Fusion versus Breakup: Observation of Large Fusion Suppression for ^{9}Be + ^{208}Pb

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Complete fusion excitation functions for ^{9}Be + ^{208}Pb have been measured to high precision at near barrier energies. The experimental fusion barrier distribution extracted from these data allows reliable prediction of the expected complete fusion cross sections. However, the measured cross sections are only 68% of those predicted. The large cross sections observed for incomplete fusion products support the interpretation that this suppression of fusion is caused by ^{9}Be breaking up into charged fragments before reaching the fusion barrier. Implications for the fusion of radioactive nuclei are discussed. [S0031-9007(99)08474-4]

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The recent availability of radioactive beams has made possible the study of the interactions and structure of exotic nuclei far from the line of stability. Unstable neutron-rich nuclei having very weakly bound neutrons exhibit characteristic features such as a neutron halo [1] extending to large radii, associated low-lying dipole modes, and a low energy threshold for breakup. These features may dramatically affect fusion and other reaction processes. For fusion to occur, the system must overcome the barrier resulting from the sum of the repulsive Coulomb potential and the attractive nuclear potential. Experiments with stable beams have shown, however, that fusion near the barrier is strongly affected [2,3] by intrinsic degrees of freedom (such as rotation, vibration) of the interacting nuclei, whose coupling with the relative motion effectively causes a splitting in energy of the single, uncoupled fusion barrier. This gives rise to a distribution of barrier heights [4], some higher and some lower in energy than the uncoupled barrier, and is manifested most obviously as an enhancement of the fusion cross sections at energies near and below the average barrier.

In the case of halo nuclei, it is well accepted that the extended nuclear matter distribution will lead to a lowering of the average fusion barrier, and thus to an enhancement in fusion cross sections [5] over those for tightly bound nuclei. The effect of couplings to channels which act as doorways to breakup is, however, controversial [6–9]. Any coupling will enhance the sub-barrier cross sections, whereas breakup may result in capture of only a part of the projectile, thus suppressing complete fusion. Model predictions [6–8], however, differ in the relative magnitudes of enhancement and suppression. To investigate the effect of the loosely bound neutrons, fusion excitation functions in the barrier region were measured for ^{9,11}Be + ^{238}U [10] and ^{9,10,11}Be + ^{209}Bi [11], each study including the reaction with the stable ^{9}Be for comparison. The fusion cross sections for ^{10,11}Be + ^{209}Bi at energies near and below the barrier were found to be similar to those for ^{9}Be, while above the barrier the ^{9}Be induced reaction gave the lowest fusion yield. It is not obvious whether this is due to differing enhancement or suppression for the stable and unstable projectiles.

To investigate the effect on fusion of couplings specific to unstable neutron-rich nuclei, it is necessary to reliably predict the cross sections expected in their absence. Thus, in the above cases, definitive conclusions are difficult unless fusion with ^{9}Be is well understood. This requires knowledge of the energy of the average fusion barrier, and ideally a measurement of the distribution of fusion barriers to obtain information on the couplings. All of this information can be obtained from precisely measured fusion cross sections $\sigma_{\rm fus}$, by taking the second derivative of the quantity $E\sigma_{\rm fus}$ with respect to energy E [12]. This function, within certain limits [3,12], represents the distribution of barrier probability with energy. The shape of the experimental barrier distribution is indicative of the couplings present, and its centroid gives the average barrier position. This information places severe constraints [13] on the theoretical models. For this reason, precise measurements, permitting extraction of barrier distributions, have resulted in a quantitative and self-consistent description of the fusion cross sections and barrier distributions for a wide range of reactions in which couplings to single-phonon [14], double-phonon [15], and rotational states [16,17] are present.

This Letter reports on precisely measured complete and incomplete fusion cross sections for the reaction of ^{9}Be + ^{208}Pb, and utilizes the barrier distribution for complete fusion extracted from these data to determine quantitatively the suppression of fusion due to breakup of ^{9}Be.

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The experiments were performed with pulsed ^{9}Be beams (1 ns on, 1 μs off) in the energy range 35.0–51.0 MeV, from the 14UD tandem accelerator at the Australian National University. Targets were of ^{208}PbS (>99% enrichment), 340–400 $\mu g \cdot cm^{-2}$ in thickness, evaporated onto 15 $\mu g \cdot cm^{-2}$ C foils. For normalization, two monitor detectors, placed at angles of 22.5° above and below the beam axis, measured the elastically scattered beam particles. Recoiling heavy reaction products were stopped in aluminum catcher foils of thickness 360 $\mu g \cdot cm^{-2}$, placed immediately behind the target; the mean range of the fusion evaporation residues at the maximum bombarding energy is 130 $\mu g \cdot cm^{-2}$. The reaction products were identified by their distinctive α energies and half-lives (270 ns to 138 days). Alpha particles from short-lived activity (half-life $T_{1/2} \leq$ 26 sec) were measured *in situ* during the 1 μs periods between the beam bursts, using an annular silicon surface barrier detector placed 8 cm from the target, at a mean angle of 174° to the beam direction. These were measured at all beam energies using the same target. An unirradiated target and catcher was used at each energy for determining the cross section of long-lived products ($T_{1/2} \geq$ 24 min). Alpha particles from these products were measured using a silicon surface barrier detector situated below the annular counter, such that the target and catcher could be placed 0.8 cm from the detector after the irradiation. The relative solid angles of the two detectors were determined using the $T_{1/2} = 24$ min ^{212}Rn activity.

Fission following fusion was measured during the irradiations using two position sensitive multiwire proportional counters (MWPCs), each with active area 28.4 × 35.7 cm^2, centered at 45° and −135° to the beam direction, and located 18.0 cm from the target. Absolute cross sections for evaporation residues and fission were determined by performing calibrations at sub-barrier energies in which elastically scattered projectiles were detected in the two monitor detectors, the annular detector and the backward-angle MWPC.

The compound nucleus ^{217}Rn formed following complete fusion of ^{9}Be with ^{208}Pb cools dominantly by neutron evaporation; the measured cross sections for 2n, 3n, 4n, and 5n evaporation residues are shown in Fig. 1(a). No proton evaporation residues were observed. In addition to the α particles from the decay of Rn nuclei, α particles from the decay of Po nuclei, which are formed as daughters of the Rn nuclei following their α decay, were also observed. The yields were, however, much greater than expected from the Rn yields, indicating that there is also a direct population mechanism. Correcting for the Rn daughter yields, the cross sections for the direct production of ^{210,211,212}Po nuclei are shown in Fig. 1(b). In principle, the Po nuclei could originate from complete fusion followed by αxn evaporation. However, the shapes of the excitation functions for these nuclei are distinctly different from those in Fig. 1(a), and are not typical of fusion evaporation. For ^{9}Be + ^{208}Pb, prompt α particles, measured in coincidence with γ-ray transitions in Po nuclei [18], showed angular distributions inconsistent with fusion evaporation, and production by an incomplete fusion mechanism was inferred [18]. To investigate the origin of the Po yield by the α-decay technique, the same compound nucleus ^{217}Rn was formed at similar excitation energies in the reaction ^{13}C + ^{204}Hg. The α spectra were measured between 1.1 and 1.3 times the average barrier energy. The ^{211,212}Po α decays, to which the measurement was most sensitive, had cross sections of <5 mb, compared with a total of ~160 mb for the ^{9}Be + ^{208}Pb reaction. Furthermore, the fusion cross sections determined from the sum of the xn evaporation and fission cross sections agreed with the predictions of a coupled channels calculation and the Bass model [19], indicating that the xn evaporation yield essentially exhausts the total evaporation residue cross section. Combined, all of these observations show that the direct Po production observed in the ^{9}Be reaction cannot be due to complete fusion. It is attributed to incomplete fusion, and will be discussed

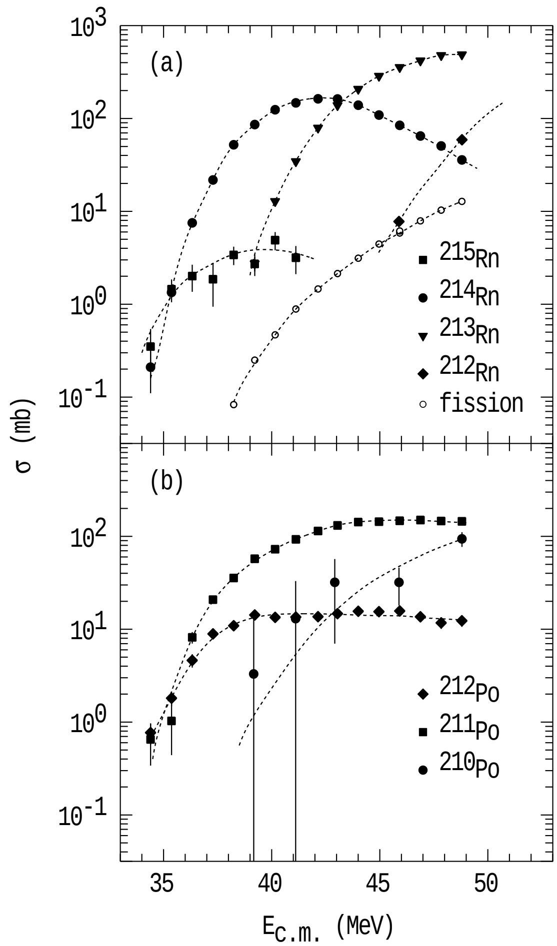

FIG. 1. (a) The measured cross sections for fission and the production of Rn isotopes, and (b) of Po isotopes following the reaction ^{9}Be + ^{208}Pb. The dashed lines guide the eye.

later. The observed fission cross sections were attributed to complete fusion of ^{9}Be + ^{208}Pb, since fission following incomplete fusion should be negligible due to the lower angular momentum and excitation energy brought in, and the higher fission barriers of the resulting compound nuclei.

Defining complete fusion experimentally as the capture of all of the charge of the ^{9}Be projectile, the complete fusion cross section at each energy was obtained by summing the Rn xn evaporation residue cross sections and the fission cross section. The excitation function for complete fusion is shown by the filled circles in Fig. 2(a), while Fig. 2(b) shows the experimental barrier distribution $d^2(E\sigma_{\rm fus})/dE^2$, evaluated from these data using a point difference formula [13] with a c.m. energy step of 1.92 MeV. The average barrier position obtained from the experimental barrier distribution is 38.3 ± 0.6 MeV. The uncertainty was determined by randomly scattering the measured cross sections, with Gaussian distributions of standard deviation equal to those of the experimental uncertainties, and redetermining the centroid. By repeating this process many times, a frequency distribution for the centroid position was obtained, allowing determination of the variance, and thus the uncertainty.

To predict the fusion cross sections expected from the measured barrier distribution, realistic coupled channels calculations [20] were performed using a Woods-Saxon form for the nuclear potential with a diffuseness 0.63 fm, depth −76 MeV, and radius parameter adjusted such that the average barrier energy of these calculations matched that measured. Couplings to the $5/2^-$ and $7/2^-$ states of the $K^\pi = 3/2^-$ ground-state rotational band [21] in ^{9}Be, and to the 3^-, 5^-, and the double octupole-phonon [22,23] states in ^{208}Pb, were included. The coupling strengths were obtained from experimental data [21,24], except for the double octupole-phonon states in ^{208}Pb, which were calculated in the harmonic limit.

The results of these calculations are shown in Figs. 2(a) and 2(b) by the dashed lines. They reproduce satisfactorily the asymmetric shape of the measured barrier distribution, but the area under the calculated distribution is much greater than that measured. The disagreement is necessarily reflected in the cross sections as well, where the calculated values are considerably larger than those measured. In contrast, for fusion with tightly bound projectiles [13–17], calculations which correctly reproduce the average barrier position and the shape of the barrier distribution give an extremely good fit to the cross sections, as expected. The disagreement for ^{9}Be + ^{208}Pb, even though the barrier energies are correctly reproduced, suggests the presence of a mechanism hindering fusion. Agreement can be achieved only if the calculated fusion cross sections are scaled by 0.68, resulting in the full lines in Figs. 2(a) and 2(b). This scaling factor will be model dependent at the lowest energies, as the calculations are sensitive to the types of coupling and their strength. However, at energies around and above the average barrier, the calculation and, hence, the scaling factor is more robust, since changes in couplings or potential, within the constraints of the measured barrier distribution, do not change the suppression factor significantly. The suppression factor of 0.68 has an uncertainty of ±0.07 arising from the uncertainty in the mean barrier energy. At above barrier energies, there is no evidence, within experimental uncertainty, for an energy dependence of the suppression factor, but a weak dependence cannot be excluded.

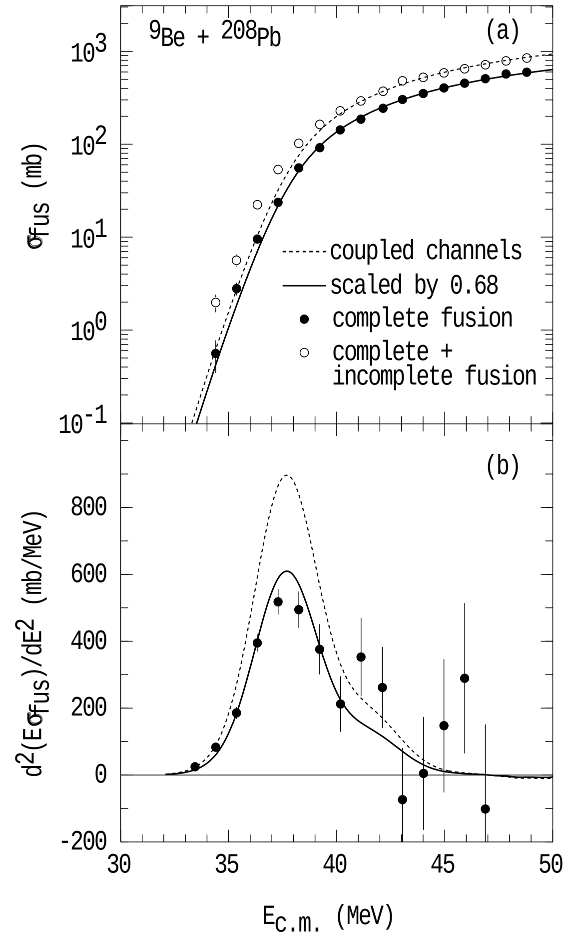

FIG. 2. (a) The excitation function for complete fusion (filled circles) and (b) the barrier distribution for the reaction ^{9}Be + ^{208}Pb. The dashed line is the result of a coupled channels calculation (see text) which ignores breakup effects. The full line is the same calculation scaled by 0.68. The sum of measured complete and incomplete fusion cross sections is given by the hollow circles.

The observed suppression of fusion may be related to the large yields of ^{210,211,212}Po which, as shown above, do not result from complete fusion. They can be formed through the breakup of ^{9}Be, probably into ^{4,5}He or two α particles and a neutron, with subsequent absorption of one of the charged fragments by the ^{208}Pb. The capture of all fragments after breakup cannot be distinguished experimentally from fusion without breakup, and is included in the complete fusion yield. Incomplete fusion products following the breakup of ^{9}Be giving ^{6,7,8}Li were not observed; they are unfavored due to large negative Q values. The large cross sections for incomplete fusion, approximately half of those for complete fusion, demonstrate that ^{9}Be has a substantial probability of breaking up into charged fragments. The sum of the complete and incomplete fusion cross sections is indicated by the hollow circles in Fig. 2(a). They match the predictions of the coupled channels fusion calculation, suggesting a direct relationship between the flux lost from fusion and the incomplete fusion yields. However, such a simple direct comparison is not strictly possible, since the cross sections for incomplete fusion may include contributions from higher partial waves which may not have led to complete fusion.

The suppression of fusion observed in this experiment is attributed to a reduction of flux at the fusion barrier radius due to breakup of the ^{9}Be projectiles. Depending on whether the breakup is dominated by the long range Coulomb or the short range nuclear interaction, different distributions of partial waves for complete fusion should result. Experimental investigations of the partial wave distributions are in progress. Comparison of the present results with those for lighter targets may give additional insights. Measurements [25,26] have shown fusion suppression for such reactions at energies well above the fusion barrier, although contrary results also exist [27]. Further measurements for lighter targets would be valuable.

In studies of breakup effects for neutron-rich unstable nuclei, the focus has been on the neutron separation energy [28], which for ^{11}Be is 0.50 MeV, compared with 1.67 MeV for ^{9}Be. This led to the expectation that ^{11}Be induced fusion cross sections would be suppressed compared with those induced by ^{9}Be. However, this was not borne out by measurement [9]. The present experiment demonstrates that breakup into charged fragments affects fusion very significantly. The two most favorable charged fragmentation channels for ^{9,11}Be are

$$^{9}\mathrm{Be} \rightarrow n + 2\alpha; \qquad Q = -1.57\ \mathrm{MeV},$$

$$^{9}\mathrm{Be} \rightarrow \alpha + {}^{5}\mathrm{He}; \qquad Q = -2.47\ \mathrm{MeV},$$

$$^{11}\mathrm{Be} \rightarrow \alpha + {}^{6}\mathrm{He} + n; \qquad Q = -7.91\ \mathrm{MeV},$$

$$^{11}\mathrm{Be} \rightarrow \alpha + \alpha + 3n; \qquad Q = -8.89\ \mathrm{MeV},$$

making ^{9}Be more unstable in this regard than ^{11}Be. Reactions with ^{9}Be therefore offer an excellent opportunity to study breakup and its effect on fusion, but they should not be taken as a stable standard against which to judge the breakup effects of their radioactive cousins.

In summary, the precisely measured fusion excitation function for ^{9}Be + ^{208}Pb, allowing determination of the fusion barrier distribution, shows conclusively that complete fusion of ^{9}Be is suppressed compared with the fusion of more tightly bound nuclei. The calculated fusion cross sections need to be scaled by a factor of 0.68 ± 0.07 in order to obtain a consistent representation of the measured fusion excitation function and barrier distribution. The loss of flux at the fusion barrier implied by this result can be related to the observed large cross sections for Po nuclei, demonstrating that ^{9}Be has a large probability of breaking up into two helium nuclei, which would suppress the complete fusion yield. These measurements, in conjunction with breakup cross sections and elastic scattering data, should encourage a complete theoretical description of fusion and breakup. Paradoxically, breakup of the stable ^{9}Be appears to be more significant than breakup of the unstable ^{10,11}Be in influencing the fusion product yields. This conclusion is favorable for using fusion with radioactive beams at near-barrier energies to form new, neutron-rich nuclei.

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