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Pre-scission ^{1}H and ^{4}He emissions in $^{16}O + ^{197}Au$ reaction

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Pre-scission ^{1}H and ^{4}He in $^{16}O + ^{197}Au$ reactions are measured in coincidence with fission fragments in the compound nucleus excitation energy of 48 to 99 MeV. Observed coincident energy spectra of ^{1}H and ^{4}He are shifted towards lower energies compared to statistical model calculations. The data are analyzed in terms of the spin-dependent level density and emission barriers for the charged particles. The analysis shows that the effect of the spin-dependent level density on the energy spectrum is small and the effective emission barriers for particle emissions are reduced by 1.0 ± 0.4 MeV for ^{1}H and 1.8 ± 0.4 MeV for ^{4}He relative to the corresponding fusion barriers calculated by using optical potentials.

It is well known that the energy spectra of light charged particles emitted from an excited nucleus deviate from those calculated for a spherical nucleus.[1–10] This phenomenon has been discussed in terms of the reduced emission barriers for charged particles and the spin-dependent level density. The cause of the reductions of the emission barriers has not been fully understood.[1,2,4–10] The deformation induced by large angular momenta has been discussed[5,9] and the importance of the spin-dependent level density which takes into account the lowering of the yrast line has been pointed out in the analysis of light mass systems.[11] This latter effect hinders the first step emission of ^{4}He and consequently reduces the high energy portions of ^{4}He energy spectra. In the present paper we report the results of the coincidence experiments between charged particles and fission fragments in the $^{16}O + ^{197}Au$ reactions and point out the importance of emission barrier reductions over the effect of the spin-dependent level density in the present heavy system.

The experimental details have been described in Ref. 12. A self-supported ^{197}Au target of a thickness of 1.2 mg/cm^2 was bombarded with ^{16}O beam from the Japan Atomic Energy Research Institute (JAERI) tandem accelerator. Fission fragments were measured with a solid state detector (SSD, 60 μm, 400 mm^2), which was set up at $\theta_{lab} = 125°$ with respect to the beam. Light charged particles were measured with three sets of a solid state detector telescope (30 and 2000 μm thickness) at the reaction plane ($\phi = 90°$) and the out-of-plane angles ($\phi = 30°$ and $60°$). The out-of-plane angle ϕ is the angle between the normal of the reaction plane and the direction of the detector telescope. These telescopes were set up at negative angles ($\theta_{lab} = -125°$ and $-135°$) in the coincidence experiment. Here, the negative angle is the angle on the side opposite to the SSD with respect to the beam.

Typical ^{1}H and ^{4}He energy spectra measured in coincidence with fission fragments at the reaction plane and the out-of-plane angles are shown in Figs. 1 and 2, respectively. The ordinate is the differential particle multiplicity. Two emission sources for ^{1}H and ^{4}He are identified in the energy spectra: the emissions from the compound nucleus (CE) and from the fission fragments (FE). Low energy bumps and the main peaks at higher energy correspond to FE and CE, respectively. The measured energy spectra were compared to the statistical model calculations using the code PACE2.[13] Here, the level density parameter of $A/10$ was assumed. The ratio a_f/a_n of the level density parameter for the saddle point deformation to that for the ground state was assumed to be unity and the fission barrier was calculated by the rotating finite range model.[14] The transmission coefficients for particle emissions were calculated by using the optical model parameters of Ref. 15 for ^{1}H and Ref. 16 for ^{4}He. The calculated energy spectra for the pre-scission ^{1}H and ^{4}He are shown as the dotted lines. The slopes for high energy parts of the calculated spectra agree with the data, while the centroids are shifted towards higher energies compared to the data.

First, we investigated the effect of the spin-dependent level density on the evaporation spectrum by modifying the yrast line. We used the parameters δ_1 and δ_2 of Ref. 11, where the energy E_l of the yrast line is parametrized as

$$E_l = \hbar^2 l(l+1)/2J_0(1+\delta_1 l^2 + \delta_2 l^4) . \quad (1)$$

The level density at total excitation energy U and spin l was calculated by evaluating the Fermi gas level density at an energy reduced by E_l. In the present calculation, a paring correction to the level density was neglected. The rigid body moment of inertia J_0 was calculated by the radius parameter $r_0 = 1.28$ fm. The calculated values E_l with $\delta_1 = 2.3 \times 10^{-4}$ and $\delta_2 = 1.6 \times 10^{-7}$ are smaller by 1.4 times at $l = 30\hbar$ and by 1.8 times at $l = 40\hbar$ than the rotating liquid drop values[17] for the compound nucleus $A = 213$. Here, the calculated range and the average values of the entrance channel angular momenta which contribute to the pre-scission ^{4}He emission are listed in Table I for each bombarding energy. The calculated energy spectrum using the above given values of δ_1 and δ_2 was quite similar to the dotted line in Fig. 2 and could not

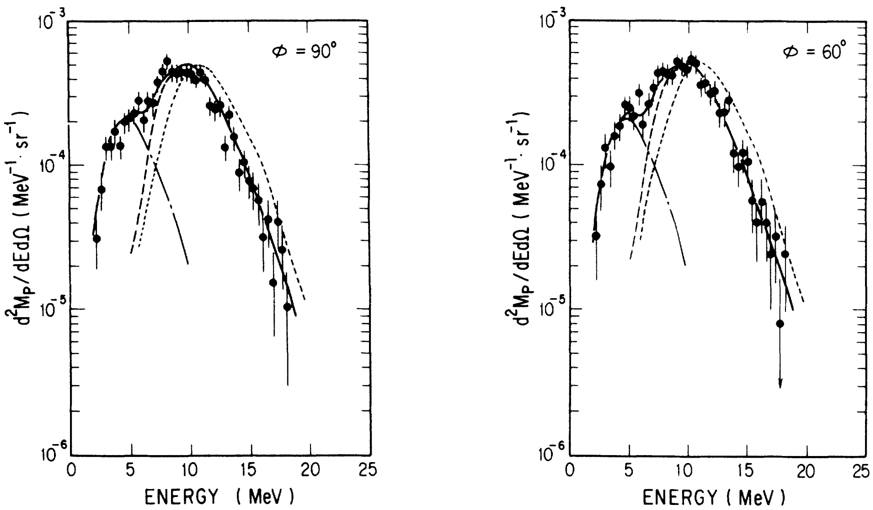

FIG. 1. ^{1}H energy spectra measured at $-125°$ in coincidence with fission fragments at the bombarding energy of 132 MeV. The dotted line is the PACE2 calculation with the standard transmission coefficients. The dashed line is the calculation with the transmission coefficients shifted by -1.0 MeV towards lower energies. The long dash-dotted line is the calculated result for FE. The sum of the CE and FE components is shown as the solid line.

be distinguished from it. The result is due to the fact that the energy of the yrast line for the heavy nucleus ($A \cong 213$) is small (≈ 4 MeV at $l = 30\hbar$ and ≈ 7 MeV at $l = 40\hbar$) compared to the total excitation energy (see Table I). Hence, the modification [Eq. (1)] of the yrast line in the level density has little effect on the energy spectrum. The same is not true for light mass systems (for instance $A \cong 60$),[5,9,11] where the energy of the yrast line calculated by the rotating liquid drop model rises more sharply with l and thus the reductions of E_l from the rotating liquid drop values become significant at high angular momenta. From the above results, we found that the modification of the level density does not help to understand the anomaly of the energy spectra when the compound nucleus is heavy.

The mean center-of-mass (c.m.) kinetic energy $\langle \varepsilon \rangle$ of ^{4}He was obtained for the CE component after subtracting the FE component from the observed coincident spectrum. Here, the FE component was calculated by PACE2 as described in Ref. 12. The observed $\langle \varepsilon \rangle$ are plotted in Fig. 3 as a function of U. The solid line represents the calculated value of $\langle \varepsilon \rangle$ by using PACE2. The calculation overestimates the $\langle \varepsilon \rangle$ values by 2 to 4 MeV depending on U. The mean c.m. kinetic energy is sensitive to the decay sequence of neutron and ^{4}He in decay chains as shown in Fig. 3, where the calculated mean c.m. energy for various multistep emissions are shown: the first step, the third step (two neutron emissions preceding the ^{4}He emission),

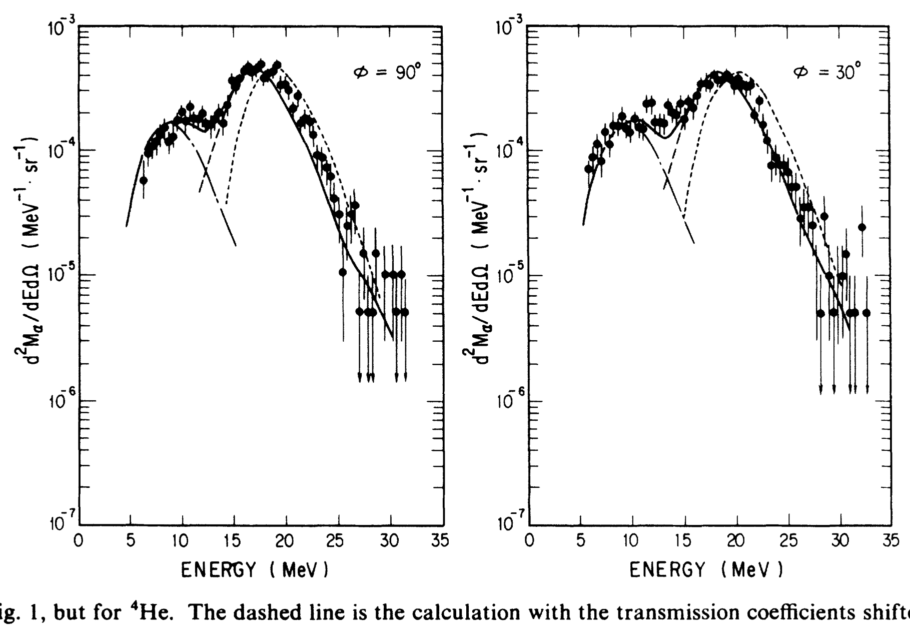

FIG. 2. Same as Fig. 1, but for ^{4}He. The dashed line is the calculation with the transmission coefficients shifted by -1.8 MeV towards lower energies.

TABLE I. Pre-scission ^{1}H and ^{4}He multiplicities.

E_{lab} (MeV)	U (MeV)	$\langle l \rangle^a$ $\hbar$	Range^a $\hbar$	l^b_{max} $\hbar$	M_p Expt.	M_p Calc.	M_α Expt.	M_α Calc.
94.0	48.3	24	20–32	32	0.003±0.001	0.003	0.012±0.003	0.002
104.1	57.6	32	22–42	42	0.007±0.002	0.007	0.018±0.004	0.007
116.1	68.7	36	22–50	52	0.018±0.004	0.012	0.033±0.007	0.016
124.1	76.2	37	22–55	57	0.025±0.005	0.017	0.041±0.006	0.021
132.5	83.9	38	22–57	61	0.038±0.008	0.022	0.049±0.007	0.027
141.2	91.9	39	20–62	65	0.051±0.008	0.027	0.063±0.009	0.034
149.3	99.4	40	20–64	68	0.064±0.010	0.034	0.083±0.012	0.040

[a]Calculated average angular momentum and range which contribute to the pre-scission ^{4}He emission.
[b]Maximum angular momentum for fusion predicted by Ref. 19.

and the fifth step (four neutron emissions proceeding the ^{4}He emission) emissions. The calculated $\langle \varepsilon \rangle$ is close to the value for the first step emission. This means that the first step emission is dominant in the statistical model calculation. The mean c.m. energy for the third step emission considerably decreases as U decreases. This is due to the fact that an average excitation energy (≈ 20 MeV) removed by two neutron emissions preceding the ^{4}He emission becomes significant at low excitation energies.

The pre-scission neutron multiplicity in the present reaction system is reported to be 2–2.5 at $U \leq 60$ MeV and ≈ 4 at $U \approx 100$ MeV.[18] The observed $\langle \varepsilon \rangle$ at $U \leq 60$ MeV is still smaller than the one for the third step emission calculation. The observed $\langle \varepsilon \rangle$ at 99 MeV is about 2 MeV less than the calculated one for the fifth step emission. The present results indicate that even if there is a mechanism in which the multistep emission is more enhanced than in the PACE2 calculation, the statistical model calculation assuming the ^{4}He emission from spherical nucleus cannot account for the observed c.m. kinetic energy. This is the second argument in favor of using the effective emission barriers which are reduced compared to the corresponding fusion barriers calculated by using the optical potentials of Refs. 15 and 16.

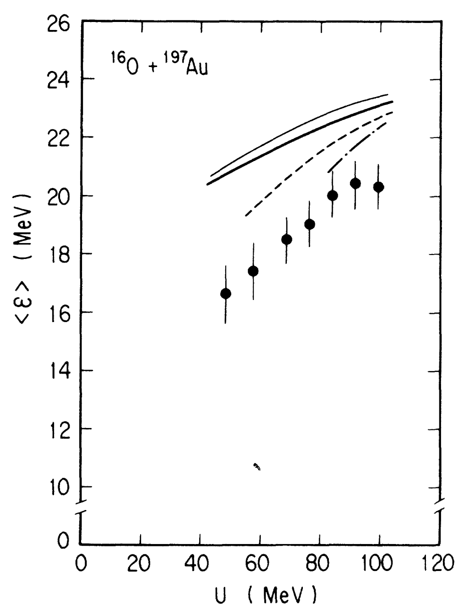

FIG. 3. Mean center-of-mass kinetic energy for the pre-scission ^{4}He particle as a function of excitation energy of the compound nucleus. The solid line is the PACE2 calculation. The thin solid line, the dashed line, and the dash-dotted line are the calculated $\langle \varepsilon \rangle$ values for the first step, third step, and fifth step emissions, respectively.

The pre-scission multiplicities for ^{1}H (M_p) and ^{4}He (M_α) were obtained by integrating the CE component and the out-of-plane angular distributions as described in Ref. 12, and are listed in Table I together with the PACE2 calculations. It should be noted that at low excitation energies ($U \leq 60$ MeV), where the effect of the delayed onset of fission is not significant,[18] the calculations underestimate the ^{4}He multiplicity. If the multistep emission is dominant, the predicted values become even smaller, because effective excitation energies for the ^{4}He emission is reduced by neutron emissions. This is the third argument in favor of the barrier reduction.

In order to obtain the effective emission barriers, the calculated transmission coefficients as a function of the center-of-mass energy of the emitted particles were shifted towards lower energies by -1.0 MeV for ^{1}H and -1.8 MeV for ^{4}He. The dashed lines (which are overlapped with the solid lines at high energies) in Figs. 1 and 2 are the calculated results by replacing the original transmission coefficients with those shifted. By taking into account an error of 0.4 MeV in the fitting procedure of the calculated spectrum to the observed one, the reduction of the effective emission barriers were determined to be -1.0 ± 0.4 MeV for ^{1}H and -1.8 ± 0.4 MeV for ^{4}He. The amount of the barrier reduction per charge of the emitted particles is similar for ^{1}H and ^{4}He.

In summary, the observed pre-scission ^{1}H and ^{4}He spectra are shifted towards lower energies compared to the statistical model calculations assuming emissions from a spherical nucleus. In order to reproduce the observed spectra, it is necessary to introduce the effective emission barriers which are reduced compared to the corresponding fusion barriers for ^{1}H and ^{4}He calculated by using the optical potentials.

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