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ABSTRACT

The existence of a finite and essentially energy-independent lower limit for the average angular momentum leading to fusion at energies well below the Coulomb barrier has been experimentally confirmed. We report the first observation of this angular momentum limit for the systems $^{12}C + ^{128}Te$, $^{7}Li + ^{133}Cs$, and $^{3}He + ^{136}Ba$. We find that the predicted values of $\bar{l}$ are consistent with experiment. The expected variation of $\bar{l}$ with entrance channel is also observed.

The distribution of angular momenta in the entrance channel leading to fusion has not been experimentally studied at energies far below the Coulomb barrier. However, in this low energy region, a qualitative change in the behavior of the average angular momentum, $\bar{l}$, has been predicted. Above and at the barrier, $\bar{l}$ decreases as the bombarding energy is lowered. Below a certain energy, however, the distribution of angular momentum leading to fusion should no longer shift to lower l-values, but is predicted to become independent of energy [1]. In particular, $\bar{l}$, is given by

$$\bar{l} = (4/3)\sqrt{\mu R_b^2 \epsilon / \hbar^2}, \tag{1}$$

where μ is the reduced mass, R_b is the radius corresponding to the top of the barrier, and ϵ is related to the curvature of the barrier. This phenomenon is a consequence of the quantum mechanical nature of barrier penetration for fusion at very low energies, and is reflected both in the distribution of partial cross sections, σ_l, and in the energy dependence of the cross sections. Furthermore, as can be seen in Eq. 1, $\bar{l}$ is predicted to depend on the reduced mass of the entrance channel.

We have made an experimental investigation of both these predictions - the constancy of $\bar{l}$ and the variation of $\bar{l}$ with the reduced mass at low energies - by measuring the subbarrier fusion cross sections for the reactions

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$^{128}Te(^{12}C,3n)^{137}Ce$, $^{133}Cs(^{7}Li,3n)^{137}Ce$, and $^{136}Ba(^{3}He,2n)^{137}Ce$. We have chosen an experimental technique that is different from those used previously in the study of angular momentum in subbarrier fusion reactions. Its features are ideally suited to this particular problem. By measuring the ratio, R, of the cross section for population of a high spin isomeric state to that of a low spin ground state, we obtain a measure of the distribution of angular momentum in the entrance channel, while, at the same time, through the observation of delayed x and γ-rays, we are able to measure the small cross sections at which the effect is predicted to occur. Measurements of the cross sections and the isomer ratios for the fusion of ^{12}C with ^{128}Te have recently been published [2)].

The ground ($J^{\pi} = 3/2^{+}$, $t_{1/2} = 9.0$ h) and isomeric ($11/2^{-}$, 34.4 h) states in ^{137}Ce (see Fig. 1) were populated by the reactions $^{128}Te(^{12}C,3n)$, $^{133}Cs(^{7}Li,3n)$, and $^{136}Ba(^{3}He,2n)$ using beams from the LBL 88-Inch Cyclotron. Targets and catcher foils of carbon and gold were arranged in a stack to permit irradiations at several energies in a single bombardment. After a bombardment of typically eight hours at intensities of $\leq$ 250 ena, the x and γ radiations from the target/catcher foils were counted off-line for several days using germanium detectors. The γ and x-ray spectra were accumulated in one hour intervals, and recorded automatically for additional analysis. The absolute fusion cross sections and isomer ratios were determined by fitting the time dependence of the characteristic x and γ-ray emissions following the bombardment. Typical decay curves for a small and a large isomer ratio are shown in Fig. 1.

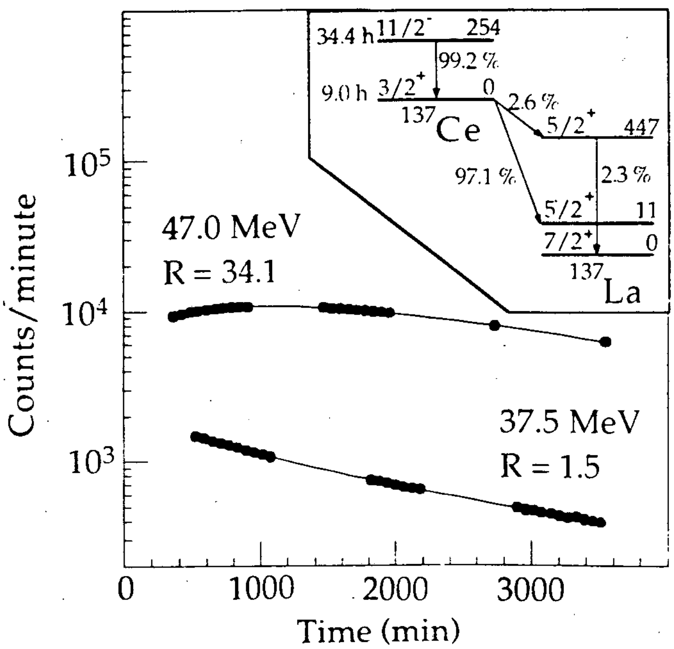

Fig. 1. The time dependence of the summed Ce and La K x-rays obtained for $^{12}C + ^{128}Te$ at $E_{c.m.} = 37.5$ and 47 MeV. The curves are fits to the data and result in the indicated values for the isomer ratio.

The experimental results for the isomer ratios of the systems ^{12}C + ^{128}Te, ^{7}Li + ^{133}Cs, and ^{3}He + ^{136}Ba, are shown in Fig. 2 as a function of bombarding energy with respect to the corresponding Coulomb barrier. As can be seen, the isomer ratios decrease rapidly as the bombarding energy is lowered and approaches the barrier. Moreover, the isomer ratios are essentially constant for energies well below the barrier. The approximate constancy of R indicates that the cross sections for fusion proceeding through partial waves *above*, and *below* some critical value also have a constant, energy independent ratio. Assuming that the individual partial wave cross sections vary smoothly with energy, this result implies a constant $\bar{l}$ for fusion.

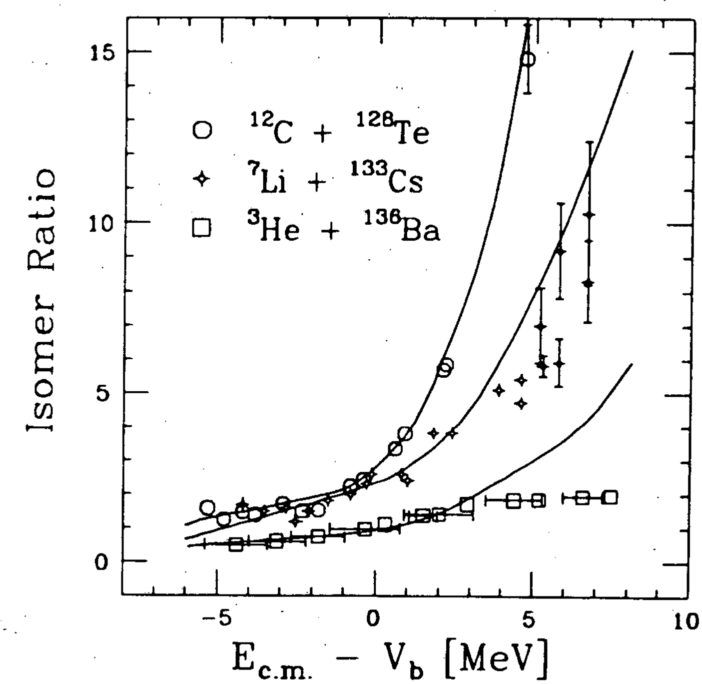

Fig. 2. The experimental isomer ratios as a function of bombarding energy with respect to the Coulomb barrier. The full curves are a prediction based on the angular momentum distribution given by CCFUS and a statistical decay calculation made with the code PACE.

It is possible to relate the isomer ratio to the angular momentum distribution in the compound nucleus allowing for the subsequent changes of this distribution caused by the evaporation of neutrons and γ-rays preceding the population of the ground state or isomer. This is done using a statistical model. The partial wave cross sections were calculated with the simplified coupled channels computer code CCFUS of Dasso and Landowne. Known electromagnetic coupling matrix elements in the projectile and target nuclei were included, and the parameters describing the nuclear-plus-Coulomb potential were obtained by scaling the values determined experimentally for ^{16}O + Sm. The statistical decay of the compound nucleus was calculated using the computer code PACE, which includes E1 and E2 γ-ray decay in competition with neutron emission. Reference 2 describes details of the model calculations, as well as the sensitivity of the predicted isomer ratios to changes in the parameters used in the statistical model. The predicted isomer ratios (full lines) for the three systems are compared to the experimental results in Fig. 2. Note that the limiting value of the ratio and, therefore, the limit of the angular momentum obtained for ^{3}He, is subtantially lower because of the reduced moment of inertia in the entrance channel. On the other hand, the values of the isomer ratios for ^{7}Li and ^{12}C projectiles below the barrier are quite similar, indicating essentially the same constant average angular momentum. Although the orbital angular momentum brought in by each system is different, the total angular momentum for the ^{7}Li case in this energy region is as large as ^{12}C because of the coupling of the ground state spins of 3/2 and 7/2 for ^{7}Li and ^{133}Cs, respectively. We also find that the energy dependence below the barrier for $\sigma(E)$ is well-reproduced by a barrier penetration calculation [2]. Thus, in this energy region, the cross sections and average angular momenta are self-consistent.

We have extended this study of the average angular momentum for fusion using the reaction $^{186}W(^{12}C,3n)^{195}Hg$. The ratio of the population of the isomeric ($J^{\pi} = 13/2^{+}$) and ground ($1/2^{-}$) states in ^{195}Hg also exhibits an energy dependence characteristic of a constant average angular momentum in the entrance channel below the barrier. Analysis is still in progress. However, the observed constant $\bar{l}$ in a nuclear system with significantly different mass and spin than ^{137}Ce corroborates the universality of this phenomenon. We are also examining the suitability of this technique for determining the absolute value of $\bar{l}$ in the entrance channel. This is of interest because it would provide an independent experimental approach to the problem, recently pointed out by Vandenbosch [3], that theoretical values of $\bar{l}$ in the entrance channel disagree with those deduced from γ-ray multiplicities and fission fragment angular correlations.

In conclusion, the nearly constant value for R measured at low energies confirms the prediction of an approximately constancy of $\bar{l}$ at energies sufficiently far below the fusion barrier. The expected variation of $\bar{l}$ with the reduced mass of the entrance channel is also observed. The predicted values of $\bar{l}$ agree with the absolute values deduced from the experiment with the aid of a statistical model.

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2. R.G. Stokstad, *et al.*, Phys. Rev. Lett. 62 , 399 (1989).
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