True parameters of the ${}^{4}_{\Sigma}$He hypernucleus

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It is shown that the true parameters of ${}^{4}_{\Sigma}$He differ from the observed ones. The reason is that the amplitude of ${}^{4}_{\Sigma}$He production in the reaction ^{4}He(K^{-},π^{-}) sharply varies just in the corresponding mass region. This leads to a small, but noticeable shift of the binding energy and the width. In addition, the data at the threshold of Σ^{0} production is found to give additional evidence that the ${}^{4}_{\Sigma}$He width cannot exceed 8.5–9.0 MeV. [S0556-2813(99)01409-0]

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The recent study of the missing mass spectrum from the reaction

$$ {}^{4}\mathrm{He}(K^{-},\pi^{-}) \tag{1} $$

at 600 MeV/c has revealed a peak in the region close to Σ production [1]. The peak corresponds to the bound ${}^{4}_{\Sigma}$He state with parameters $E_{\mathrm{ex}}=-7$ MeV and $\Gamma=7$ MeV (E_{ex} is the missing mass to a pion measured from the sum of masses $\Sigma^{0}+{}^{3}$He). Here we give the central values of the parameters, obtained in Ref. [1] with the help of several simple versions of the background approximation.[1]

The production of ${}^{4}_{\Sigma}$He actually realizes the unique case when the amplitude of resonance production is a sharply varying function of mass just in the region of resonance mass. If the amplitude strongly changes on the resonance width, it can lead to an appreciable shift of the observed energy and width compared with the true values. As will be shown below, the amplitude of ${}^{4}_{\Sigma}$He production in the process (1) rapidly varies in the E_{ex} interval from -10 MeV to 0, that is, just in the region of ${}^{4}_{\Sigma}$He mass.

The missing mass spectrum from the reaction

$$ {}^{4}\mathrm{He}(K^{-},\pi^{+}) \tag{2} $$

was also studied in Ref. [1]. A comparison of the data on channels (1) and (2) shows the following. Almost all events of the reaction (2) are situated at $E_{\mathrm{ex}}>0$. They form a broad maximum which is usually associated with a quasifree Σ^{-} production [2]. In contrast to this, the channel (1) has also many events in the E_{ex} region from -40 to -10 MeV. They are obviously due to the tail of Λ production. In addition, the channel (1) has an enhancement at E_{ex} near zero, and a distinct peak at $E_{\mathrm{ex}}=-7$ MeV corresponding to the bound ${}^{4}_{\Sigma}$He state (see the histogram in Fig. 1). In what follows, our primary attention will be focused on the region of the resonance peak. However, at first it is necessary to discuss the physical nature of the ''background,'' that is, the tail of Λ production and the region of ''quasifree'' Σ production.

An attempt to describe E_{ex} spectrum from -40 to -20 MeV in terms of quasifree Λ production was unsuccessful. The corresponding curve decreased too rapidly in obvious contradiction with the data. The model of quasifree Λ production with subsequent rescattering on the residual nuclear system was therefore applied. The ^{4}He wave function in the oscillator potential was used, and the oscillator parameter p_0 was considered as fitting. Small values of p_0 result in a too rapidly decreasing curve. For large p_0 values the curve, on the contrary, falls down too slowly, which contradicts the data at E_{ex} in the region 30–50 MeV. The optimum value is $p_0=150$ MeV/c which leads to the curve in Fig. 1. Certainly, such procedure is rather rough, and the corresponding errors will be considered later on.

As to the region $E_{\mathrm{ex}}>0$, the simplest mechanisms are quasifree Σ production which can be accompanied by Σ rescattering on residual nuclear system or by $\Sigma\rightarrow\Lambda$ conversion. The analysis of $(K^{-},\pi^{\pm})$ reactions on ^{9}Be, ^{12}C, and ^{4}He was performed in Ref. [3]. It was shown that the quasifree production gives a peak which is narrower and leftward shifted compared with the experimental one. At the same time an account of elastic and inelastic rescatterings together with the interference of corresponding amplitudes results in a

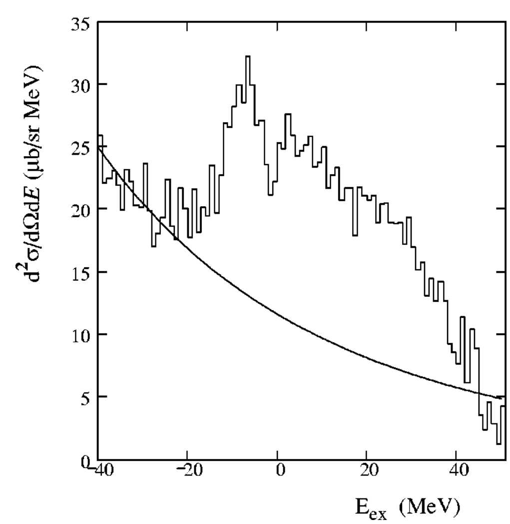

FIG. 1. The data of Ref. [1] on the differential cross sections of the reaction ^{4}He(K^{-},π^{-}). The solid curve is the approximation of the tail of direct Λ production.

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[1]The threshold of $(\Sigma^{-}+\mathrm{t})$ channel is situated 2.6 MeV lower than the threshold of the $(\Sigma^{0}+{}^{3}\mathrm{He})$ channel. So $E_{\mathrm{ex}}=-7$ MeV corresponds to the binding energy 4.4 MeV.

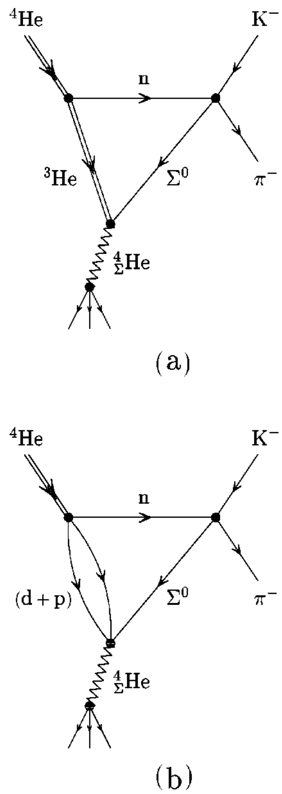

FIG. 2. Graphs for ${}^{4}_{\Sigma}$He production in the reaction ^{4}He(K^-,π^-).

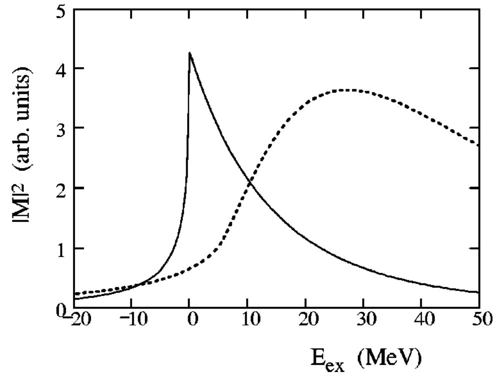

FIG. 3. $|M_\triangle|^2$ for the triangle graphs of Fig. 2 with two-particle (solid curve) and three-particle (dotted curve) intermediate states.

good description of E_{ex} spectra. Thus, it is possible to suppose that the origin of the main part of the Fig. 1 spectrum in general is clear. It allows us to study the region of ${}^{4}_{\Sigma}$He peak and $E_{ex}\sim 0$ in more detail.

The most probable mechanism of ${}^{4}_{\Sigma}$He production is presented in Figs. 2(a) and 2(b). At first, the Σ hyperon is born on one of the neutrons, and then it coalesces with the residual nuclear system. The difference between Figs. 2(a) and 2(b) is that in the first case we have the two-particle intermediate state ^{3}He-Σ^0, and in the second case the three-particle state p-d-Σ^0 is present (there could also be a four-particle state p-p-n-Σ^0). An amplitude of Fig. 2(a) has singularities of two kinds: the root threshold singularity at $E_{ex}=0$ and the triangle logarithmic singularity located in complex plane. The latter is also situated near $E_{ex}=0$ for kinematical conditions of Ref. [1]. The modulus squared of the triangle graph amplitude $M_\triangle$ for this case is shown (without the Breit-Wigner factor) by the solid curve in Fig. 3. Here and further we use the oscillator wave function of ^{4}He with the parameter $p_0=90$ MeV/c which gives the best description of ^{4}He(e,ep) data at small spectator momenta [4]. According to the evaluation of Ref. [1], the bound state of ${}^{4}_{\Sigma}$He is located at $E_{ex}=-7$ MeV and has the width about 7 MeV. Figure 3 shows that $|M_\triangle|^2$ strongly varies on the resonance width. It can noticeably influence the result of ${}^{4}_{\Sigma}$He parameters estimation from the experimental data.

It is worth noting that such sharp behavior of the amplitude is well known for the case of stopped kaon capture $K^-d\to p\Lambda\pi^-$. The pion spectrum for this reaction has a distinct peak [5] associated with the triangle graph with the conversion $\Sigma\to\Lambda$ (see Ref. [6]). A cusp behavior was also indicated in Ref. [7] devoted to stopped K^- capture in ^{4}He. A possibility of the distortion for Breit-Wigner form in the case of near threshold resonance was also mentioned in Ref. [8].

The sharp behavior of $|M_\triangle|^2$ is characteristic only for the triangle graph of Fig. 2(a) with a two-particle intermediate state. The graph of Fig. 2(b) with a three-particle intermediate state leads to a smooth amplitude whose maximum is shifted right (see also Ref. [9]). This is shown by the dotted curve in Fig. 3. Therefore the comparative contribution of Figs. 2(a) and 2(b) graphs is rather important. It is determined by the relations of the left lower and upper vertices of both graphs. As to the nuclear vertices, their relation can be obtained from the available data on the ^{4}He(e,ep) reaction [4]. They show that the vertex of two-particle ^{4}He decay is much more than the vertices of three and four-particle decays at relative momenta up to 250 MeV/c. There is no direct information on the vertices of virtual ${}^{4}_{\Sigma}$He decays. Owing to a lack of data on sigma-nuclear interactions, the reliable evaluations are now hardly possible. However, we have no reasons to assume that the two-particle channel is preferred here. Therefore it is possible to assert only that the contribution of Fig. 2(a) graph in any case should be noticeable against a ''background'' of the Fig. 2(b) graph. It is also indirectly confirmed by the results of Ref. [7].

There is one more interesting point originating during the analysis of the data. The modulus squared of Fig. 2(a) is the product of the modulus squared of triangle graph with constant lower vertex, which is shown by a solid line in Fig. 3, and the Breit-Wigner resonance factor. It is easy to see that this product has two peaks. The first corresponds to the resonance, and the second is located at $E_{ex}\approx 0$. The ratio of these peaks depends on the width of the resonance. For the case of narrow resonance, the ''cusp'' maximum near $E_{ex}=0$ will be suppressed by the Breit-Wigner factor, and for the case of broad resonance this maximum will be large. It imposes additional constraints on the resonance width. The point is that, though the data have an enhancement near $E_{ex}=0$, it is not large. Moreover, a ratio of magnitudes of indicated maxima

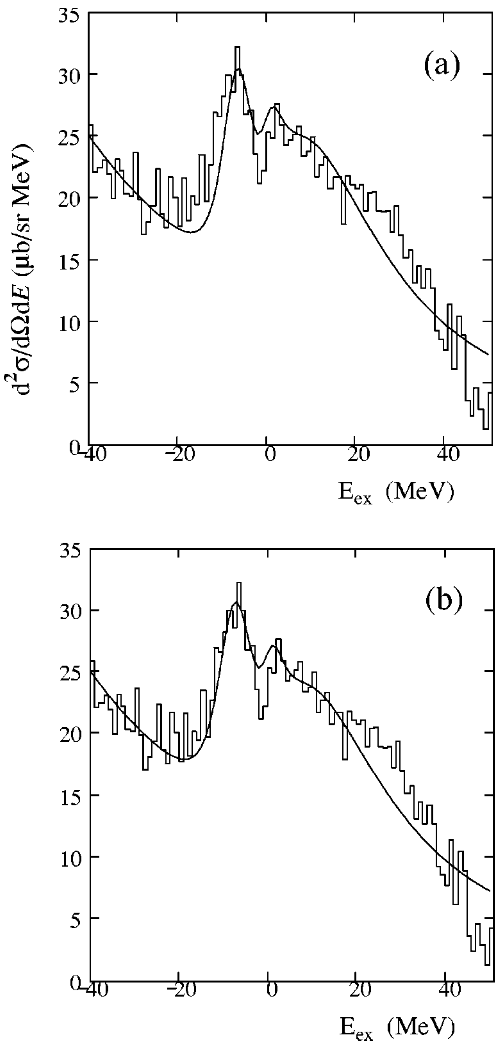

FIG. 4. Theoretical description of the E_{ex} spectrum for the reaction ${}^4\mathrm{He}(K^-,\pi^-)$: (a) with ${}^4_\Sigma$He parameters from Ref. [1]; (b) with the binding energy 5.4 MeV and the width 8.5 MeV. The curves take into account a detector resolution of 3.63 MeV FWHM [1].

in total result [with account for Fig. 2(b)] is sensitive to the relative contribution of Figs. 2(a) and 2(b). The relative magnitude of the maximum at $E_{ex}=0$ decreases with increasing a partial yield of continuum [Fig. 2(b)] in the intermediate state. This fact appears to be rather important for fitting the data.

A rapid variation of the ${}^4_\Sigma$He production amplitude as a function of E_{ex} was not taken into account in the analysis of Ref. [1]. It made the procedure not quite correct. Let us look at what results correctly account for the production mechanism, corresponding to the graphs of Figs. 2(a) and 2(b). We shall begin by attempting to describe the E_{ex} spectrum with the parameters from Ref. [1], that is, the binding energy 4.4 MeV (this corresponds to $E_{ex}=-7$ MeV) and the width 7 MeV. The best description for this case is shown in Fig. 4(a). It is necessary to accept here that the ratio of Figs. 2(a) and 2(b) is not more than 1:5. Otherwise there would be a too large enhancement at $E_{ex}=0$ in obvious contradiction with the data.[2] It is possible to see that the peak is described not so well, especially the left wing.

The situation can be improved by a modification of ${}^4_\Sigma$He parameters. Various versions of the fitting procedure have shown that the best description of E_{ex} spectrum could be obtained with the binding energy 5.4 MeV (this corresponds to $E_{ex}=-8$ MeV) and the width 8.5 MeV. This fit is shown in Fig. 4(b). A smaller width would lead to a poor description for the left wing of the resonance peak. The larger width would lead to too strong peak at $E_{ex}=0$. The latter is also essential in another respect. As indicated above, the technique for inclusion of the Λ production tail is incomplete. If the solid curve in Fig. 1 were more rapidly decreasing, then, after its subtraction, the resonance left wing would be broader. It would demand a larger value of the width. However, as it appears, a width more than 8.5–9.0 MeV is forbidden as it would strengthen the peak near $E_{ex}=0$. In addition, to keep the magnitude of this peak in reasonable limits, it is necessary to suppose that the contribution of multiparticle intermediate states in Fig. 2 is several times more than the contribution of two-particle states. From here follows that the probabilities of virtual ${}^4_\Sigma$He decays to three- and four-particle channels are much larger than to two-particle ones.

In summary we shall mark the following.

(1) The amplitude of ${}^4_\Sigma$He production was shown to be a sharply varying function of mass just in the resonance region.

(2) It results in a small, but noticeable shift of ${}^4_\Sigma$He parameters in comparison with the results of Ref. [1]. The central value of the binding energy is increased by 1 MeV and the central value of the width is increased by 1.5 MeV. This shift, though, is not large and does not exceed the limits of the errors indicated in Ref. [1], nevertheless can be important for estimations of Σ-nuclear interaction [10].[3]

(3) From the comparison of the cross section near $E_{ex}=0$ with calculations, the additional evidence is obtained that ${}^4_\Sigma$He width does not exceed 8.5–9.0 MeV. The indication is also obtained on the preferred role of multiparticle channels for virtual ${}^4_\Sigma$He decay.

(4) The considered case can be of interest in more general aspect as the unique example of a resonance on a sharply varying background.

(5) The appearance of more statistically based data will require to refine the calculations in several points: (a) using a

[2]We mean the ratio without account of Breit-Wigner resonance factor. The contribution of Fig. 2(b) graph to actual spectrum remains small as the resonance factor hardly suppresses the whole area $E_{ex}>10$ MeV.

[3]After this article was submitted for publication, Ref. [11] became known to the author. Application of sigma-nuclear potentials has allowed us to advance here in numerical estimations, but has made the results model dependent. Let us underline that the change of the observed resonance shape is associated not only with a threshold singularity, considered in Ref. [11], but also with a proper triangle singularity of Fig. 2(a).

realistic ^{4}He wave function; (b) account of a form factor in the vertex of the resonance production in Fig. 2(a); (c) elaboration of a reliable model for the Λ production tail in (K^-,π^-) processes.

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