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Fusion enhancement with neutron-rich radioactive beams

K. E. Zyromski,[1] W. Loveland,[1] G. A. Souliotis,[1] D. J. Morrissey,[2] C. F. Powell,[2] O. Batenkov,[3] K. Aleklett,[4]
R. Yanez,[4] I. Forsberg,[1] M. Sanchez-Vega,[4] J. R. Dunn,[1] and B. G. Glagola[5]
[1]*Department of Chemistry, Oregon State University, Corvallis, Oregon 97331*
[2]*National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, Michigan 48824*
[3]*Khlopin Radium Institute, St. Petersburg, Russia*
[4]*Department of Neutron Research, Uppsala University, Uppsala, Sweden*
[5]*Physics Division, Argonne National Laboratory, Argonne, Illinois 60439*

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We measured the fusion-fission excitation functions for the ^{32}S+^{181}Ta reaction and the ^{38}S+^{181}Ta reaction. (The radioactive ^{38}S beam was produced by projectile fragmentation.) The thresholds were measured to be 137.5±1.0 and 130.7±2.0 MeV for the ^{32}S and ^{38}S-induced reactions, respectively. This result agrees with the systematics of fusion excitation functions and may be significant in the synthesis of new heavy nuclei. [S0556-2813(97)50802-8]

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One of the interesting aspects of the study of nuclear reactions induced by radioactive beams is the possibility of using n-rich radioactive projectiles to synthesize new, neutron-rich heavy nuclei [1]. It has been shown [1] that new areas in the atomic physics and chemistry of the transactinide elements could be developed using intense n-rich radioactive beams.

Various authors [2–4] have suggested that there will be significant enhancements to the fusion cross sections for n-rich projectiles due to the lowering of the fusion barrier and the excitation of the soft dipole mode. They have further speculated that the use of these projectiles might lead to the successful synthesis of new or superheavy elements. Several new radioactive beam facility proposals have focused, in part, on these possible attractive features of using n-rich radioactive beams. The goal of this project was to make a measurement of the fusion enhancement factors for n-rich projectiles (of interest in the synthesis of new heavy nuclei).

A readily available n-rich projectile that can act as a prototype for the projectiles likely to be involved in future heavy element synthesis is ^{38}S. [^{38}S ($t_{1/2} \simeq 170$ m) can be produced at the MSU A1200 radioactive beam facility by fragmentation of ^{40}Ar.] By measurement and comparison of fusion cross sections and excitation functions for the fusion of ^{32}S and ^{38}S with ^{181}Ta, we can evaluate quantitatively the expected fusion enhancement factors. ^{38}S ($N/Z = 1.38$) is as n-rich as any radioactive projectile nucleus available in reasonable intensities from radioactive beam facilities [5]. Comparison of its fusion properties with those of ^{32}S ($N/Z = 1$) should be a meaningful comparison. Specifically, ^{38}S can act as a prototype for the less available ^{54}Ca whose fusion enhancement factors have been calculated [4] and the results from this study may provide impetus for more realistic calculations. Neither ^{32,38}S or ^{181}Ta are ''magic'' nuclei, and thus any special effects present in the fusion of shell stabilized nuclei will not be present. PACE calculations [6] indicated that 99% of the products formed in this reaction would fission so that the fusion-fission excitation functions should be equivalent to the fusion excitation function.

Because the fusion-fission excitation function for the ^{32}S + ^{181}Ta reaction had not been measured, we began by using the ATLAS accelerator facility to make this measurement. Well-focused, collimated ^{32}S beams of well-defined energy (typical energy spread = 0.2 MeV) from ATLAS struck a 0.46 mg/cm^2 Ta target mounted in the center of the 36″ scattering chamber. An array of 16 silicon surface barrier detectors (300 mm^2) were used to detect the coincident fission fragments from this reaction emerging at angles from 15° to 160°. Cross-section measurements were made at sixteen ^{32}S energies between 150 and 300 MeV. At each energy, the measured fragment angular distributions were transformed into the center of mass, fit with a 1/sin θ distribution and integrated to give the total fission cross section. (No significant differences in deduced total fission cross sections resulted when a more exact [7] form of the fragment angular distribution was used.) The absolute magnitude of the cross sections was determined by normalizing the observed elastic scattering cross section in the forward detectors to the Rutherford scattering cross section. The resulting fusion-fission excitation function is shown in Fig. 1.

The compound nucleus is ^{213}Ac, formed at excitation en-

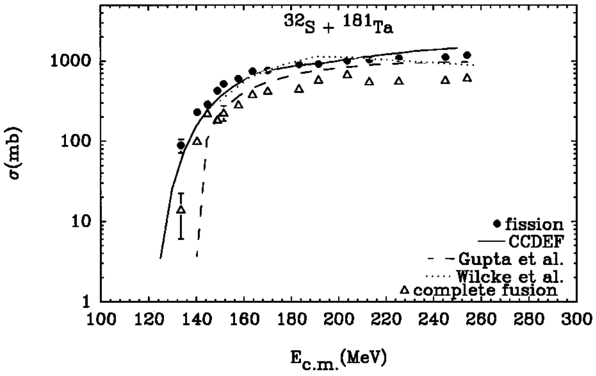

FIG. 1. Fission excitation function for the ^{32}S + ^{181}Ta reaction. ● experimental fission data, full curve-CCDEF calculation [10] dashed line systematics of Ref. [16], dotted line-systematics of Ref. [15], △ deduced complete fusion cross section

ergies of 47–174 MeV. According to PACE [6] simulations with a value of $a_f/a_n = 1.00$ [8] and temperature dependent values of a [9], the fraction of the reactions that leads to fission is 0.99 and it does not change appreciably with projectile energy. Furthermore, in our related study of ^{38}S + ^{181}Ta reaction, a measured upper limit of $< 3\%$ for the fraction of reactions leading to residue formation was found. Therefore we have taken the fusion-fission excitation function to be the fusion excitation function for this reaction.

Because of our desire to compare these data with our less precise measurements of the ^{38}S+^{181}Ta reaction, we have made a simple analysis of the data which can be applied in both reactions. We have performed a coupled channels calculation using the codes CCFUS and CCDEF [10]. In the coupled channels calculation, we have included the deformation of the target nucleus [11], the excitation of the first quadrupole and octupole states of projectile [with $B(E2)$ and $B(E3)$ values from [12] and [13]], and the excitation of the low-lying states of the ground state rotational band of ^{181}Ta (B values from [14]). The strength of the nuclear potential was varied to give the best overall fit to the experimental data, giving $V_b = 137.5 \pm 1.0$ MeV. The resulting fit to the data is shown in Fig. 1 along with semiempirical predictions of the fusion excitation function for this reaction [15,16]. The predicted values of the one-dimensional fusion barrier height are similar to the measured value. The better fit of the coupled channel calculations below the fusion barrier shows the importance of sub-barrier fusion enhancement in this system.

It has been shown [18,19] that for reactions like the ^{32,38}S+^{181}Ta reaction or the related ^{32}S+^{182}W reaction that a significant fraction of the fission events result from ''quasifission'' as well as ''true complete fusion.'' Quasifission is the process where the interacting nuclei merge to form a mononucleus, but the system does not evolve inside the fission saddle point. Comparison of the fission excitation function for the combined processes with one-dimensional potentials such as those used in coupled channels calculations is appropriate. But for the purpose of estimating heavy element production by complete fusion, one must separate the contributions of quasifission and true complete fusion in the data. Using the methods outlined in Refs. [18,19] which depend on analyzing the shape of the fission fragment angular distributions, we have estimated the relative contributions of quasifission and complete fusion to the observed cross sections. The results for the ^{32}S + ^{181}Ta reaction are shown in Fig. 1. Approximately half the fission events are due to quasifission. The reaction threshold shifts up by an energy of 7.3 ± 1.5 MeV in this case.

Using the projectile fragmentation/radioactive beam facility at Michigan State University, we measured the fusion excitation function for the ^{38}S+^{181}Ta reaction. A primary 40 MeV/nucleon ^{40}Ar beam was fragmented in a 120 mg/cm^2 Be production target in the A1200 fragment separator. After passage through an achromatic wedge, degrader, and momentum defining slits (to assure high beam purity) in the A1200, the beam was transported to the $N3$ area. The beam intensity was measured to be 2000–7000 ^{38}S/s on a 2×2 cm Ta target (of thickness 0.46 mg/cm^2) with a primary Ar beam current of 15 particle nA. The experimental apparatus used to measure the fusion cross sections is shown in Fig. 2.

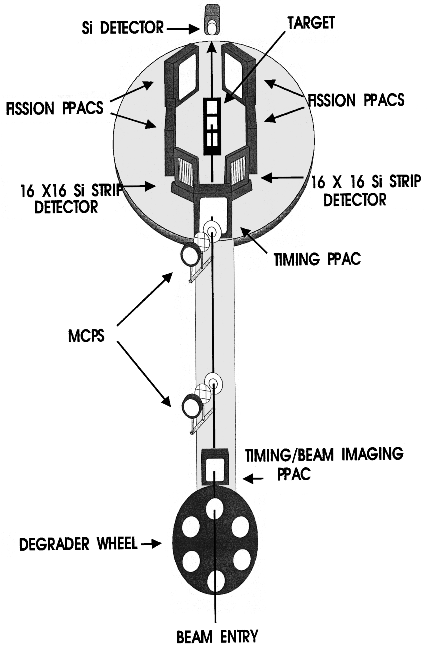

FIG. 2. Schematic diagram of experimental apparatus.

The 8.5 MeV/nucleon ^{38}S beam was degraded to 150–260 MeV by an Al degrader that was rotated to change its thickness. The energy straggling of the transmitted ions was about 15 MeV (FWHM) for degradation to 200 MeV. The degraded beam passed through a set of microchannel plate detectors and PPACs separated by 96 cm wherein the time of flight of the ions was measured. The time resolution of the MCP-MCP pair was measured to be 40 ps FWHM for an 8.5 MeV/nucleon ^{40}Ar beam (during the experiment). This time resolution allows measurement of the energy of each beam particle to within acceptable limits (<1 MeV). The efficiency of the ''beam timing system'' was measured to be 99.99%. Position sensitive PPACs mounted on either side of the Ta target detected prompt fission fragments, resulting from the de-excitation of the completely fused nuclei. (The efficiency of the PPACs for detecting fission fragments was typically >85 %.) For tuning and measuring beam currents, a semiconductor detector was placed at 0° and at these low ^{38}S intensities the beam was allowed to strike it.

Silicon strip detectors or an array of surface barrier detectors were mounted at backward angles to observe any α

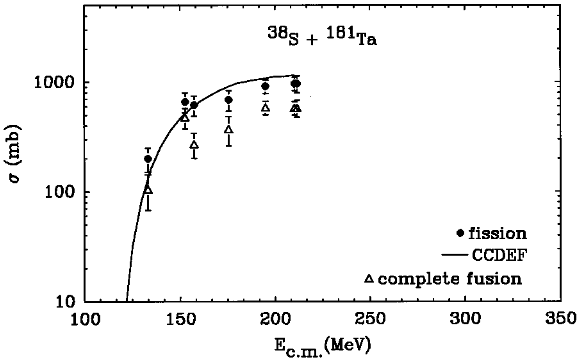

FIG. 3. Measured fission excitation function for the ^{38}S+^{181}Ta reaction. ● experimental fission data, △ deduced complete fusion cross sections, full curve-CCDEF calculations

TABLE I. Comparison of fusion barrier heights (MeV)

Reaction	Measured	Ref. [16]	Ref. [17]	Ref. [15]
^{32}S+^{181}Ta	137.5 ± 1.0	139.7	134.1	137.9
^{38}S+^{181}Ta	130.7 ± 2.0	132.2	130.7	-

particles from the decay of evaporation residues that stop in the target or fission fragments. No residue decay α particles were detected, giving rise to the previously discussed upper limit of 3% of all events that could lead to residue production. Folding angle distributions for the fission fragments were deduced from the coincident PPAC/strip signals. The differential fission cross sections, deduced from the PPAC and semiconductor signals, were fit with a 1/sin θ distribution and integrated to yield the total fission cross sections. Absolute cross sections were determined by comparison with measurements of the known [20,21] fission cross section for the interaction of 149 MeV ^{16}O with ^{197}Au made with the same setup.

The resulting fission excitation function is shown in Fig. 3. We fit the observed ^{38}S + ^{181}Ta excitation function with the coupled channels codes CCFUS and CCDEF [9] using the same procedure as with the ^{32}S-induced reaction. We deduced a fusion barrier height of 130.7 ±2.0 MeV for the ^{38}S+^{181}Ta reaction that is to be compared with a measured value of 137.5±1.0 MeV for the ^{32}S + ^{181}Ta reaction. These values of the fusion barrier height agree with various systematics (Table I). From the point of view of synthesis of new heavy nuclei, this energy shift of about one neutron binding energy can affect the production rates by factors of 10–1000, i.e., by the ratio of Γ_f/Γ_n [22]. Because the fission angular distributions are not known well enough to allow the same analysis as used in the ^{32}S-induced reaction to these data, we have simply applied the same quasifission correction factors at equivalent excitation energies to arrive at the deduced complete fusion cross sections shown in Fig. 3. The difference between the threshold for ‘‘fusion-fission’’ and ‘‘true complete fusion’’ is 6.9±2.8 MeV, resulting in a shift of the true complete fusion threshold of 7.2 ± 3.9 MeV in going from ^{32}S to ^{38}S.

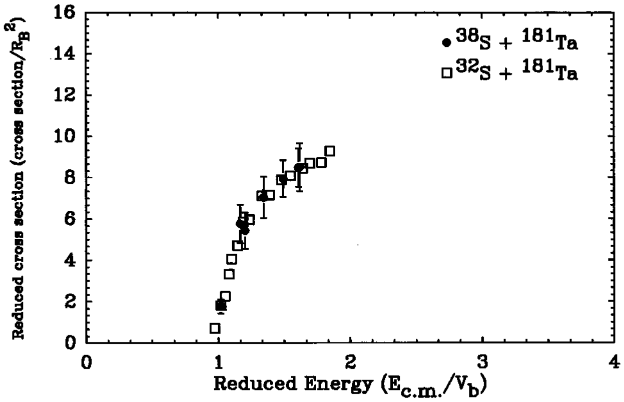

FIG. 4. Reduced excitation functions for the S + Ta reaction

It is interesting to test whether there is any evidence in this data for anything other than a simple shift in the height of the fusion barrier as the projectile shifted from ^{32}S to ^{38}S. We show (Fig. 4) a reduced excitation function for the two systems. Within the uncertainties in the data, there is no evidence for any changes in excitation functions (barrier shape) in the two reactions. Finally, we point out that the observed shift in the fusion barrier heights between the two reactions agrees with previous measurements and the expected lowering of the fusion barrier due to formation of a neck between the colliding nuclei [23].

In conclusion, we believe we have shown: (a) it is possible to study the fusion of neutron-rich heavy nuclei using existing radioactive beam facilities, (b) the fusion barrier heights for neutron-rich nuclei are substantially lower than for nuclei near the valley of β stability, and (c) the lowering of the fusion barrier height is large enough to significantly affect the synthesis of heavy nuclei.

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