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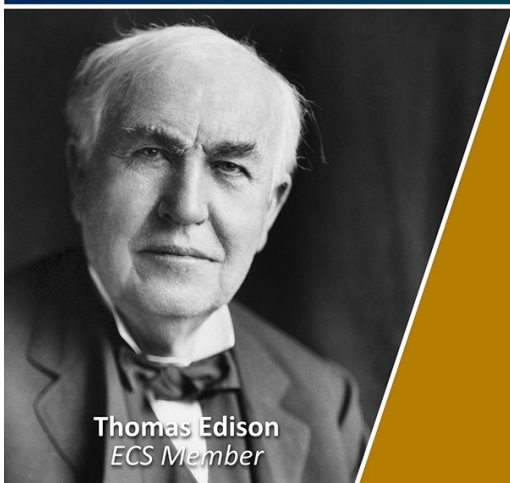
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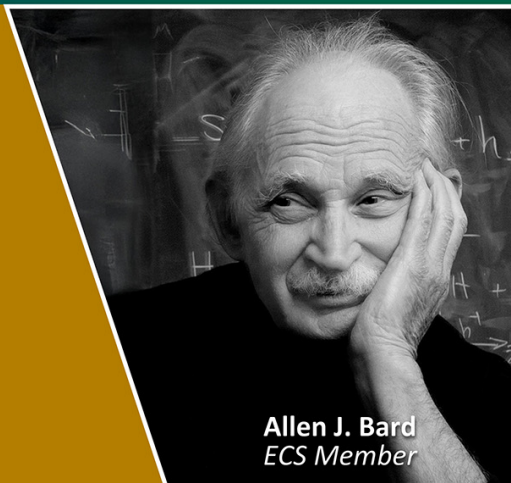
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## Alpha cluster structure in $^{56}\text{Ni}$

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**Abstract.** The inelastic  $\alpha$ -scattering experiment on  $^{56}\text{Ni}$  in inverse kinematics was performed at an incident energy of 50 MeV/u at GANIL. A very high multiplicity for  $\alpha$ -particle emission was observed with our phase-space limited experimental set-up. The maximum observed multiplicity, which cannot be explained by means of the statistical decay model, amounted to seven. The ideal classical gas model at  $kT = 3$  MeV fairly well reproduced the experimental momentum distribution and multiplicity of alpha particles. This result strongly suggests that an alpha-gas state in  $^{56}\text{Ni}$  may be excited via inelastic alpha scattering.

### 1. Introduction

Alpha cluster states were predicted in the 1960s by Ikeda et al.[1]. About 30 years later, several theorists started to discuss the possibility of  $\alpha$ -particle condensation in low-density nuclear matter [2], as various exotic features were expected because this might correspond to a nuclear phenomenon analogous to the Bose-Einstein condensation for a finite number of dilute bosonic atoms. They predicted that the condensation could occur in the low-density region, and that the condensate states in

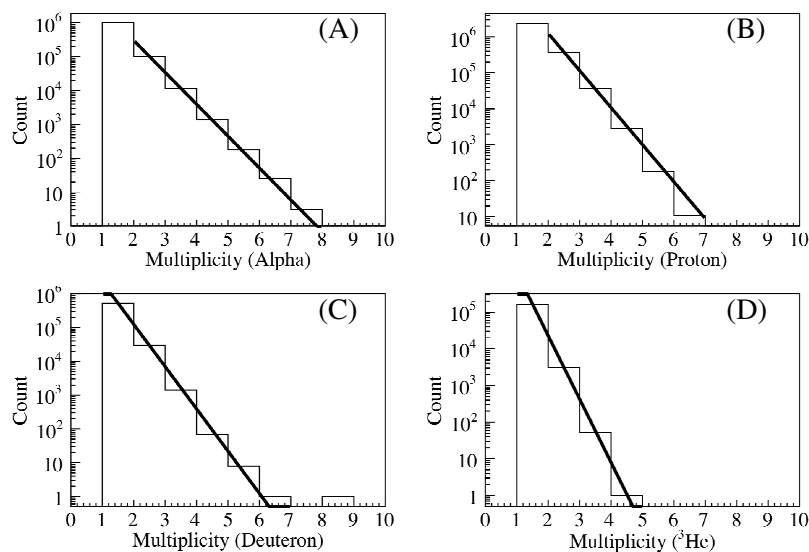


finite nuclei may exist in excited states with a dilute density composed of weakly interacting gas of  $\alpha$ -particles [3, 4]. However, experimentally, almost no information about such states has been obtained except for light nuclei such as  $^8\text{Be}$ ,  $^{12}\text{C}$  [5] and  $^{16}\text{O}$ .

## 2. Experiment

We performed the  $^4\text{He}(^{56}\text{Ni}, ^4\text{He})$  inelastic scattering experiment at an incident energy of 50 MeV/u at GANIL. Originally, the aim of the experiment has been to search for the compression modes in  $^{56}\text{Ni}$  which is almost the heaviest  $N=Z$  nucleus to be obtained as secondary beam at the present RI beam facility. A recoiled  $^4\text{He}$  particle as a target was measured using the active target system MAYA [6]. The MAYA detector is optimized to measure nuclear reactions with RI beams in reverse kinematics. It consists of an active gas target and an ancillary SSD+CsI detector wall located at forward angles.

## 3. Analysis



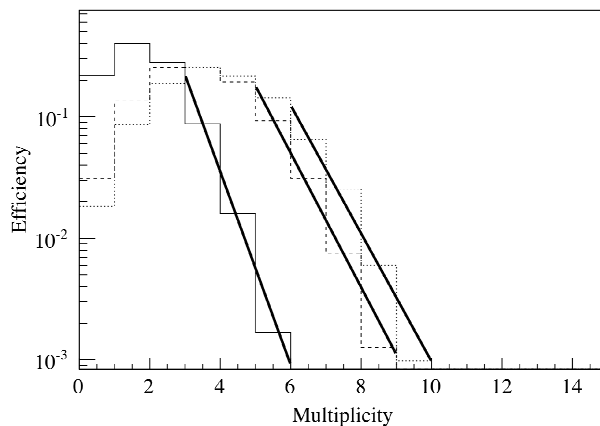
**Figure 1.** Multiplicity distributions of  $^4\text{He}$  (A), proton (B), deuteron (C), and  $^3\text{He}$  (D). The histograms and solid lines correspond to the experimental data and the results of fitting.

An analysis of the data was performed for the detector wall. In this analysis, we found that many particles are emitted at forward angles with high multiplicities. In Fig. 1, multiplicity distributions of  $^4\text{He}$ , proton, deuteron, and  $^3\text{He}$  are shown. As shown in Fig. 1 the maximum observed multiplicity for alpha particles is seven. It means that half of the mass of  $^{56}\text{Ni}$  is observed to be carried away by means of emitting alpha particles. The multiplicity distributions are well reproduced by an exponential function  $\exp(-\lambda m)$ , where  $m$  is the multiplicity. The decay constant  $\lambda$  is determined to be 2.17 for alpha particles. This  $\lambda_{4\text{He}}$  value is the smallest among the decay constants for p, d, and  $^3\text{He}$ , here  $\lambda_p = 2.37$ ,  $\lambda_d = 2.88$ , and  $\lambda_{3\text{He}} = 3.98$ . The  $\lambda$  constant is considered to be the sum of the multiplicity dependence of the cross-section for the  $^{56}\text{Ni}(^4\text{He}, m-\alpha)$  reaction and the experimental acceptance for particles. The experimental acceptance for particles is roughly estimated to be around 15%, and to be the major part of  $\lambda$ . Consequently, the multiplicity dependence of the cross section is relatively small. This experimental result is surprising, because it is natural to expect that the charged particle decay from highly excited states is strongly suppressed by the Coulomb barrier. Usually, in medium-heavy and heavy nuclei neutron decay is the predominant process for damping of highly excited states at the excitation energy above the particle decay threshold. The experimental result obtained in the present

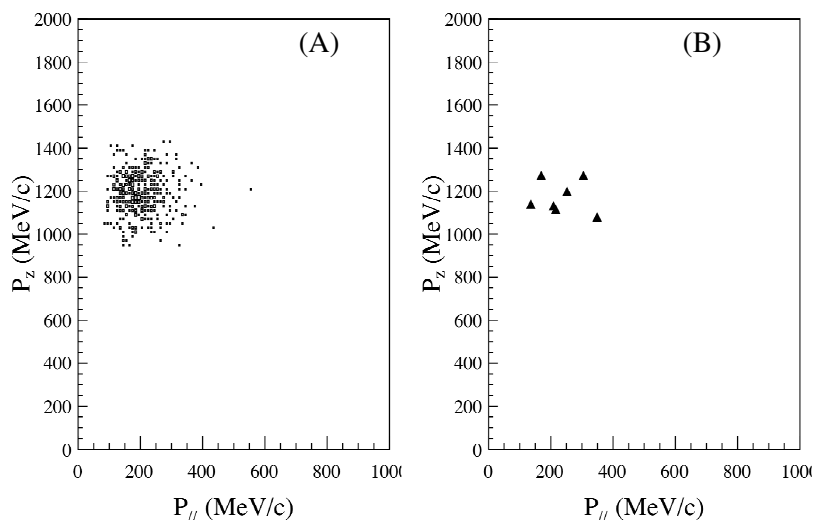
experiment shows strong evidence for multiple-particle decay, and may suggest a possible existence of a condensed state.

### 3.1. Statistical decay model

In order to eliminate the possibility for statistical decay from compound states which have small overlap with an alpha cluster state, we performed statistical decay model calculation based on the Hauser-Feshbach formalism using the code CASCADE [7]. In the calculation, spin, isospin, and parity of the excited states in daughter nuclei are used as the input parameters. Individual level parameters for the low-excitation energy region were taken from the experimental data. Global parameters for the level-density formula were used to describe the unknown levels at high excitation energies. All the decay channels:  $\gamma$ , proton-, deuteron-, and alpha- decays are taken into account.



**Figure 2.** Detection efficiency for a fourteen alpha event at  $kT=1$  MeV (solid histogram), 3 MeV (dashed histogram), 5 MeV (dotted histogram). The solid lines are the results of fitting with an exponential function  $\exp(-\lambda m)$ .

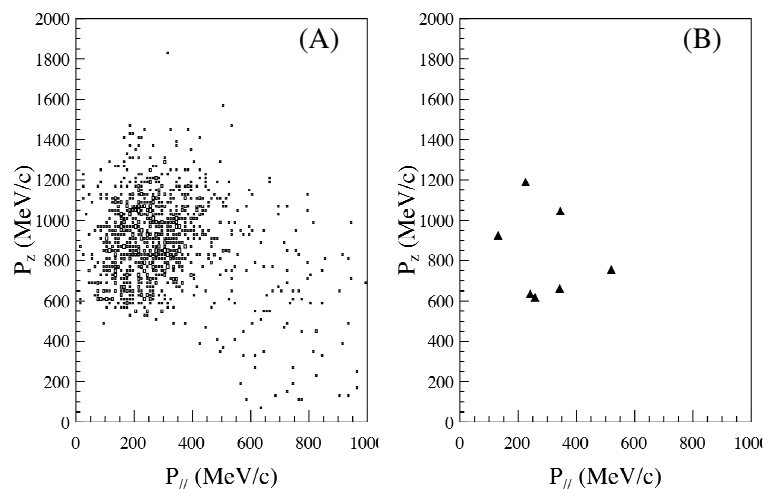


**Figure 3.** Results of simulations based on the classical ideal gas model. (A) Momentum distributions of alpha particles from events with multiplicity larger than 5. (B) Momentum distribution for one event with multiplicity seven.

The spin and parity for the excited states in  $^{56}\text{Ni}$  were set to be  $J^\pi=0^+$ , assuming that a strong monopole resonance was strongly excited at high excitation energy of 150 MeV. The maximum angular momentum for decay products was set to  $40\hbar$ . According to the result of the statistical decay model calculation, the probability for 7-alpha decay is less than 0.01%. Therefore, the statistical decay model cannot explain the experimental result. One of the possible explanations is that these many-alpha particle emissions may come from an exotic excited state such as a diluted  $\alpha$ -gas state.

### 3.2. Ideal gas model

In order to understand the events with high multiplicity of alpha particles, we performed a simulation based on the simple statistical model. In this model, we assumed that the excited state in  $^{56}\text{Ni}$  consists of seventeen independent alpha clusters, and that the distribution of the kinetic energy for each alpha particle follows the Boltzmann distribution for the classical ideal gas at temperature  $T$ . In the simulation, the detection probability was estimated event by event for fourteen alpha particles. The kinetic energy and the direction of momentum in the centre of mass system of  $^{56}\text{Ni}$  were randomly given by the Boltzmann distribution. The SSD+CsI detector wall of MAYA is segmented into  $10 \times 8$   $\Delta E$ - $E$  cells. Because each cell can identify only one charged particle in one event, we omitted in the present analysis the cell signals with a multiple-hit of charged particles. Since the thickness of the  $^4\text{He}$  gas target is about 40 cm and it is located in front of the detector wall, the scattering angles depend on the vertex point of the reaction. In order to take into account this effect, the vertex points are determined in the active gas target, when the polar angles and azimuthal angles of the recoil alpha particles are reconstructed.



**Figure 4.** (A) The experimental momentum distributions of alpha particles from events with multiplicity larger than 5. (B) The momentum distribution for one event with the multiplicity seven.

In Fig. 2, the results of simulation for the detection efficiency of alpha particles from  $^{56}\text{Ni}$  at  $kT = 1, 3,$  and  $5$  MeV are shown, where  $k$  is the Boltzmann constant. The temperature of  $kT = 3$  MeV corresponds to the excitation energy of 150 MeV in  $^{56}\text{Ni}$ . In Fig. 2, we see that the efficiency for detecting many alpha particles is low. Furthermore, the efficiency is especially low at lower temperature. Because at the lower temperature, alpha particles move with small kinetic energies in the c.m. system of  $^{56}\text{Ni}$ , and are therefore boosted to very small angles in the lab system, only a few alpha particles can be identified. At  $kT = 1, 3,$  and  $5$  MeV, the detection efficiency for an event with seven alpha particles detected out of fourteen in total is  $<0.1\%, 0.8\%$  and  $1.8\%$  respectively. Taking

this into account, the cross-section for excitation of the alpha gas state via inelastic alpha scattering is estimated to be 1~10 mb at 50 MeV/u. This uncertainty mainly comes from the ambiguity in the excitation energy. Fig. 3 shows the two-dimensional scatter plot of the momentum distribution of alpha particles obtained by simulation at  $kT = 3$  MeV. The left panel shows the superposition of all the events with a multiplicity larger than five. The right panel shows an example of the momentum distributions for one event of multiplicity seven.

Fig. 4 shows the two-dimensional scatter plot of the momentum distributions of alpha particles obtained in the experiment. The left panel shows the superposition of all events with multiplicity larger than five. The right panel shows the momentum distribution for an event with multiplicity seven. In Fig. 4(A), alpha particles with  $P_{\parallel}$  higher than 500 MeV/c are interpreted as recoiled target alpha particles, which are not shown in Fig. 3(A) obtained by the simulation. Although the momentum distribution of alpha particles is slightly wider compared with that of the simulation, the characteristics of the momentum distribution are well reproduced by the simple ideal gas model.

#### 4. Summary and conclusion

We performed the  ${}^4\text{He}({}^{56}\text{Ni}, {}^4\text{He})$  inelastic scattering experiment at an incident energy of 50 MeV/u. The inverse kinematics method was utilized to measure the reaction on the unstable  ${}^{56}\text{Ni}$  nucleus. Multi-alpha decay events were observed. The maximum multiplicity observed for alpha particle was seven. This result is striking, because such high multiplicity cannot be explained by using a simple statistical-decay-model calculation. In order to understand this situation, we performed a simulation based on the ideal alpha-gas model. In this model, the momentum distribution follows the Boltzmann distribution. The experimental data are fairly well reproduced by taking into account the acceptance of the detector for multi-alpha particles events. This result strongly suggests the existence of an alpha gas state at high excitation energies in  ${}^{56}\text{Ni}$ .

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