Search for particle-bound neutral nuclei in heavy-ion-induced reactions

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(Received 10 July 1989)

An experimental test for the production of bound multineutron systems in the low center-of-mass energy environment of kinematically reversed heavy-ion reactions is described. The cross section for ^{A}n production, where $A \leq 5$, is estimated to be $< 2\ \mu b$, integrated over angles, energies, and A.

I. INTRODUCTION

Most theoretical calculations published to date would predict that bound neutral nuclei do not exist. However, such calculations generally involve the extrapolation of models of nuclear structure well beyond their ranges of known validity, and the results are generally very sensitive to the model parameters used. Obviously, the discovery of a bound neutral system would contribute significantly to the continuing development of nuclear models.

One experimental fact which provides motivation for theoretical and experimental investigations of neutral nuclei is the nonexistence of the $^{8}He \rightarrow ^{4}He + 4n$ decay, which serves to establish an upper limit of 3.1 MeV for the binding energy of the tetraneutron.[1] In addition, Tribble *et al.*[2] have shown that the (^{4}He,^{8}He) reaction can be well described as a direct, one-step process, thereby providing a hint of some autonomy for four-neutron clusters in nuclei. Finally, the recently reported evidence for a weakly coupled dineutron "halo" in ^{11}Li (Ref. 3) provides a strong incentive to explore the possibility of bound neutron clusters having $A \geq 3$.

Experimental efforts by other investigators to observe bound multineutron systems have involved transfer reactions among light nuclei,[4,5] the spallation of large nuclei with high-energy protons,[6,7] ^{3}He-induced fusion-evaporation reactions,[8] and double-charge-exchange (DCX) reactions,[9,10] among others. Detraz[6] presented positive evidence for the existence of bound clusters having masses from 5 to 9, presumably produced in high-energy spallation reactions, but subsequent experiments of this type failed to provide confirmation. As pointed out by de Boer *et al.*,[8] contributions from high-energy tritons produced in the spallations, which would induce (t,p) reactions in the detecting material, were probably underestimated in the work of Detraz. In any case, if the clusters are just barely bound, they may well be too fragile for a measurable number of them to have survived the reactions used to produce them in any of the previous experiments, as the center-of-mass energies used were all quite high (several tens of MeV, at least) compared to the expected low binding energies of the clusters.

In-beam γ-ray experiments involving fusion-evaporation reactions and particle-γ coincidence techniques have revealed that the emission of bound clusters of nucleons (e.g., deuterons or tritons) competes rather effectively with the evaporation of individual nucleons (e.g., pn or $p2n$) over the low-energy portion of the γ-ray yield curve.[11] In other words, a loosely bound cluster is most likely to survive reactions (without breaking up) in which the center-of-mass kinetic energy of the cluster is low. Therefore, if bound neutron clusters can exist, it seems possible they might be created in and survive heavy-ion reactions in which the cluster is gently released in the center-of-mass frame. Further, the use of "reverse" kinematics, in which the projectile is significantly more massive than the target nucleus, would serve to "focus" the light reaction products in the forward direction in the laboratory, and thus greatly enhance the efficiency of whatever method is used to detect the clusters.

II. EXPERIMENTAL METHOD

In this work, a neutron-rich compound nuclear system (^{59}Fe) was created using a beam of 250-MeV ^{50}Ti nuclei and a 7.0-mg/cm^2-thick ^{9}Be target. This corresponds to a maximum of only 38 MeV in the center-of-mass frame, of which at least 14.9 MeV or 24.2 MeV is needed to open the $4n$ or $5n$ channel, respectively. In either case, much of the excess could remain as excitation energy in the residual Fe nucleus with the cluster acquiring very little kinetic energy in the center-of-mass frame. The energy of the beam exiting the target was about 83 MeV, while the Coulomb barrier in the laboratory for ^{50}Ti on ^{9}Be is somewhat higher (about 100 MeV). Thus, an effective target thickness of 6.4 mg/cm^2 was used to compute cross-section products.

Adjacent to and downstream from the target were sufficient combined thicknesses of Ta and Al ($\sim$3 mm each) to stop the beam and the most energetic tritons which could be created in the target. The beam current at the target position was integrated to provide a basis for data normalization. Immediately downstream from the target and beam stoppers and outside the vacuum was positioned a cylindrical jar containing 1.013 kg of high-purity (99.995%) Sc_2O_3, which is isotopically pure in ^{45}Sc. The axis of the jar coincided with the beam axis. γ rays from the target were monitored with an n-type high-purity Ge detector during bombardment, and evidence was observed for the emission of up to five neutrons from the ^{59}Fe compound system. Bound clusters of neutrons, if produced, would be emitted in the forward hemisphere, and thus could activate the Sc_2O_3 if the (β decay) half-lives of the clusters were in the nanosecond range or longer. In particular, if two or three neutrons were to be simultaneously transferred to ^{45}Sc, ^{47}Sc or ^{48}Sc would be formed, respectively. The β-decay half-lives of these isotopes are 3.35 d and 43.67 h, respectively, so their presence could be detected via off-line accumulation of β-delayed γ-ray spectra (see Fig. 1). Factors contributing to the selection of Sc_2O_3 as the "cluster detector" included the isotopic purity in ^{45}Sc, the convenient half-lives of ^{47}Sc and ^{48}Sc, and the fact that false evidence for the existence of clusters was unlikely to result from single-neutron-induced reactions with contaminants in the sample.

The in-beam activation was performed at the Holifield Heavy Ion Research Facility (HHIRF) over a period of about four days, during which 2141 $p\,\mu$C of ^{50}Ti accumulated in the beam stop. The activation was carefully logged to account for interruptions in bombardment owing to minor accelerator problems. After the activation, spectra from the Sc_2O_3 sample were recorded for about 98 h using six Ge detectors in a separate setup. The spectra were stored on tape and reset at 1.5-h intervals. A computer code was written to calculate the efficiency of the Ge detector system for observing γ rays from a large cylindrical, attenuating source. This calculation and the approximations made therein are described elsewhere.[12] Uncertainties arising from these approximations alone are about 10%. Other systematic uncertainties, related primarily to detector geometry, contribute about 15%, resulting in an overall systematic uncertainty of approximately 20%. Another uncertainty arises from sensitive dependence of the limiting kinematic cone on the energy of the outgoing clusters, but it is clear from kinematics calculations that almost all of the lower energy clusters, i.e., the ones most like to survive, would have passed through the Sc_2O_3 sample. Finally, the data should be corrected for attenuation of the cluster "beam" due to breakup in the Ta, Al, Sc_2O_3, and the bottom of the jar containing the Sc_2O_3. Such weakly bound clusters would be expected to have very large effective radii, and thus large breakup cross sections. Using a (sharp cutoff) radius of 4 fm for ^4n, geometric cross sections for interaction with the various absorbers range from about 0.85 b for the hydrogen in the polyethylene jar to 3 b for the Ta beam stop. Taking these as reasonable (albeit rough) estimates for cluster breakup cross sections, about one-third of the cluster "beam" is lost on average, with most of this occurring the Sc_2O_3 sample. It should be noted, however, that a large cluster radius would also give rise to large two- and three-neutron stripping cross sections for producing ^{47}Sc and ^{48}Sc, respectively.

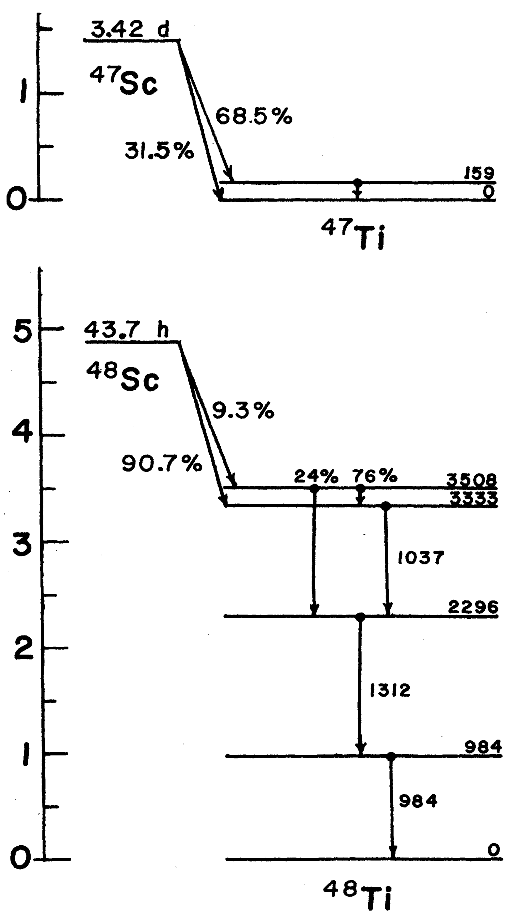

FIG. 1. Decay schemes of ^{47}Sc and ^{48}Sc [taken from *Table of Isotopes*, 7th ed., edited by C. M. Lederer and V. S. Shirley (Wiley, New York, 1978)]. Vertical energy scale is in MeV; energies of levels and strong transitions are given in keV.

III. RESULTS AND DISCUSSION

No evidence for γ rays from the decay of ^{47}Sc or ^{48}Sc was observed (see Fig. 2). Upper limits on γ-ray peak areas were extracted both by using a Gaussian peak-fitting routine and by simply integrating the background over appropriate intervals in the spectra. These results, and corresponding 1σ upper limits on the products of the cross sections for production of neutron clusters in the ^{9}Be target (σ_1) and for the production of a neutron-rich Sc isotope (σ_2) are summarized in Table I for the stronger γ-ray transitions.

The Q values for transferring two or three neutrons to ^{45}Sc are quite favorable (+19.4 MeV and +27.6 MeV, respectively) and there would be no Coulomb barrier for such a reaction, so such contributions to the cross-section product could be several hundred mb. For example, the ^{9}Be(^{50}Ti,^5n)^{54}Fe(6 MeV) reaction at 200-MeV bombarding energy would produce ^5n clusters having energies in the 10–20 MeV range in the laboratory. According to fusion-evaporation calculations using the code CASCADE,[13] the cross sections for production of ^{47}Sc and ^{48}Sc are 104 mb and 0.1 mb, respectively, when ^{45}Sc is bombarded by 15-MeV ^5n projectiles. The production of ^{47}Sc by low-energy tetraneutron bombardment is predicted by CASCADE calculations to be similarly strong. Further, a (t,p) reaction study[14] shows several strongly excited states in ^{47}Sc, which suggests the structure of that nucleus is favorable for its production via a direct stripping process as well as fusion evaporation. The stripping pro-

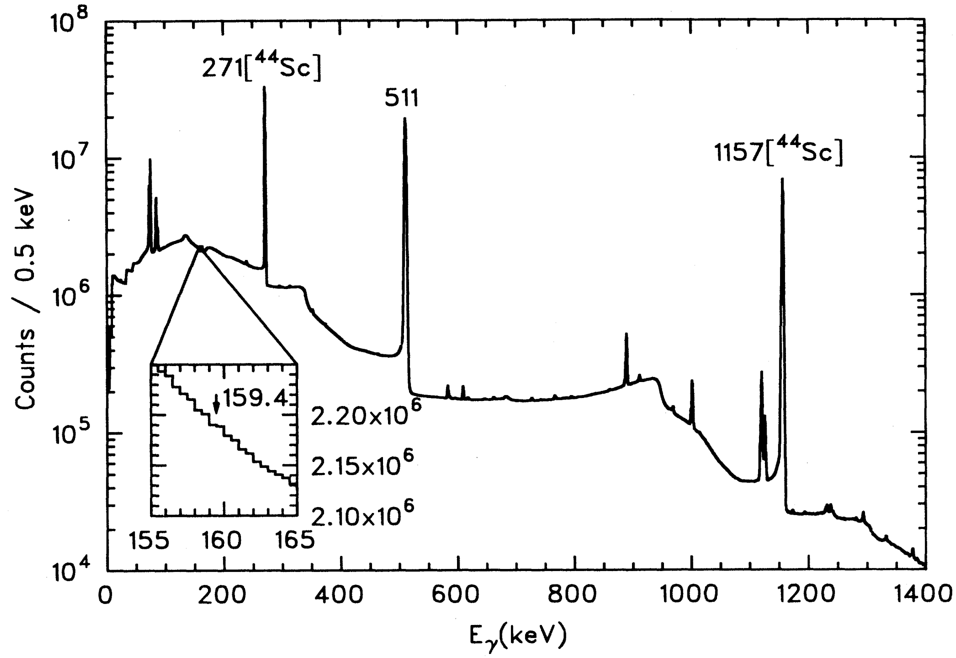

FIG. 2. γ-ray spectrum from the Sc_2O_3 sample after irradiation as described in the text. As indicated on the figure, the strongest transitions are those from the decay of ^{44}Sc. Inset shows detail in the region of the 159-keV transition in ^{47}Ti.

cess should be further enhanced by the assumed large cluster radii already mentioned. If one uses 200 mb for the total cross section for creating ^{47}Sc and assigns a factor of 2 to account for uncertainties and attenuation, one obtains an upper limit for the target-integrated cross section of about 2 μb for production of clusters which are (initially) stable to neutron emission, summed over all $A \leq 5$ (see the ^{47}Sc data in Table I).

IV. CONCLUSIONS

In view of this null result in what should be a favorable environment for neutron clusters to avoid immediate disintegration, the prospects for observing bound multineutron systems would seem to be rather poor. However, some improvement in sensitivity could be realized if activation beams having greater neutron excess (^{48}Ca, for example) and greater intensity were available at appropriate energies, and if a more efficient counting system could be used. In regard to the latter, it is worthwhile to note that a Compton-suppressed Ge system provides *less* sensitivity in counting a source of given initial activity, unless the suppression factor exceeds the factor by which the solid angle is reduced with the installation of a suppressor. Thus, it would be necessary to design the counting system for the specific γ-ray energies involved.

ACKNOWLEDGMENTS

Special thanks are due H. Rizzo of Lawrence Livermore National Laboratory for making the high-purity Sc_2O_3 available to us on a temporary basis. The authors are indebted to H. K. Carter of Oak Ridge Associated Universities for his assistance during the off-line counting phase of the experiment, to M. M. Hindi of Tennessee Technological University (TTU) for assisting with the data analysis, and to S. J. Sanders of Argonne National Laboratory for performing the CASCADE calculations. Contributions made by TTU undergraduate students T. R. Campbell and R. W. Tramel are also appreciated. This work was supported by the U.S. Department of Energy under Contract No. DE-AS05-79ER10335 and Special Research Grant No. DE-FG05-87ER40314.

TABLE I. Summary of 1σ upper limits for the production and detection of multineutron clusters. Systematic uncertainties in cross-section products are estimated to be 20%. The estimated upper limit in σ_1 has been raised a factor of 2 to account both for these uncertainties and the attenuation of the cluster "beam." See the text for further details.

				Gaussian fit		Background integration		Estimated σ_2		Estimated
Nuclide	E_γ[a] (keV)	Total efficiency	Decay branch	Maximum counts	$\sigma_1\sigma_2$ (mb^2)	Maximum counts	$\sigma_1\sigma_2$ (mb^2)	Cascade (mb)	Total (mb)	max σ_1 (μb)
^{47}Sc	159.4	0.0398	0.685	5920	0.204	4475	0.154	100	200	2
^{48}Sc	983.5	0.0107	1	1940	0.173	1370	0.122	0.1		
	1037.5	0.0102	0.978	1449	0.138	1000	0.096			
	1312.09	0.0085	1	730	0.082	518	0.058			

[a]See Fig. 1.

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