Sub-barrier fusion in the ^{48}Ca + ^{208}Pb reaction

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The study of the heaviest elements offers one an opportunity to study nuclear structure and nuclear dynamics under the influence of large Coulomb forces. Many years ago, Oganessian recognized the special importance of the doubly magic ^{208}Pb in the synthesis of the heaviest elements [1]. He showed the low excitation energies of the compound nuclei in reactions with ^{208}Pb or ^{209}Bi targets (so-called "cold fusion") (Figure 1) could be utilized to produce heavy nuclei via reactions like ^{208}Pb(X,n) or ^{209}Bi(X,n).

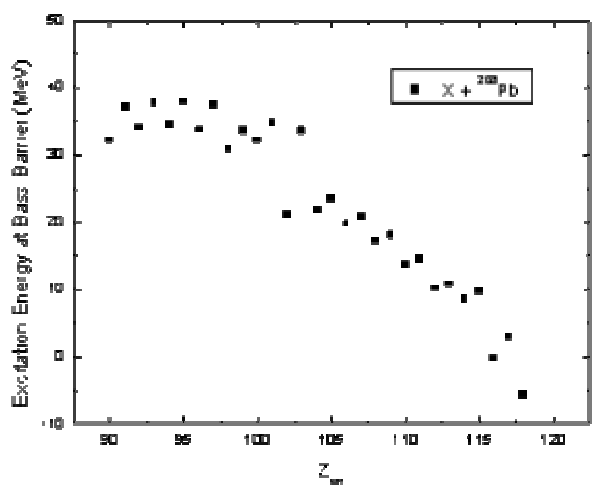

Figure 1. Excitation energies at the Bass barrier for reactions with ^{208}Pb targets.

Using this cold fusion approach, elements 107-112 were successfully synthesized at GSI [2]. The cross sections for these reactions decreased sharply with increasing Z. Attempts to produce element 113 using the cold fusion reaction ^{209}Bi(^{70}Zn,n) were not successful [2] with an upper limit cross section of 0.6 pb. Attempts to produce element 118 using the ^{208}Pb(^{86}Kr,n) reaction were also unsuccessful [3] with an upper limit cross section of ~ 0.2 pb. These findings have generally been taken to indicate the need for significant technical advances before further element synthesis with cold fusion reactions is feasible.

The reaction of the two doubly magic nuclei, ^{48}Ca and ^{208}Pb is one of the most interesting and experimentally challenging cold fusion reactions. The optimal excitation energy for a "1n" reaction is about 13 MeV. As seen in Figure 1, this requires a reaction that occurs significantly below the fusion barrier for the ^{48}Ca + ^{208}Pb system. We report an experimental study of the cold fusion reaction ^{208}Pb(^{48}Ca,n) and a search for the occurrence of the radiative capture reaction ^{208}Pb(^{48}Ca,γ). This study was

undertaken to better understand the capture and fusion probabilities in cold fusion reactions involving n-rich projectiles that might be of interest in the synthesis of heavy nuclei.

The reaction of ^{48}Ca with ^{208}Pb has been extensively studied [4-17,27] , especially the ^{208}Pb(^{48}Ca,2n) reaction. Some of these experimental studies have used this reaction to do nuclear spectroscopy of the transfermium nuclei [10,13-15] but most studies have dealt with measuring cross sections for this reaction. Extensive measurements also exist for the related reaction of ^{48}Ca with ^{206}Pb [18]. For the ^{208}Pb(^{48}Ca,n) reaction, cross sections of <27, 260 ± 30and 180 ± 53 nb have been reported for projectile energies of 208, 212, and 216 MeV, respectively.[7] To the best of our knowledge, no previous measurements of the radiative capture cross section have been made for this system

The reaction of ^{48}Ca with ^{208}Pb was studied at the 88-Inch Cyclotron of the Lawrence Berkeley National Laboratory, using the Berkeley Gas-filled Separator (BGS) [19]. The experimental apparatus was a modified, improved version of the apparatus used in [19], including improved detectors and data acquisition system, continuous monitoring of the separator gas purity, and better monitoring of the ^{48}Ca beam intensity and energy. A $^{48}Ca^{10+}$ beam was accelerated to various energies at typical beam currents of ~ 200 particle nanoamperes. The beam went through the 0.040 mg/cm^2 carbon entrance window of the separator and struck a ^{208}Pb target placed 0.5 cm downstream from the window. The targets were 460 mg/cm^2 thick (sandwiched between 35 mg/cm^2 C on the upstream side and <9 mg/cm^2 C on the downstream side). Nine of them were mounted on a wheel that rotated at 300 rpm. Beam energies at the center of the target were determined using the range-energy data of Hubert et al.[20] The beam intensity was monitored by two silicon detectors (mounted at ± 27° with respect to the incident beam) that detected elastically scattered beam particles from the target. Attenuating screens were installed in front of these detectors to reduce the number of particles reaching them (and any subsequent radiation damage to the detector.) The run lasted 60 hours.

The EVRs (E ~ 40 MeV) were separated spatially in flight from beam particles and transfer reaction products by their differing magnetic rigidities in the gas-filled separator. The separator was filled with helium gas at a pressure of 0.8 torr. For all the measurements, the magnetic field of the separator was set to 2.107 Tm, a setting that produced an optimum distribution of the EVRs on the focal plane detector for the ^{208}Pb(^{48}Ca, 2n)^{254}No reaction. (Using the semi-empirical relationships in [5] would give a predicted value of the optimum Br of 2.099 Tm). The efficiency of the separator for transport of recoils from the target to the focal plane detector was measured to be 57% for the reaction of 200 MeV ^{48}Ca with ^{176}Yb, assuming a cross section for this reaction of ~ 790 mb. (This latter value was extrapolated from the measured data of Sahm, et al. [21]). Monte Carlo simulations of the ion optics of the BGS [3] are consistent with this value (51%). We measured a transport efficiency of 45% for the reaction of 215 MeV ^{48}Ca + ^{208}Pb $\rightarrow$ ^{254}No + 2n. (This efficiency is based on a cross section for the ^{208}Pb^{48}Ca, 2n) reaction of 3.4 mb. [7] This value of the efficiency was used in all calculations.

In the focal place region of the separator, the EVRs passed through a 10 cm x 10 cm parallel plate avalanche counter (PPAC) [22] that recorded the time, DE, and x,y position of the particles. This PPAC has an approximate thickness equivalent to 0.6 mg/cm^2 of carbon. The time-of-flight of the EVRs between the PPAC and the focal plane detector was measured. The PPAC was used to distinguish (97.5 - 99.5% efficiency) between particles hitting the focal plane detector that were beam-related and events due to the decay of implanted atoms.

After passing through the PPAC, the recoils were implanted in a 32 strip, 300 mm thick passivated ion implanted silicon detector at the focal plane that had an active area of 116 mm x 58 mm. The strips were position sensitive in the vertical (58 mm) direction. The position resolution along each strip was measured to be 0.70 mm for recoil-a correlations in the ^{208}Pb(^{48}Ca,3n) reaction. The energy response of each strip of the focal plane detector was calibrated using implanted recoils. An average energy resolution of ~ 40 keV for 5-9 MeV a-particles was measured for this detector.

In searching for the cold radiative capture channel $^{208}Pb(^{48}Ca,\gamma)$, one must be cautious not to confuse the decay of 2.91s ^{256}No (E_α=8.448, 8.402 MeV) with the decay of 2.3 s ^{252}No (E_α=8.42, 8.37 MeV). (^{252}No can be produced by the $^{208}Pb(^{48}Ca,4n)$ reaction or by the $^{206}Pb(^{48}Ca,2n)$ reaction from any ^{206}Pb impurities in the ^{208}Pb target). These channels can be resolved by either looking at EVR-α-α correlations for the ^{252}No decay which leads to 36s ^{248}Fm (E_α=7.87,7.83 MeV) rather than the 25.4 hr ^{252}Fm (from the ^{256}No) or by looking for the more prevalent spontaneous fission branch of the ^{252}No (SF 26.9%) vs an SF branch of 0.53% for ^{256}No. In addition, the $^{208}Pb(^{48}Ca,4n)$ reaction is energetically forbidden for projectile energies less than 223 MeV.

In studying the product of the $(^{48}Ca,n)$ reaction, ^{255}No, one must be careful to disentangle the decay of ^{255}No ($t_{1/2}$=3.1 min, E_α 7927, 8007, 8077, 8121 keV), ^{254}No ($t_{1/2}$=55s, E_α=8093 keV) and ^{253}No($t_{1/2}$=1.7 min, E_α=8010 keV). We used two approaches to this decay curve resolution. At the higher energies, we used the 7927 line to calculate the cross section after resolving its decay curve while at the lower energies, we resolved the complex decay curves.

For center of target projectile energies of 204, 206.5, 207.8, 209.1, and 211.6 MeV with associated particle doses of 2.50 x 10^{16}, 2.40 x 10^{16}, 1.90x10^{16}, 3.50x10^{16}, and 4.90x10^{16}ions, no events corresponding to the production of ^{256}No were observed. This corresponds to one-event upper limit cross sections of 134, 139, 176, 95 and 68 pb, respectively.

Heavy ion radiative capture has been observed previously [23] and was the basis for an unsuccessful attempt to synthesize element 116 using the $^{208}Pb(^{82}Se,\gamma)$ reaction [2]. Two mechanisms for a possible cold radiative capture reaction of the type $^{208}Pb(^{48}Ca,\gamma)$ are fusion of the projectile and target nuclei in which the giant dipole resonance (GDR) of the compound system is excited and decays by the emission of GDR photons or production of a completely fused system whose (E*,J) are within one neutron binding energy of the yrast line, leading to a γ-ray cascade down to the ground state without particle emission. The latter possibility for the ^{208}Pb + ^{48}Ca reaction seems less likely given the data of Reiter et al.[15]who showed the entry distributions in the (E*,J) plane for the $^{208}Pb(^{48}Ca,2n)$ reaction at a similar energy (~ 215 MeV) are sharply tilted relative to the yrast line, suggesting that the initial compound system states do not fulfill the condition of being within one neutron binding energy of the yrast line.

The giant dipole resonance in ^{256}No should be around E* ~ 12-13 MeV, according to the systematic rule that the resonance position is given by 79 $A^{-1/3}$ [24] with a width of 4-6 MeV, which is similar to the range of excitation energies studied (E*=12-18 MeV) (neglecting the splitting of the GDR in the deformed ^{256}No). Thus, from an energetic point of view, decay by GDR photons was possible.

We can make some crude estimates to see if the observed upper limits for the radiative capture reaction are reasonable. If we write for the radiative capture cross section, $\sigma_{x,\gamma}$

$$\sigma_{x,\gamma}=\sigma_C \cdot P_{CN} \cdot W_\gamma$$

where σ_C is the capture cross section, P_{CN} the probability of going from the capture configuration to the completely fused configuration and W_γ is the probability of de-excitation by emission of GDR photons, we can make some order of magnitude estimates for the quantities involved to see if the failure to observe radiative capture is reasonable. The capture cross sections have been measured to be ~ 5 mb for the energy range in question [9], W_γ has been estimated to be 5 x 10^{-5} [23] and thus to get the observed upper limit cross section of 100 pb, we would need P_{CN} to be < 4 x 10^{-3}. Use of the semi-empirical estimates of P_{CN} in ref [25] for this case would give P_{CN} to be ~ 2 x 10^{-3} in agreement with the observed upper limit. Thus, because the centroid of the GDR resonance was 5-10 MeV below the Bass barrier for the reaction in question, our ability to observe cold radiative capture was reduced.

In Figure 2, we show the measured excitation function for the $^{208}Pb(^{48}Ca,n)^{255}No$ reaction along with a previous measurement. At projectile energies of 211.6 and 215.2 MeV (E*=18.6 and 21.7 MeV) , we are unable to resolve the decays of ^{255}No and ^{254}No with the entire decay curve being consistent with being

due to ^{254}No. . The peak cross section for the 1n channel is ~100 nb at a projectile energy of 209.1 MeV (E*=16.1 MeV). The capture cross section at this projectile energy is ~9 mb [9]. If we write the evaporation residue production cross section, σ_{EVR}, as

$$\sigma_{EVR}=\sigma_C \cdot P_{CN} \cdot W_{SUR}$$

then the product of P_{CN} and W_{SUR} is 1.1 x 10^{-5}. This estimate is interesting because it is a low value. Two possible ways of looking at this are as follows. If we take the estimates [26] of W_{SUR} ($=\Gamma_n/\Gamma_{total}$)=10^{-2} for ^{256}No excited to 16.1 MeV, then P_{CN} is 10^{-3} which is an unexpectedly large fusion hindrance for this reaction where Z_1Z_2=1640. On the other hand, if we use the semi-empirical systematics of Armbruster [25] for P_{CN}, we would estimate P_{CN} for this reaction to be 6 x 10^{-3} and a value of W_{SUR}=1.9 x 10^{-3} would result. We are attempting to resolve this ambiguity.

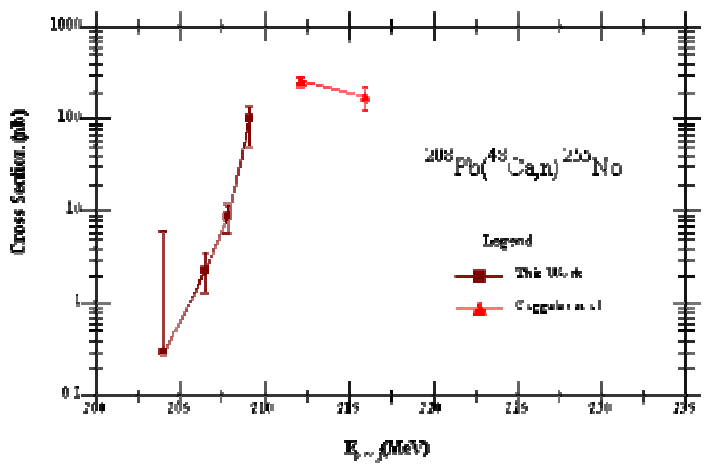

Figure 2. Measured cross sections for the ^{208}Pb(^{48}Ca,n) reaction.

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