Observation of kinematic focusing of the products of the three-particle decay of $^9Be(5/2^-)$

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Experimental data on the "democratic decay" of $^9Be^*(5/2^-)$ reveal the kinematic focusing which has been predicted for $^9Be^*$ and $^9B^*$. Evidence for the appearance of a new "good" quantum number in democratic decay has been found.

In studies of three-particle decays of $A = 6$ states, Bochkarev *et al.*[1,2] obtained data on the properties of "democratic decays" of nuclei, i.e., n-particle decays ($n \geqslant 3$) which do not reduce to a cascade of well-separated decays into fewer than n fragments. In particular, (1) they observed exotic democratic decay modes which resulted from a momentum focusing and a spatial focusing of the particles of a kinematic nature,[1–3] and (2) it was stated[1] that the democratic decays of light nuclei may be characterized by an additional "good" quantum number: the hypermoment K. Testing the suggestion that K plays an important role requires further research on the democratic decays of nuclei. There is the possibility that new manifestations of kinematic focusing will be observed; i.e., this effect should be of a universal nature. There is also interest in a competition between the mechanism of democratic decay and the cascade decay of nuclei.

In this letter we examine decays to the $\alpha + \alpha + N$ states of $^9Be^*$ and $^9B^*$ from the isodoublet with $J^\pi = 5/2^-$. The intensity of the democratic decay is high here, since the competing cascade decay through $^8Be(0^+)$ uses up only 0.5%–20% of the width of $^9Be^*$ and $^9B^*$ (Refs. 4 and 5; this quantity requires experimental refinement, since the data from Refs. 4 and 5 differ).

The democratic decay process was studied under the assumption that K alone dominates the expansion of the amplitude for the democratic decay in a hyperspherical basis.[6] Because of the increase in the three-particle centrifugal energy[6] with increasing K, a study was made of the lowest value of K for $\alpha+\alpha+N$ with $J^\pi = 5/2^-$: $K_{min} = 3$. At $K = 3$ there are two democratic decay modes: with $L = 2$ and 3, where L is the total orbital angular momentum in $\alpha + \alpha + N$. Summed with the spin of the nucleon, L contributes an angular momentum $J = 5/2$. Since it was found[3] in the study of $A = 6$ that K_{min} may be suppressed by the Pauli principle, a study was made of the effective interaction of all particles in states with $K = 3$ of $^9Be^*$ and $^9B^*$ on the basis of the $\alpha + \alpha + N$ model. The technique of Raynal-Revai coefficients was used. It was found that at $L = 2$ there are both an $\alpha\alpha$ attraction in the d state [the $^8Be^*(2^+)$ resonance] and an αN attraction in the p state (a ^5He, ^5Li resonance). Accordingly, for $^9Be^*$, $^9B^*$ the process with K_{min} is allowed. The $L = 3$ wave, which is also associated with a d $\alpha\alpha$ attraction, stems from a p αN attraction, with a weight (44%) smaller than that of $L=2$ (90%). Furthermore, $L=3$ corresponds with a significant weight (24%) to an s state of αN; this circumstance could additionally suppress $L=3$ in $^9Be^*$, $^9B^*$ (the filling of the 1s shell in α). This structural feature of $^9Be^*$, $^9B^*$—the predominance of $L=2$—may be reflected in the distributions of the products of the democratic decays of $^9Be^*$, $^9B^*$. Finally, to find the total decay amplitude we supplemented the democratic decay with the cascade $^9Be^*$, $^9B^* \to N + {}^8Be(0^+)$, $^8Be \to \alpha + \alpha$, described in the R-matrix approach.

We can write the distributions of decay products in the $A=9$ rest frame which are set by the total amplitude for the case of a uniform population of the $^9Be^*$, $^9B^*$ spin projections. The probability for the emission of nucleons with an energy E_N in the Ω_N

$$d^2p/dxd\Omega_N = a\frac{2^6}{3\pi^2}x^{3/2}(1-x)^{5/2} + (1-a)\frac{Q\Gamma_0}{8\pi^2}[(E_0-Q(1-x))^2+\Gamma_0^2/4]^{-1},$$

direction is where $x = 9E_N/8Q$, Q is the energy for the decay of $^9Be^*$, $^9B^*$ into $\alpha+\alpha+N$, and the values $\Gamma_0 = 7$ eV and $E_0 = 97$ keV correspond to ^8Be. The probability of the democratic decay is a; the probability for a decay through ^8Be is $1-a$ ($\int(d^2p/dxd\Omega_N)\times dxd\Omega_N = 1$). The democratic decay modes of $L=2$ and 3 are indistinguishable in (1). The probability for α-particle emission is

$$d^2p/dyd\Omega_\alpha = (a-b)\frac{2^6}{3\pi^2}y^{3/2}(1-y)^{3/2}(0.8y+0,1)$$

$$+b\frac{2^6}{3\pi^2}y^{1/2}(1-y)^{1/2}(-0,06y^3-0,102y^2$$

$$0,254y+0,0116)+(1-a)$$

$$\frac{5}{24\pi}z^{-1/2}(1-z)^{-1/2}\Big|_{y\in[0,1(9-8z-6\sqrt{z(1-z)});\,0,1(9-8z+6\sqrt{z(1-z)})]} \qquad (2)$$

where $y = 9E_\alpha/5Q$, and $z = 1-(E_0/Q)$. The three terms in (2) describe democratic decay with $L=2$, democratic decay with $L=3$, and a cascade through ^8Be, respectively. Their probabilities are $a-b$, b, and $1-a$. The components of the distribution from a kinematically complete experiment are written in the same order:

$$d^3p/dxd\Omega_N d\Omega_{\alpha-\alpha} = (a-b)\frac{2^3}{\pi^3}x^{3/2}(1-x)^{5/2}\sin^2\alpha$$

$$+b\frac{2^4}{7\pi^3}x^{3/2}(1-x)^{5/2}(2+\cos^2\alpha)+(1-a)\frac{Q\Gamma_0}{32\pi^3}[(E_0Q(1-x))^2+\Gamma_0^2/4]^{-1}, \qquad (3)$$

where $\alpha = p_{\alpha-\alpha p\alpha\alpha-N}$ is the angle between the relative momentum of the $\alpha\alpha$ pair, $\mathbf{p}_{\alpha-\alpha}$ and that of the center of mass of this pair and the nucleon, $\mathbf{p}$ $\alpha\alpha-N$. In a comparison of (1)–(3) with experimental data, a and b are adjustable parameters.

It can be seen from (1)–(3) that the contribution of the democratic decay have characteristic shape which is sharply different from that in the case of an uncorrelated separation of $\alpha + \alpha + N$, i.e., sharply different from the phase volume (the situation is illustrated clearly in the lower part of Fig. 1). Such correlations embody the expected kinematic focusing of products. On the whole, the experimental data on the ^{9}Be*, ^{9}B* decay make it possible (1) to observe a new manifestation of the kinematic focusing during democratic decay, (2) to test the suggestion that K is a good quantum number through a comparison with (1)–(3) where the number of parameters is small, and

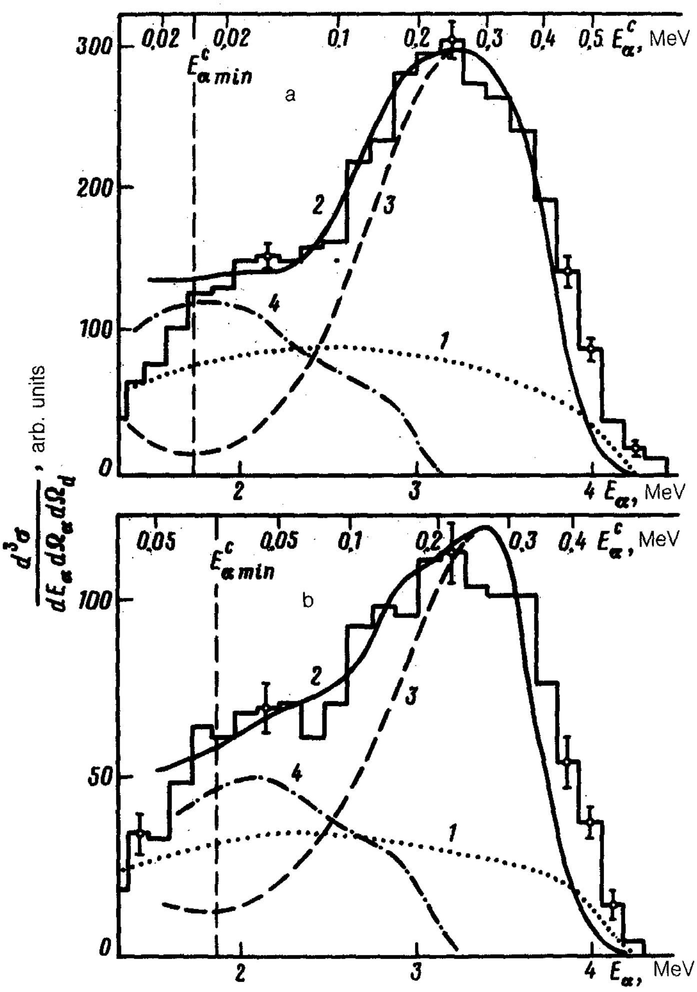

FIG. 1. Spectra of α particles in the laboratory frame from the decay $^9\mathrm{Be}^*(5/2^-) \to \alpha + \alpha + n$, found during the detection of $\alpha + \mathrm{d}$ coincidences from $^9\mathrm{Be(d, d)}^9\mathrm{Be}^*$ at $E_\mathrm{d} = 13.6$ MeV at angles (a) $\theta_\mathrm{d} = 80°$, $\theta_\alpha = -45°$ and (b) $\theta_\mathrm{d} = 85°$, $\theta_\alpha = -45°$. The upper scale shows the α energy in the rest frame of ^{9}Be*. 1-Phase volume for $\alpha + \alpha + n$; 2-description of the spectrum by expression (2) with b = 0; 3-contribution of democratic decay with $L = 2$; 4-contribution of the decay through $^8\mathrm{Be}(0^+)$.

where the components have an extremely nontrivial form, (3) to take up the question of the competition between democratic decay and a cascade (the parameter a), and (4) to study the competition between the democratic decay modes with $L=2$ and 3 (the parameter b). Under the assumption that a democratic decay reflects the structure of the ^{9}Be*, ^{9}B* wave function in the internal region, we would expect the democratic decay with $L=2$ to be predominant.

The spectra of α particles from ^{9}Be*, populated in the reaction ^{9}Be(d, d)^{9}Be*(5/2$^-$) at $E_d = 13.6$ MeV, measured in Ref. 7, are shown in Fig. 1 for two arrangements of the detectors which were detecting $\alpha + d$ coincidences (the energy loss of the α particles in the target and in the dead layer of the detector are taken into account in

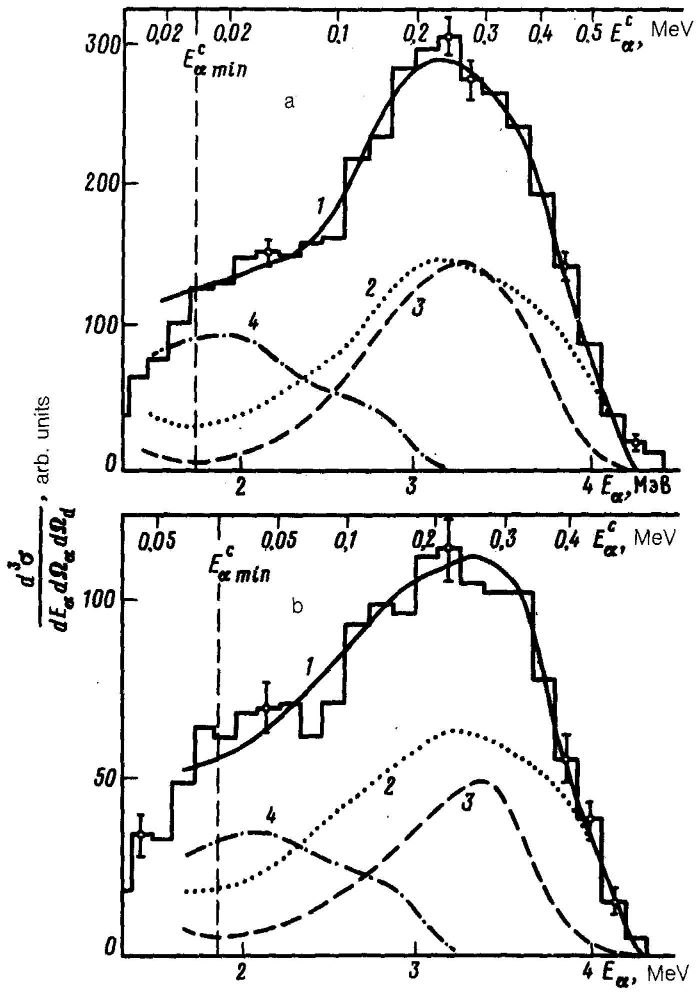

FIG. 2. The same as in Fig. 1. Lines 1-Result of the description of the α spectrum by expression (2); 2-contribution of the democratic decay with $L=3$; 3-contribution of the democratic decay with $L=2$; 4-contribution of the cascade through ^{8}Be(0$^+$).

Fig. 1). The spectra in Fig. 1 have a characteristic shape which is strikingly different from that of the phase volume (lines 1).[1)] The peak in the hard region, which reflects a correlation between a neutron and an undetected α in terms of the energy of their relative motion, cannot be described by a final-state αn interaction. The spectra were analyzed with the help of (2). In a first step it was assumed that $L = 2$ (i.e., $b = 0$) dominates the democratic decay. As a result, it was found possible to describe the data (lines 2 in Fig. 1). The $L = 2$ process (lines 3) explains the peak in the spectra. The cascade through ^{8}Be (lines 4) corresponds to a probability $\approx 20\%$. In the second step of the analysis of the α spectra, the democratic decay with $L = 3$ [$b \neq 0$ in (2)] was also included. The result (lines 1 in Fig. 2) gives a good description of the spectra (the contribution of the decay through ^{8}Be is $\approx 15\%$). It turns out that the experimental data allow a large weight ($\approx 50\%$) for the democratic decay with $L = 3$. The shape of this component (lines 2 in Fig. 2), however, is approximately the same as that of the component corresponding to democratic decay with $L = 2$ (lines 3), so further experiments are required for reaching a detailed understanding of the competition between the democratic decay modes with $L = 2$ and 3. It follows from Fig. 2 and also from Fig. 1 that the peak in the α spectra stems from a democratic decay, whose distinctive shape is a consequence of the kinematic focusing.

Let us summarize. 1. The kinematic focusing of particles during democratic decay which was predicted above has been found in this study in the α spectrum from ^{9}Be*. We wish to stress that the effect which we found is associated with the J^π of ^{9}Be*, not with the Pauli principle, as it was in the case of the focusing which was observed in Ref. 3 for the $A = 6$ system. 2. Our comparison of the α spectra with theoretical predictions confirms the suggestion by Bochkarev *et al.*[1] that K is a good quantum number during democratic decay. A detailed study of the competition between the various decay modes will require measurements of the spectra of all particles from ^{9}Be*, ^{9}B. Particularly promising from the kinematic standpoint are complete experiments, because of the radical difference between the angular parts of the democratic decays with $L = 2$ and 3 in (2).

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[1)] The energy spread caused by the nonpoint geometry of the experiment was taken into account in all the calculations, by the method of Ref. 8

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