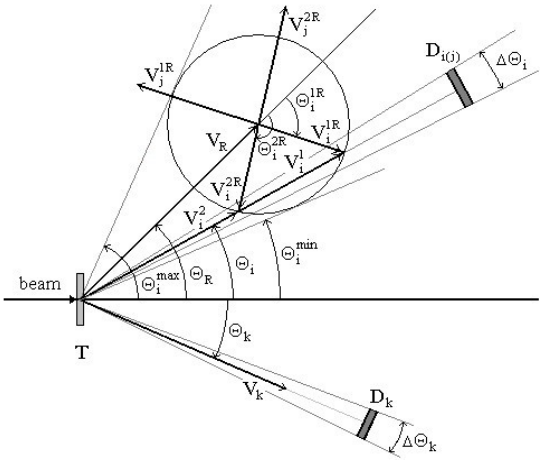

Fig. 1. *Vector's velocity diagram for reaction (4a)*

In many cases the cross sections (5) may also have a continuum part caused by the emission of particles k from the decay of nuclear unbound states produced in accompanied reaction channels. For defining the contribution of these processes the well-known procedures of the inclusive spectra analysis is used (see, e.g. [9]).

3. DETERMINATION OF RESONANCE DECAY PROBABILITY IN EXCLUSIVE EXPERIMENTS

At the decay of nucleus R with excitation energy E^* into the channel $R\rightarrow i+j$ the emission angles of decay products Θ_i, φ_i, Θ_j, φ_j and their velocities V_i, V_j in the laboratory system are defined by the vectors $\boldsymbol{V}_R$ and $\boldsymbol{V}_i^{\boldsymbol{R}}$, $\boldsymbol{V}_j^{\boldsymbol{R}}$ (Fig. 1). The velocities V_i^R and V_j^R depend on the Q-value of decay $R\rightarrow i+j$: $Q=E_{i-j}=E^*-E_{thr}$, where E_{thr} is the energy of decay threshold, E_{i-j} – relative energy of particles i and j. The range of possible emission angles $\Delta\Theta_i= \Theta_i^{max}-\Theta_i^{min}$, $\Delta\varphi_i=\varphi_i^{max}-\varphi_i^{min}$ is defined by the ratio V_i^R/V_R and can be simply evaluated (at $V_i^R<<V_R$) as:

$$\Delta\Theta_i = \Delta\varphi_i \approx 2arctg(V_i^R/V_R). \quad (7)$$

At the fixed angle Θ_k=const the particle i as a decay product of unbound state R with excitation energy E^* can be observed within the "cone" defined by the possible emission angles $\Delta\Theta_i$, $\Delta\varphi_i$. The information about of excitation and decay probability of nucleus R into the channel $i+j$ (reaction (4a)) are contained in the differential cross sections

$$\frac{d^4\sigma}{d\Omega_k dE_k d\Omega_{i(j)} dE_{i(j)}}, \quad (8)$$

which are obtained from coincidence spectra of particles k and i (or k and j). Theoretical interpretation of cross sections (8) is rather complicated that is why the triple differential cross sections are used for the analysis:

$$\frac{d^3\sigma}{d\Omega_k d\Omega_{i(j)} dE_k}, \quad (9a)$$

$$\frac{d^3\sigma}{d\Omega_k d\Omega_{i(j)} dE_{i(j)}}. \quad (9b)$$

(9a) and (9b) are the result of integrating of cross sections (8) over the energy $E_{i(j)}$ or E_k around the corresponding kinematical curves (functions $E_i(E_k)$ or $E_j(E_k)$ determined by the energy and momentum conservation law).

By integrating of (9a) over the energy of particle k in the same range as (5) the double differential cross section

$$\frac{d^2\sigma}{d\Omega_k d\Omega_{i(j)}} \quad (10)$$

can be obtained. This cross section characterises the probability of formation and decay of nucleus R within the solid angle $d\Omega_{i(j)}$ simultaneously. The total probability of decay into $i+j$ channel is defined by the ratio

$$P(i+j) = \frac{d\sigma_{dec}}{d\Omega_k} \Big/ \frac{d\sigma_{exc}}{d\Omega_k}, \quad (11)$$

where

$$\frac{d\sigma_{dec}}{d\Omega_k} \quad (12)$$

is the result of integrating (9) over the solid angles Ω_i or Ω_j which determined by the range of all possible angles Θ_i, φ_i or Θ_j, φ_j (see Eq. (7) and Fig. 1). For reaction (4b) the probability of decay into the channel $m+n$ can be defined in the same way by the measurements of coincidence spectra of particles k (Θ_k=const) and $m(n)$ within the solid angle $\Omega_{m(n)}$.

4. PECULIARITIES OF RESONANCES DECAY PROBABILITY MEASUREMENTS

The procedure of determination of reaction cross sections (6) is well known and in most cases not difficult. Now the technique of coincidence measurements is also well developed. But the long measurement's time is the main shortcoming of such experiments. However the differential cross sections (8)-(10) of different reactions like (4) have been measured in lots of experiments. It gave the possibility to study reaction dynamics effects as well as to get the values of resonance parameters of many nuclear unbound states produced by these reac-

tions. But the branches ratio data have not been obtained even until now because of the absence of experimental data about the cross sections (12). The cross sections (10) have been usually measured at limited sets of registration angles of reaction products. But the detailed angular correlations data covered the whole range of emission angles $\Delta\Theta$, $\Delta\varphi$ (see (7)) are needed to obtain the cross sections (12). For most unbound states produced by reactions (4) at low and middle energies of incident particles this angular range is sufficiently large.

The most favourable conditions of the decay probability measurements have unbound states with the excitation energy slightly exceeds the decay threshold into the one of the possible channels (e.g. i+j). For such states the angular range of decay consists of $\Delta\Theta_{i(j)}$~10°…30°, that is quite acceptable for the measurements. The vivid example of state with excitation energy near the decay threshold is the mentioned above "thermonuclear resonance" ^{5}He*(16.75 MeV). At the formation of this resonance in reaction

$$d+{}^7Li \rightarrow \alpha+{}^5He^* \rightarrow \begin{cases} \rightarrow \alpha+\alpha+n & (13a) \\ \rightarrow \alpha+t+d & (13b) \end{cases}$$

at deuteron energies E_d > 30 MeV it is easy to provide such solid angle $\Delta\Omega_{t(d)}$ of tritons or deuterons registration which would cover all the possible decay angles into the channel $^5He^* \rightarrow t+d$. The whole range of these angles is very small due to the small value of relative energy of deuterons and tritons ($E_{t\text{-}d}$= 0.05 MeV) while $^5He^*$ centre of mass energy at different emission angles in reaction (13) at E_d=30 MeV consists of 10…20 MeV. In this case the decay products can be registered by the detectors with relatively small aperture.

Generally the multi-element silicon detectors with large total square of sensitive surface can be effectively used for registration of decay products [10]. The whole range $\Delta\Theta_{i(j)}$ can be covered by full aperture of such detector. At the same time the cross sections (8)-(10) are measured with high angular resolution because of simultaneous using each element of detector. At $\Delta\Theta_{i(j)}\leq$10° the whole decay cone can be covered even by one-element detector with not very big aperture.

According to the theory of many particle nuclear reactions [11] the cross sections of reactions (4) depend on the three-body scattering amplitudes, which in the assumption of dominating role of pair forces are defined by the two-particle amplitudes, which correspond to the interaction of every particle pair in the final state. That is why it is very important to choose for measurements such regions of phase space where the interaction of one particle pair dominates. In our case it is the pair of particles i and j, which interaction is responsible for formation of the R resonance in reaction (4a).

The velocity diagram on Fig. 1 corresponds to the ideal conditions of decay probability measurements for the states with Γ=0. For real states the change of excitation energy within the limits of ΔE^*~$(2…3)\Gamma$ causes certain modification of energy of particles k (ΔE_k) detected at fixed angle Θ_k also as modification of energy (ΔE_R) and emission angle ($\Delta\Theta_R$) of nuclei R and relative energies of decay products ΔE_{ij} =ΔE_{mn}=ΔE^*. The mentioned factors (ΔE_R, $\Delta\Theta_R$ and ΔE_{ij}) lead to the change of maximal and minimal observation angles of nuclei R decay products, that is to the range $\Delta\Theta_{i(j)}$, $\Delta\varphi_{i(j)}$ widening. The additional widening of this range and modification of differential cross sections (8), (9) are caused by a number of conditions of carrying out the real experiments. There are beam energy dispersion (ΔE_p), beam spot size on the target, target thickness, solid angles ($\Delta\Omega_k$, $\Delta\Omega_{i(j)}$) and energy resolution of the detectors used for the reaction products registration. .

One of the best methods of taking into account all these factors is the simulation of the investigated processes by Monte-Carlo method [12]. Fig. 2 contains the simulated differential cross sections (8), (9) which correspond to the excitation and decay of ^{7}Li*(7.45 MeV) nuclei into the ^{6}Li+n channel in reaction

$$\alpha+{}^7Li \rightarrow \alpha+{}^7Li^* \rightarrow \alpha+{}^6Li+n \qquad (14)$$

at the beam energy of 27.2 MeV.

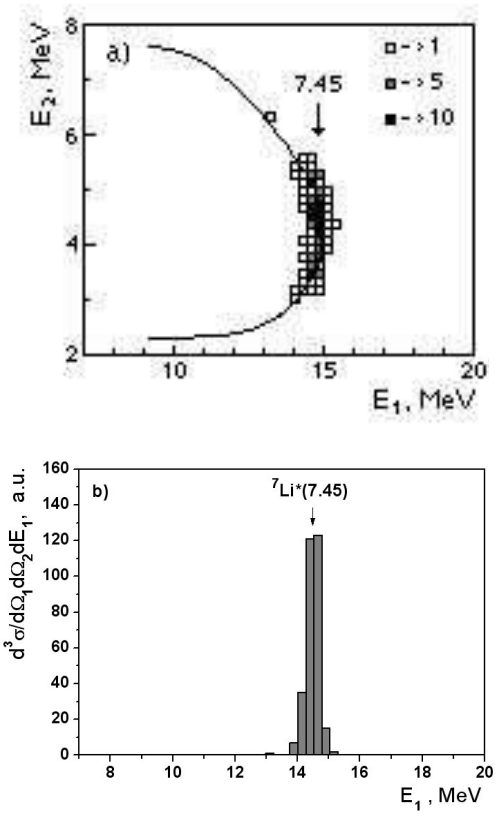

Fig. 2. *Monte-Carlo simulation of α-^{6}Li coincidence spectra (a,b – differential cross sections (8) and (9), respectively) for reaction (14) in the region of excitation and decay of ^{7}Li*(7.45 MeV) into the ^{6}Li+n channel. E_1 and E_2 are the energies of α-particles and ^{6}Li nuclei registered at Θ_1=34°, φ_1=0° and Θ_2=44.5°, φ_2=180°, respectively*

The real conditions of coincidence measurements have been used for these simulations. In particular, the solid angles of α-particles and ^{6}Li registration were $\Delta\Omega_1$=0.76·10^{-3} sr and $\Delta\Omega_2$=2.72·10^{-3} sr, respectively. The total solid angle of decay into the ^{6}Li+n channel consists of $\Delta\Omega_2$=3.55·10^{-2} sr. The space distribution of α-^{6}Li co-

incidence events simulated for ^{6}Li-detector plane is shown in Fig. 3.

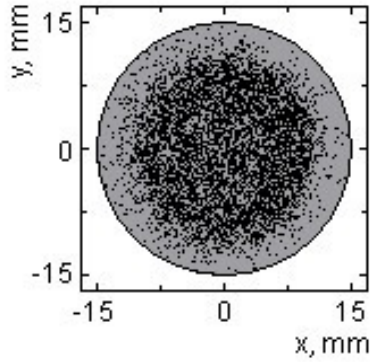

Fig. 3. *The space distribution of α-^{6}Li coincidence events simulated for reaction (14) and shown in the plane of ^{6}Li-detector placed at the distance of 127 mm from the target. The point x=y=0 corresponds to the angles Θ_2=46.5°, φ_2=0°*

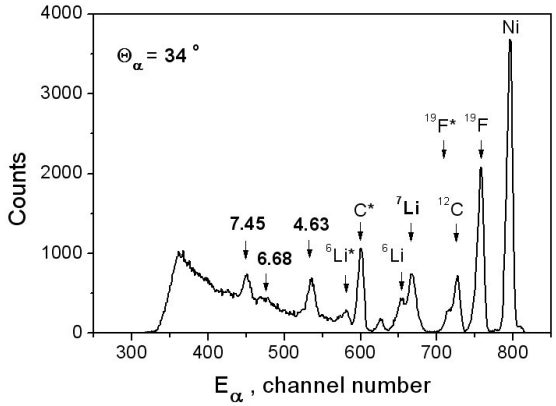

Fig. 4. *Inclusive spectrum of α-particles for reaction (14)*

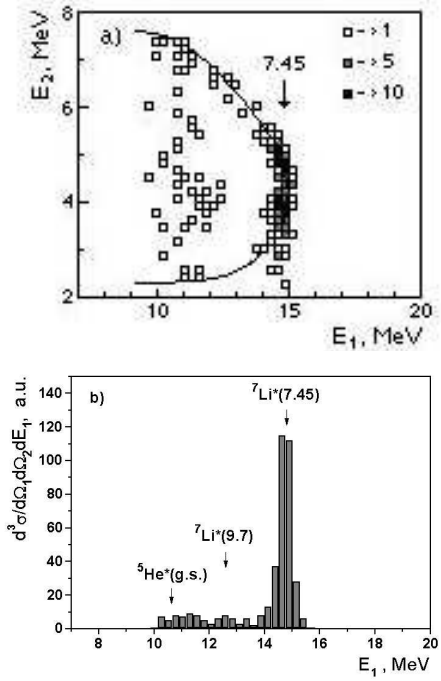

Fig. 5. *α-^{6}Li coincidence spectra (a,b – differential cross sections (8) and (9), respectively) measured for reaction (14). E_1 and E_2 are the energies of α-particles and ^{6}Li nuclei registered at Θ_1=34°, φ_1=0° and Θ_2=44.5°, φ_2=180°, respectively. Solid line is the kinematical curve for reaction (14)*

If the detector's aperture does not completely covers the angular range of decay it would be appropriate to calculate a "registration efficiency":

$$\varepsilon = N_{i(j)} / N_R, \qquad (15)$$

where N_R – the number of excited recoil nuclei R or corresponding particles k detected without coincidences with other particles, $N_{i(j)}$ – the number of particles k detected in coincidences with one of the particles from decay $R \rightarrow i+j$. The number N_R defines the value of cross sections (5), (6) and $N_{i(j)}$ – of cross sections (8)-(10).

5. EXAMPLE OF METHOD APPLICATION

The Monte-Carlo simulations of differential cross sections (5), (6), (8)-(10) and "registration efficiency" (15) were used to choose the optimal conditions of ^{7}Li*(7.45 MeV) decay probability measurements in reaction (14). This experiment was performed at the incident α-particle's energy of 27.2 MeV at the cyclotron U-120 of the Institute of Nuclear Research (Kyiv).

The inclusive spectrum of α-particles (differential cross section (5)) that was measured for this reaction at the angles Θ_α=34°, φ_α=0° [13] is shown in Fig. 4. The peaks observed in the spectrum correspond to the elastic and inelastic scattering of α-particles by ^{7}Li and target admixture nuclei of ^{6}Li, ^{12}C, ^{19}F and Ni. Continuum part of spectrum observed at low energies is caused by the registration of α-particles as the products of decay of nuclear unbound states produced by inelastic scattering and others accompanied reaction channels. Using the procedure given in [9] the differential cross section (6) corresponding to the excitation of ^{7}Li*(7.45 MeV) nucleus has been obtained from this spectrum. According to the kinematics of reaction ^{7}Li(α,α)^{7}Li* the centre of mass of ^{7}Li* must move at the angles Θ_{7Li^*}=46.5°, φ_{7Li^*}=180°.

The α-^{6}Li coincidence spectra have been measured around this direction within the range $\Delta\Theta_{6Li}=\Delta\varphi_{6Li}$=12° (at fixed angles Θ_α=34°, φ_α=0°) which covered all possible emission angles of ^{6}Li as a product of ^{7}Li*(7.45 MeV) decay. The example of coincidence spectra (differential cross sections (8) and (9)) is shown in Fig. 5. The most intensive peak in Fig. 5b corresponds to the contribution of ^{7}Li*(7.45 MeV) excitation and decay into ^{6}Li+n channel.

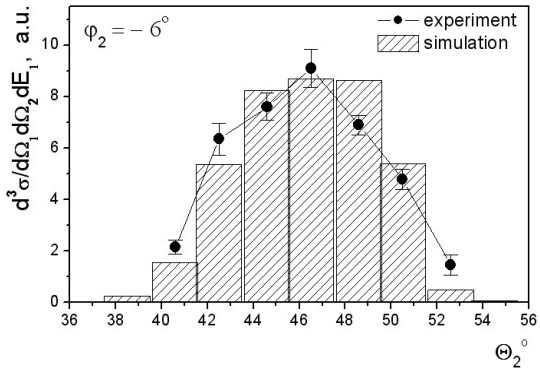

Fig. 6. *The Θ_2-angular dependence of measured and simulated differential cross sections (10) for one of the angle values $\varphi_2 = \varphi_{6Li} = -6°$*

By integrating the cross sections (9) over E_α energy within this peak the differential cross sections (10) have been obtained. Their angular dependence is shown in Fig. 6. And finally by integrating the measured cross sections (10) over the Θ_2, φ_2 angles the cross section (12) has been obtained. Its ratio to cross section (6) determined from the inclusive α-particle spectrum according to (11) is the probability of ^{7}Li*(7.45 MeV) decay into the ^{6}Li+n channel.

The value of ratio (11) consists of $P(n+^6Li) = 0.49 \pm 0.06$ that significantly differs from the results of binary reactions studies. This level was observed as pronounced resonance at low energy interaction of neutrons with ^{6}Li nuclei [14] and α-particles with tritons [15]. The resonance has a large neutron width and a small α-width $(\gamma_n^2/\gamma_\alpha^2 = 48$, $\Gamma_n(E_r)/\Gamma(E_r) = 0.77$, $\sigma_n/\sigma_{tot} = 0.71$ [14], where σ_{tot} is the total neutron cross section, σ_n is the cross section of n+^{6}Li elastic scattering).

Extremely large width ($\Gamma \sim 0.5$ MeV) of ^{5}He* "thermonuclear resonance" with respect to the standard value ($\Gamma \sim 0.076$ MeV [16]) was deduced from experimental data for reaction (13a) in Ref. [17]. The strong modification of branching ratio for this resonance was also observed at the study of reactions (13a) and (13b) at deuteron energy of 37 MeV [18]. The spectrum of α-particles measured in coincidences with tritons (reaction (13b)) is shown in Fig. 7. High registration efficiency ($\varepsilon = 0.46$, see Eq. (15)) for reaction channel (13b) was achieved due to the large solid angle ($\Delta\Omega_2 = 1.82 \cdot 10^{-2}$ sr) of detector used for the registration of tritons. The pronounced peak at the energy of $E_\alpha = 14.8$ MeV corresponds to the contribution of narrow ($\Gamma = 24$ keV, [16]) resonance of ^{6}Li*(2.185 MeV). The broadening of the observed peak is mainly caused by large value of the solid angle $\Delta\Omega_2$. It is well reproduced by Monte-Carlo calculations. The middle part of spectrum corresponds to the possible contribution of other states of ^{5}He* with excitation energy $E^* > 18$ MeV [16,19] or ^{6}Li* with $E^* > 4$ MeV [16].

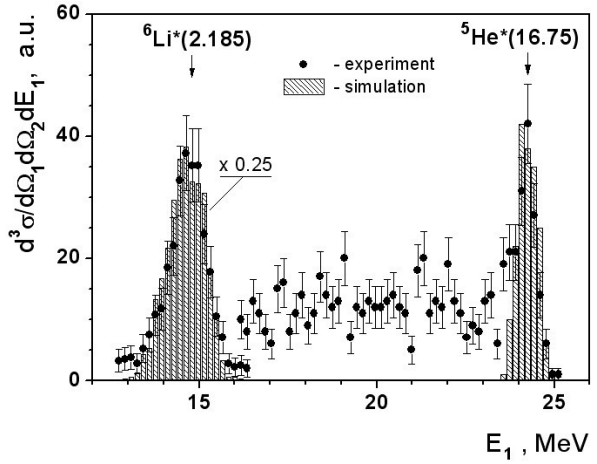

Fig. 7. *Reaction ^{7}Li(d,αt)d at $E_d = 37$ MeV. The spectrum of α-particles ($\Theta_1 = 45°$, $\varphi_1 = 0°$) measured in coincidences with tritons ($\Theta_2 = 79°$, $\varphi_2 = 180°$). The results of Monte Carlo simulations of the excitation and decay of ^{5}He*(16.75 MeV) and ^{6}Li*(2.185 MeV) unbound states are shown as histograms*

Contrary to the binary reactions the formation and decay of ^{7}Li*(7.45 MeV) in three particle reaction (14) as well as ^{5}He*(16.75 MeV) in reaction (13) occurs with the presence of accompanying α-particles. The influence of its Coulomb field may be one of the reasons for a modification of resonance decay branches ratio in comparison with the binary reactions [11,20,21].

CONCLUSIONS

The method proposed for the determination of decay branching ratio for nuclear unbound states produced by three-particle reactions (4) is based on the measurements of differential cross sections of these reactions in kinematically complete and incomplete experiments. The method has many advantages over the known procedures, developed for binary reactions (1). Firstly, this is a method of direct measurement of decay probability of resonance states into one or two channels as it is defined as a ratio of experimentally observed magnitudes, namely the number of nuclei decaying into the given channel to the number of excited nuclei (see (11)). Secondly, the method needs no implication of theoretical analysis. Thirdly, there is no need to measure the cross sections of reactions at different energies of incident particles.

Besides mentioned above resonances of ^{5}He* and ^{7}Li* the method can be used for the measurement of the decay probability of many other nuclear states. It is most suitable for the states which excitation energy slightly exceeds the decay threshold into one of the probable channels, for example: ^{4}He*(21.1 MeV)→ ^{3}He+n, ^{5}He*(19.8 MeV)→ ^{3}He+2n, ^{5}Li*(16.6 MeV)→ ^{3}He+d, ^{7}Li*(9.9 MeV)→^{6}He+p, ^{8}Be*(18.91 MeV)→ ^{7}Li+p, ^{8}Be*(22.2 MeV)→^{6}Li+d and others. The experimental data about the decay branches ratios for such nuclei states are important for testing of existing theories of many particle reactions and further study of influence effects of accompanying particles on the processes of formation and decay of short lived nuclear states. The results of experimental and theoretical works [13,20,21] prove the availability of this research direction.

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МЕТОД ИЗМЕРЕНИЯ РАСПРЕДЕЛЕНИЯ ВЕТВЕЙ РАСПАДА НЕСВЯЗАННЫХ СОСТОЯНИЙ ЯДЕР В ТРЕХЧАСТИЧНЫХ РЕАКЦИЯХ

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Предложен прямой метод определения распределения ветвей распада несвязанных состояний ядер. Метод основан на комплексном исследовании трехчастичных реакций в кинематически полных и неполных экспериментах. Вероятность распада резонансов определяется как отношение экспериментально наблюдаемых величин, а именно, дифференциальных сечений, соответствующих процессам возбуждения резонансов и их распада. Наиболее благоприятные условия для таких измерений имеют несвязанные состояния с энергией возбуждения, незначительно превышающей порог распада в один из возможных каналов. Анализируются особенности предлагаемого метода, приведены примеры его использования.

МЕТОД ВИМІРЮВАННЯ РОЗПОДІЛУ ГІЛОК РОЗПАДУ НЕЗВ'ЯЗАНИХ СТАНІВ ЯДЕР В ТРИЧАСТИНКОВИХ РЕАКЦІЯХ

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Запропоновано прямий метод визначення розподілу гілок розпаду незв’язаних станів ядер. Метод базується на комплексному дослідженні тричастинкових реакцій у кінематично повних та неповних експериментах. Ймовірність розпаду резонансів визначається як відношення експериментально спостережуваних величин, а саме диференціальних перерізів, що відповідають процесам збудження резонансів та їх розпаду. Найбільш сприятливі умови для таких вимірювань мають незв’язані стани з енергією збудження, що незначно перевищує поріг розпаду в один з можливих каналів. Аналізуються особливості запропонованого методу, наведено приклади його застосування.