Search for oscillations in evaporation α-particle spectra from hot compound nuclei

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The inclusive α-particle spectra from $^{16}O+^{89}Y$, $^{12}C+^{93}Nb$, and $^{16}O+^{93}Nb$ reactions around 6–7 MeV/nucleon incident energy (laboratory) have been studied. These spectra have been fitted very well using an algebraic expression for the statistical emission of particles from the compound nucleus and subsequent daughter nuclei. We do not find any statistically significant oscillations in the remaining spectra after subtracting out the contributions due to initial and sequential emissions from the compound nuclei, thus showing no direct evidence for the existence of α particles as independent particles in the nuclei.

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I. INTRODUCTION

The search for the existence of complex particles as independent particles inside a nucleus is still an ongoing effort [1–3]. If a complex particle such as a α particle can indeed exist as an independent particle inside a compound nucleus, then because of α particle resonances in the nuclear potential well, the transmission coefficient of α particles (from the potential well) should show oscillations as a function of α-particle energy for each partial wave. Since several such partial waves contribute, so the oscillations will tend to be washed out in the spectrum of α particles emitted from the compound nucleus. However, complete cancellation of such oscillations is not expected and so there should be tiny oscillations left in the spectrum of α particles emitted from the compound nucleus. Moretto *et al.* [1] and Jing [2] suggested that such oscillations might be observable in evaporation spectra of very high statistical quality.

It is well known that a highly excited compound nucleus deexcites by emitting predominantly neutrons, protons, α particles, and γ-ray photons or it may undergo a fission process. The statistical properties of the compound nucleus such as its temperature, deformation, etc., can be deduced from the observed particle spectra. Earlier works [4–6] showed that standard statistical model codes such as CASCADE and PACE can usually give a reasonably good (within 10%–15%) and in some cases only a qualitative description of evaporation spectra from compound nuclei. But these codes are not really suitable to fit evaporation spectra with very high precision (within $\approx 1\%$). The reason is that these are very large and complex codes with a large number of parameters. So they are not suitable to be put inside a fitting routine and search for the best fit parameters. In order to obtain high precision fits to high statistics evaporation spectra, it would be very convenient to use an algebraic representation of statistical evaporation spectrum using only a few parameters. Moretto [7] derived such an algebraic expression to represent the statistical emission of particles from a hot compound nucleus. According to Moretto's formula, the statistical evaporation spectrum from a compound nucleus can be described [1,2,7] by the following formula:

$$P(x) \propto \exp(-x/T)\,\mathrm{erfc}\left(\frac{p-2x}{2\sqrt{pT}}\right), \tag{1}$$

where $x = E_{\mathrm{c.m.}} - V_c$ Here V_c is the Coulomb barrier energy, $E_{\mathrm{c.m.}}$ the center of mass energy, and p is a parameter called the amplification factor and it measures the change of Coulomb barrier due to the shape fluctuation of the compound nucleus. T is the temperature of the compound nucleus.

Moretto *et al.* [1] and Jing [2] measured α spectra from a ^{3}He+natural Ag reaction with very high statistics. They fitted such spectra with a statistical evaporation formula as given by Eq. (1) and obtained a very good fit in each case. After subtracting out the fitted spectrum from the experimental one, they found oscillations in the remaining spectrum at the (1–2)% level and speculated [1,2] that these oscillations could be the signature of the existence of α particles as independent particles inside the potential well of the compound nucleus. If these oscillations are real and cannot be understood in terms of well-known physical processes such as sequential decay from daughter nuclei, then they most likely point towards the existence of α particles as independent particles inside the nuclei. So it is important to confirm the existence of such oscillations in the evaporation α spectra and find out if any well-known physical process can account for them. In order to find out if these oscillations might be related to any kind of entrance channel effect, the same compound nucleus ^{105}Ag was produced at the same excitation energy and with a similar spin distribution by using $^{16}O+^{89}Y$ and $^{12}C+^{93}Nb$ reactions at suitable energies and α spectra from the nucleus were studied.

II. EXPERIMENTAL PROCEDURE

We undertook a study of α spectra at back angles from ^{105}Ag nucleus at an excitation energy of 76 MeV using $^{16}O+^{89}Y$ and $^{12}C+^{93}Nb$ reactions. A 10 pnA 95.9 MeV beam of ^{16}O from BARC-TIFR pelletron macine (located at Tata Institute of Fundamental Research, Mumbai, India) was used to bombard a 1 mg/cm^2 thick ^{89}Y target. Four $\Delta E - E$ telescopes were placed at different angles between 140° and 170° to record alpha spectra. Similarly, a 10 pnA 85.5

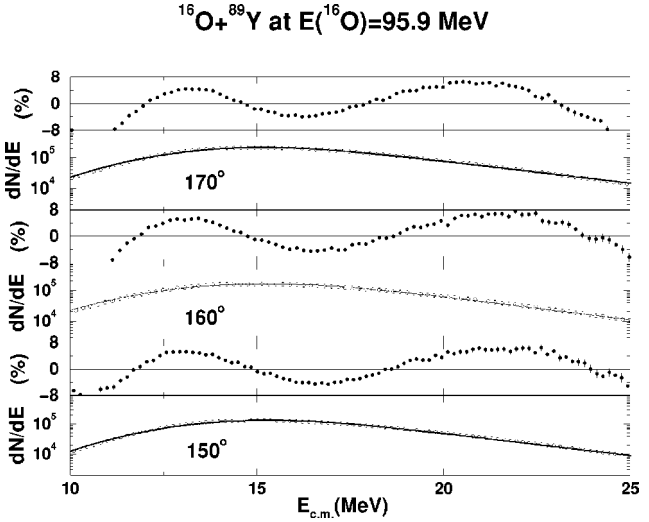

FIG. 1. Lower panels: experimentally measured α spectra at $\theta_{lab}=150°$, 160°, 170° from the $^{16}O+^{89}Y$ reaction have been fitted with Eq. (1). Upper panels: percentage difference between the experimental data and the fits.

MeV ^{12}C beam from pelletron machine at Nuclear Science Center, New Delhi, India was used to bombard a 1 mg/cm^2 thick ^{93}Nb target and alpha spectra were recorded at back angles. Monitor detectors were kept at forward angles (25°) for beam monitoring and normalization purposes.

We also studied α emission from ^{109}In nucleus at an excitation energy of 96 MeV by bombarding a 1.2-mg/cm^2-thick ^{93}Nb target with a 5 pnA 116 MeV ^{16}O beam from Variable Energy Cyclotron Centre, Kolkata, India. Alpha spectra were recorded from 100° to 150° using a ΔE-E telescope. At each angle, counting was performed for at least 24 hours to obtain a high statistics α spectrum. Energy calibrations of α spectra were done by using well-known α lines from a ^{229}Th source and elastic peaks from forward angle scattering of ^{12}C and ^{16}O by a gold target.

III. ANALYSIS AND RESULTS

The α spectrum obtained at each angle was converted to the center of mass frame assuming two-body kinematics. In Fig. 1 and 2 (lower panels), we show α spectra (in the center of mass frame) taken at $\theta_{lab}=150°$, 160°, 170° from a $^{16}O+^{89}Y$ reaction and those taken at $\theta_{lab}=143.7°$, 151.7° from a $^{12}C+^{93}Nb$ reaction, respectively. The spectrum taken at $\theta_{lab}=130°$ from $^{16}O+^{93}Nb$ reaction is shown in Fig. 3 (lower panel). These are our cleanest spectra with very good statistics($\geqslant 10^4$ counts per 0.3 MeV). These spectra were fitted with a statistical evaporation formula as given by Eq. (1) considering only the statistical uncertainties of the data points. The uncertainty in our absolute energy calibration is around ± 0.5 MeV, but this uncertainty has not been considered in the fitting procedure. Excellent fit was obtained in each case. So the algebraic expression [Eq. (1)] can describe the experimental spectra with very high precision. From such fits, we obtained that the temperature of the α emitting ^{105}Ag compound nucleus ($E_X=76$ MeV) is around 3 MeV and that

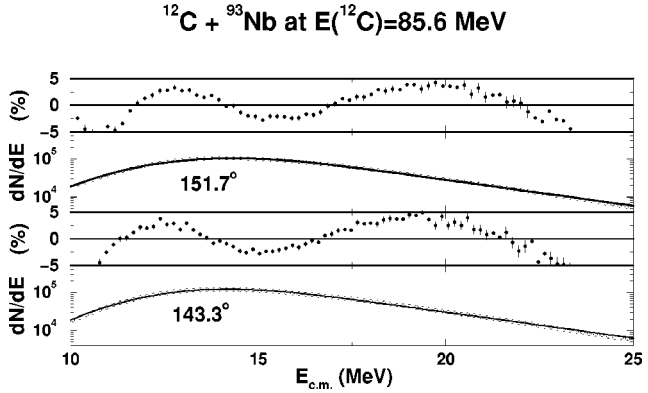

FIG. 2. Lower panels: experimentally measured α spectra at $\theta_{lab}=143.3°$ and 151.7° from the $^{12}C+^{93}Nb$ reaction have been fitted with Eq. (1). Upper panels: percentage difference between the experimental data and the fits.

of the ^{109}In compound nucleus ($E_X=96$ MeV) is around 3.5 MeV. After subtracting out fitted alpha spectra from the corresponding experimental spectra, we find oscillations at the level of 5%–7% in each remaining spectrum as shown in Figs. 1, 2, and 3 (upper panels).

In order to check if the observed oscillations are produced by any instrumental effect, we took high statistics data from a pulser with a 0–4 V ramp through the same instrumental setup. The spectrum thus obtained does not show any sign of oscillation, thus confirming that the observed oscillations are not due to any type of instrumental effect.

Although the magnitudes of these oscillations are considerably higher than those seen (at the level of 1%–2%) in Refs. [1,2], the widths and shapes of these oscillations are very similar to earlier results [1,2]. The likely reason for seeing bigger oscillations in our work is because of the production of compound nuclei with much higher angular momenta which lead to a comparatively larger mean energy shift of the sequentially emitted α particles.

Moretto *et al.* [1] and Jing [2] attempted to interpret this type of oscillations (first seen in the evaporation α spectra from the ^{3}He+natural Ag reaction) as the modulations associated with the optical potential felt by the α particle inside the nucleus. However, since α particles are emitted sequentially from a hot nucleus, the effect of sequential decays from the daughter nuclei should also be considered. So we fitted

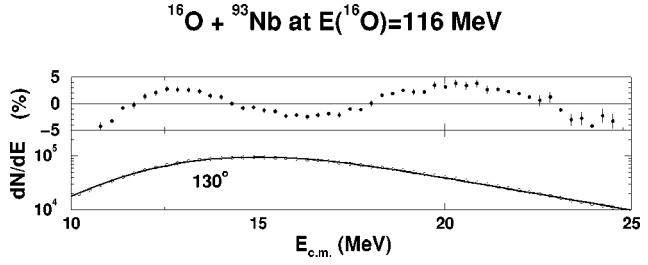

FIG. 3. Lower panel: experimentally measured α spectra at $\theta_{lab}=130°$ from $^{16}O+^{93}Nb$ reaction have been fitted with Eq. (1). Upper panel: percentage difference between the experimental data and the fits.

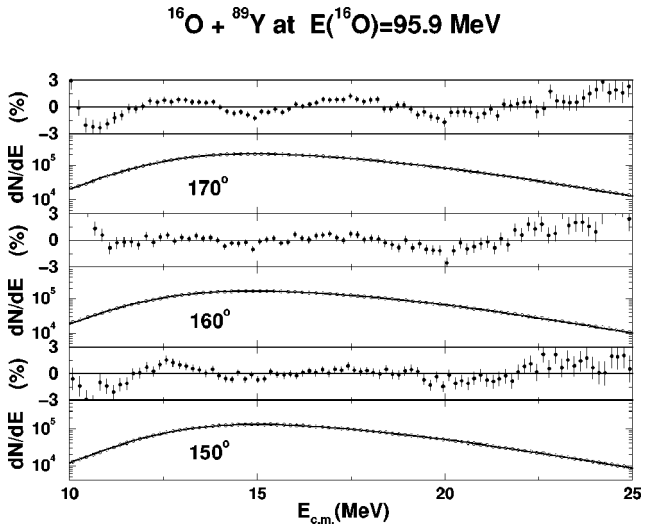

FIG. 4. Lower panels: experimentally measured α spectra at $\theta_{lab}=150°$, 160°, 170° from the $^{16}O+^{89}Y$ reaction have been fitted with statistical emissions from two compound nuclear sources. Upper panels: percentage difference between the experimental data and the fits.

experimental α spectra with statistical evaporation spectra from two compound nuclear sources by adding another term similar to Eq. (1). The second term will have different values of temperature (T), Coulomb barrier (V_c), and parameter (p) corresponding to those of daughter nuclei. It was found that by adding a second term to Eq. (1), the quality of fit improves and, in each case, as the fitted spectrum is subtracted out, the oscillations in the remaining α spectrum are reduced substantially. In Figs. 4, 5, and 6 (lower panels), we show a two-source fitting to the α spectra from $^{16}O+^{89}Y$, $^{12}C+^{93}Nb$, and $^{16}O+^{93}Nb$ reactions. The oscillations (upper panels) in the residual α spectra (after subtracting out fitted two-source evaporation spectra) are very much reduced compared to those in Figs. 1, 2, and 3 (upper panels). We do not find any indication of oscillations in most of the spectra shown in Figs. 4, 5, and 6 (upper panels). However, we find

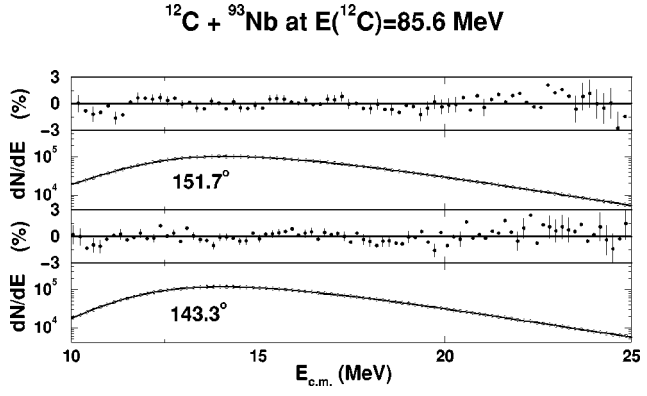

FIG. 5. Lower panels: experimentally measured α spectra at $\theta_{lab}=143.3°$ and 151.7° from the $^{12}C+^{93}Nb$ reaction have been fitted with statistical emissions from two compound nuclear sources. Upper panels: percentage difference between the experimental data and the fits.

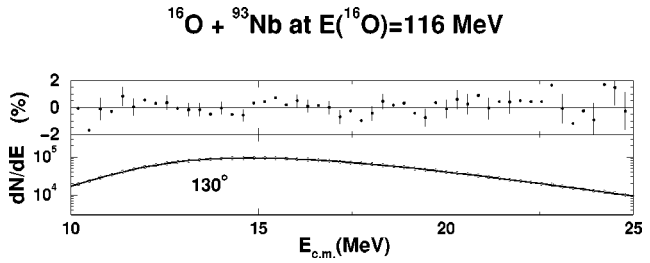

FIG. 6. Lower panel: experimentally measured α spectra at $\theta_{lab}=130°$ from the $^{16}O+^{93}Nb$ reaction have been fitted with statistical emissions from two compound nuclear sources. Upper panel: percentage difference between the experimental data and the fits.

some remaining oscillations at the level of 1.5% at $\theta_{lab}=170°$ α spectrum for $^{16}O+^{89}Y$ (Fig. 4) and at $\theta_{lab}=130°$ α spectrum for $^{16}O+^{93}Nb$ (Fig. 6) reactions. We have the highest statistics data at these angles and can learn more about small effects from these spectra. So these spectra were fitted with statistical evaporation spectra from three compound nuclear sources by adding two terms similar to Eq. (1). The quality of fit further improves as a result of such a three-source fitting, and as shown in Fig. 7 (upper panels), there remains essentially no oscillation in the remaining spectra after subtracting out the fitted spectra from the experimental spectra.

Compared to single-source fitting, the quality of fit is certainly expected to improve for multisource fitting because of the increase in the number of free parameters. However, as we shall discuss below, the parameters obtained from such

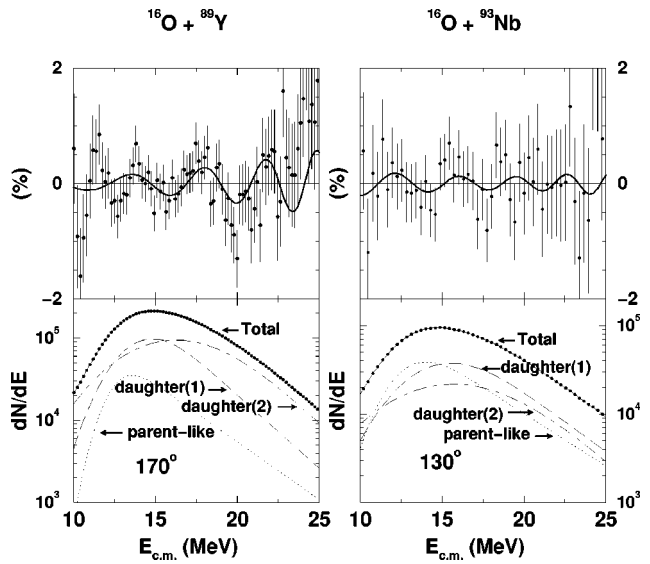

FIG. 7. Lower panel: experimentally measured α spectra from the $^{16}O+^{89}Y$ reaction at $\theta_{lab}=170°$ and $^{16}O+^{93}Nb$ reaction at $\theta_{lab}=130°$ have been fitted with statistical emissions from three compound nuclear sources [parentlike, daughter (1), and daughter (2) sources]. Contribution from each source is shown separately. Upper panel: percentage difference between the experimental data and the fits. The residual spectra are fitted with Legendre polynomials P_n ($E_{\text{c.m.}}$) for $n \geqslant 37$.

TABLE I. Temperature and Coulomb barrier considering two compound nuclear sources.

Reactions studied		Parameters of first source (parentlike)		Parameters of second source (daughterlike)	
	Angle (lab)	T_1 (MeV)	V_1 (MeV)	T_2 (MeV)	V_2 (MeV)
	150°	2.92±0.15	12.05±0.20	2.38±0.10	13.47±0.20
$^{16}O+^{89}Y$	160°	2.84±0.15	11.77±0.20	2.28±0.10	13.44±0.20
	170°	2.92±0.15	11.93±0.20	2.22±0.10	13.56±0.20
$^{12}C+^{93}Nb$	143.3°	3.27±0.20	12.17±0.25	2.39±0.20	13.51±0.30
	151.7°	3.14±0.15	12.32±0.20	2.73±0.10	12.95±0.20
$^{16}O+^{93}Nb$	130°	3.43±0.25	12.51±0.30	3.0±0.20	14.87±1.0

multisource fitting are consistent with the physics of sequential emission from daughter nuclei. The actual number of daughter nuclei contributing significantly to the observed alpha spectra is not just 1 or 2, but that number is more likely 15–20 for the excitation energy we are dealing with. However, we find from our analysis that the effect of parent and all daughter nuclei can be represented very well by three-source fitting. These three sources comprise parentlike and daughterlike sources representing averages over hotter and colder sets of nuclei, respectively. The parentlike or daughterlike source does not necessarily represent individual nucleus, but generally represents the average effect of many nuclei. The temperature of the parentlike source should be higher than that of the daughterlike source. For prolate deformation, we expect the Coulomb barrier of the parentlike source to be lower than that of the more spherical daughterlike source.

We tabulate below the temperatures and Coulomb barriers of different sources for α emissions as obtained from our best fit to the data. The tabulated uncertainties of these parameters were estimated from the variation of these parameters that can increase the chi square value of the fit to double its lowest obtained value. In Table I we show the results of two-source fitting and in Table II those of three-source fitting. In each case, we find that the temperature of the initial parentlike source is highest and it gets reduced for subsequent daughterlike sources. This is because of the reduction of the excitation energy of the compound nucleus due to sequential emission of particles. Since the same compound nucleus ^{105}Ag was formed at the same excitation energy (E_x=76 MeV) by $^{16}O+^{89}Y$ and $^{12}C+^{93}Nb$ reactions, so we obtain approximately the same temperature (3 MeV) by fitting α spectra from both reactions. The observed oscillations are clearly not related to any kind of entrance channel effect, because their behavior has been found to be identical (Figs. 1, 2, 4, and 5) for both $^{16}O+^{89}Y$ and $^{12}C+^{93}Nb$ reactions forming the same compound nucleus ^{105}Ag at the same excitation energy.

We also find from Tables I and II that the Coulomb barrier (V_c) experienced by α particles coming from the initial parentlike source is lowest and V_c increases for subsequent emissions. For $A\approx100$ nuclei, at E_x=76 MeV and 96 MeV, the most important evaporation channel is the neutron channel. Neutron emission rather than charged particle emission would precede α emission most of the time. Hence the atomic numbers of parent and daughter nuclei would remain about the same. So the observed difference between the Coulomb barriers experienced by α particles coming from parentlike and daughterlike sources is most likely due to the expected change of shape of the nucleus from prolate to near spherical. We think that initially the original parent compound nucleus is formed in a deformed prolate shape (because of its high angular momentum) and then gradually it becomes less deformed and approaches a spherical shape by losing excitation energy and angular momentum due to the sequential emission of particles. As the deformation of a prolate nucleus is reduced, its Coulomb barrier V_c would increase and we think that this effect is seen in Tables I and II. So the parameters we get from multisource fitting are consistent with the physics of sequential emission from daughter nuclei.

It is possible to determine the deformation of the excited parentlike source from such an observed change in the Coulomb barrier of α particles. From Tables I and II, we find a more than 10% change in the value of the Coulomb barrier between the excited parentlike source and its less excited daughterlike sources. Assuming that the shape of the excited nucleus is prolate and that of the daughter nucleus is spherical, we find the deformation parameter δ=0.2 for the excited parentlike source in the case of a 10% reduction in the value of the Coulomb barrier of the parentlike source compared to

TABLE II. Temperature and Coulomb barrier considering three compound nuclear sources.

Reactions studied		Parameters of first source (parentlike)		Parameters of second source [daughter(1)]		Parameters of third source [daughter(2)]	
	Angle (lab)	T_1 (MeV)	V_1 (MeV)	T_2 (MeV)	V_2 (MeV)	T_3 (MeV)	V_3 (MeV)
$^{16}O+^{89}Y$	170°	2.96±0.10	11.58±0.15	2.51±0.15	12.28±0.20	2.31±0.15	13.74±0.20
$^{16}O+^{93}Nb$	130°	3.67±0.10	12.32±0.15	3.22±0.15	13.58±0.20	2.67±0.15	13.61±0.20

that of the daughterlike source.

In Fig. 7 (lower panels), we show contributions to statistical evaporation α spectra from parentlike and susequent two daughterlike sources denoted as daughter (1) and daughter (2). The temperature of the parent nucleus is higher than that of any daughter nucleus. On the other hand, the Coulomb barrier of the parent nucleus is lower than that of any daughter nucleus. So the parent nucleus should have significantly higher α-emission probability compared to any daughter nucleus. However, we find from the fits shown in Fig. 7 that the contribution from the parentlike source is much less than the yields from the daughterlike sources.

As discussed before, the actual number of daughter nuclei contributing significantly to the observed alpha spectra is about 15–20 for the excitation energies we are dealing with. The sum total of α-emission probabilities from all the daughter nuclei is significantly higher than the α-emission probability of the initial parent compound nucleus. In Fig. 7, the curves labeled as ''daughter (1)'' and ''daughter (2)'' are daughterlike sources representing the total effect of many daughter nuclei. Similarly, the curve labeled as ''parentlike'' does not necessarily always represent the effect of initial parent compound nucleus only, but can in general represent the effect of several comparatively hotter nuclei. So in Fig. 7, for our three-source fit, the contribution from the parentlike source is always much less than the total contributions from all daughter nuclei, although the contribution from any individual daughter nucleus is certainly less than that from parent compound nucleus.

The number of nuclei contributing to parentlike or daughterlike sources may change (thus changing the realtive yields from those sources) for different fitting procedures. In the case of three-source fit of the α spectrum from the $^{16}O + ^{89}Y$ reaction (Fig. 7), we find that the contribution from the parentlike source is less than 20% that of the total α yield. But a two-source fit of the same data shows that the contribution from the parentlike source is about half of that of the total α yield. In the case of a three-source fit of the α spectrum from $^{16}O + ^{93}Nb$ data(Fig. 7), we find that the contribution from the parentlike source is about one-third of that of the total α yield. According to statistical model code CASCADE, the contribution from the initial parent compound nucleus is about 28% that of the total α yield for the $^{16}O + ^{89}Y$ reaction at $E_{lab}(^{16}O) = 95.9$ MeV and for the $^{16}O + ^{93}Nb$ reaction at $E_{lab}(^{16}O) = 116$ MeV; the contribution from the initial parent compound nucleus is about 22% that of the total α yield. We find from our fits that irrespective of the different fitting procedures used, the contribution from the parentlike source is never more than half of the total contributions from daughter nuclei for the reactions studied in this work. The temperature of the parentlike source has always been found to be higher than that of any corresponding daughterlike source. The Coulomb barrier of the parentlike source has always been found to be lower than that of any corresponding daughterlike source. All these observations are consistent with the expectations of statistical model calculations.

In Fig. 7 (upper panels), we show the residual α spectra after subtracting out three-source fitted spectra from the experimental spectra. There is certainly no broad oscillation left as was seen in Figs. 1, 2, and 3 (upper panels) and also in Refs. [1,2]. If any oscillation is left, it is much higher frequency oscillations contrary to the low frequency oscillations seen in Figs. 1, 2, and 3 (upper panels) and Refs. [1,2]. The residual spectra in Fig. 7 are fitted with Legendre polynomials $P_n(E_{\text{c.m.}})$ and we find that very high n values ($n \geqslant 37$) are required to fit the residual spectra. The Legendre polynomial fit shows that the upper limit on the amplitude of such high frequency oscillation is less than 0.5%. A straight line passing through the mean value of data points also gives a similar chi square value like the high n ($n \geqslant 37$) Legendre polynomial fit. So we conclude that there is no statistically significant oscillation seen in our study of α spectra. We find that the α spectra can be very well understood by considering statistical α emission from the original compound nucleus and its daughters. Since no statistically significant oscillatory structure has been seen in α spectra, so from this work, we conclude that there is no evidence for the existence of α particles as independent particles inside compound nuclei.

IV. CONCLUSION

In summary, our work shows that the observed evaporation α spectra can be described very well using the algebraic expression of Eq. (1) representing the statistical emission of particles from a compound nucleus. The quality of fit improves considerably as the sequential decays from the daughter nuclei are also considered. After subtracting out fitted statistical spectra (including the effect of sequential decays) from the experimental spectra, we do not find any statistically significant oscillatory structure in the remaining spectra. So there is no evidence for the existence of α particles as independent particles in the compound nuclei. These oscillations are also clearly not related to any kind of entrance channel effect.

In earlier works [1,2], oscillatory structures were seen in the residual spectra apparently because of ignoring sequential decays. Recently, in their Annual Report [8], the same group has also concluded that the oscillations seen in the evaporation α spectra from the $^{3}He + Ag$ reaction can be understood in terms of sequential emission from daughter nuclei.

From our studies, we also get information about the temperature and Coulomb barrier of excited parentlike and daughterlike sources and so can estimate the average deformation of excited nuclei from the change in the Coulomb barrier between parentlike and daughterlike sources.

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