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Heavy ion radiative capture cross sections

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Cross sections for the radiative capture and one nucleon emission reactions have been obtained by mass identification of reaction products at 0° using thin targets for the systems $^{12}C + {}^{14}N$ (70 and 59 MeV), $^{30}Si + {}^{14}N$ (70 and 59 MeV) and $^{27}Al + {}^{14}N$ (59 MeV). The cross sections for radiative capture are in all cases < 500 nb. The measurement of the $^{30}Si + {}^{14}N$ cross section is in disagreement with previous work performed using thick targets. This discrepancy is discussed.

[NUCLEAR REACTIONS $^{12}C+{}^{14}N$ (70 and 59 MeV), $^{30}Si+{}^{14}N$ (70 and 59 MeV), $^{27}Al+{}^{14}N$ (59 MeV) upper limits radiative capture cross sections + estimate of one nucleon emission cross section for $^{30}Si+{}^{14}N$ (70 MeV).]

I. INTRODUCTION

Radiative capture cross sections have been measured for ^{14}N on ^{12}C, ^{30}Si, and ^{27}Al using a direct residual nucleus counting technique which differs from the methods employed in earlier experiments. Previously reported[1-5] measurements of heavy ion radiative capture cross sections utilized either prompt γ-ray detection or the off-line measurement of the radioactivity of the residual nucleus. Typically the cross sections obtained in the earlier measurements are in the range of 1–100 μb depending upon the energy and the nuclei involved. The results of this work can be directly compared with those of Zeller *et al.*[1] for ^{14}N capture by ^{30}Si at 59 MeV and a disagreement of a factor of at least 100 has been found. Because of this discrepancy and the fact that only upper limits have been determined by this experiment, the experimental technique is discussed in some detail in Sec. II. A possible explanation of the discrepancy is presented in Sec. III along with the results of this experiment.

Good measurements of heavy ion radiative capture cross sections are, in principle, extremely interesting since the majority of the cross section is expected to be produced by compound nuclei whose angular momentum is close to the yrast angular momentum for a given excitation energy.[1,6] It is currently an open question as to whether or not the highest angular momenta in compound nuclei formed in light heavy ion reactions are limited by the yrast line or by dynamic considerations.[7] For the system $^{14}N+{}^{12}C$ the moment of inertia implied by associating l_c, the cutoff (critical) angular momentum in the compound nucleus, with the yrast angular momentum is in good agreement with the rigid body value for an ^{26}Al radius of 3.94 fm.[8] However, such comparisons are probably not very useful at present since we do not know to what extent yrast states should be characterized by a rigid body moment of inertia.

The simplest model of the radiative capture process for heavy ions[1] involves attributing the capture cross section to that part of the angular momentum population for which $E_x - E_{\text{yrast}} < E_B$, where E_B is the binding energy of the least bound particle (n,p,α). However, for nucleons E_B has been recently shown to depend strongly on the structure of the yrast state, and this fact together with uncertainties in the shape of the high angular momentum tail of the compound nucleus population makes a simple calculation somewhat idyllic. If a calculation involving the above considerations could be carried out, radiative capture cross sections should provide a meaningful comparison between l_c and l_{yrast}.

II. EXPERIMENTAL METHOD

The experiments were carried out using beams of ^{14}N ions (4+) from the ISN variable energy cyclotron. The principle of the method employed makes use of the kinematical properties of the radiative capture reaction. The compound nucleus recoils in the laboratory at 0° to the projectile direction and with the velocity of the center of mass

of the projectile and the target. Thus these nuclei may be directly observed providing they can be separated from the beam particles. Furthermore, such nuclei may be distinguished from evaporation residues and direct reaction products of the same mass and charge produced from contaminants in the target due to the monochromaticity of their velocity spectrum. Thus use of hyperpure targets is not essential. Another advantage arises from the fact that detection efficiency is practically 100%. Thus cross sections as low as ~10 nb may be measured without excessive difficulty.

The principle of the experimental setup is shown in Fig. 1. The detection system consists of a pair of electrostatic deflection plates producing an electric field in the horizontal plane perpendicular to the beam direction, followed by a time-of-flight spectrometer which together with an energy measurement permits mass identification of the deflected products. Good separation of beam particles and compound nuclei was achieved in our experiments with electric fields of ~15 kV/cm, the beam particles being deflected by ~1–2° and the compound nuclei at angles between 4° and 7° depending on the beam energy and the compound nuclei ionic charge states. Under these conditions the beam passes between the deflector plates and its intensity may be conveniently measured in a Faraday cup.

The electrostatic deflector was composed of two aluminum plates 30 cm long and separated by 3 cm. The potential difference applied to these plates varied between 30 and 50 kV according to the measurement undertaken. The angular acceptance at the entry to the deflector was defined by a carbon foil collimator and was 2.3° in the horizontal plane, the target being located 20 cm in front of this collimator.

The measurement of the time of flight of ions after deflection was achieved using a channel plate start detector and a Si surface barrier stop detector of 450 mm^2 surface area which also furnished an energy signal. The principle of this system is described in Ref. 10. The time resolution was ~300 psec.

The time-of-flight spectrometer was mounted on a mobile support capable of rotation about an axis situated in the geometrical center of the deflector plates. The effective angular acceptance of the detection system is difficult to evaluate exactly in the horizontal plane since it is influenced by the finite size and divergence of the beam, the angular straggling in the target and in the ^{12}C foil used in the start detector. Furthermore, emission of γ rays from the compound nucleus produces a small additional divergence in the directions of recoiling compound nuclei. It was estimated, taking into account all these factors, that compound nuclei could be produced in a cone of ±0.3° around the 0° direction and the collimators of the detection system were thus designed to limit the geometrical acceptance angle to ±0.35°.

Compound nuclei emitted from the target at 0° may be detected after deflection at an angle

$$\theta = \tan^{-1} \frac{1}{2} \frac{VqL}{Ed} ,$$

where V is the voltage applied to the plates, L the plate length, d the plate separation, E the particle kinetic energy, and q the ionic charge of the deflected particle. The ionic charge distribution for ions of energy E was estimated using the formula (Ref. 11)

$$\bar{q} = Z \left\{ 1 - \exp \left[-\frac{3.8585}{Z^{0.447}} (E/A)^{1/2} \right] \right\} ,$$

$$d = 0.5 \{ \bar{q} [1 - (\bar{q}/Z)^{1.67}] \}^{1/2} ,$$

where $\bar{q}\ e$ is the most probable charge, A and Z are the mass and charge numbers of the ion, re-

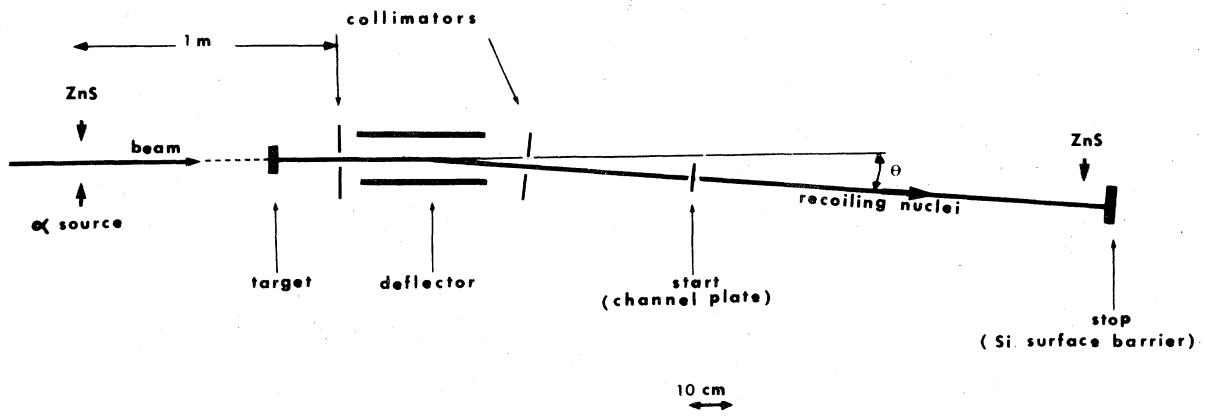

FIG. 1. Schematic representation of the experiment for radiative capture measurements.

spectively, and d is the standard deviation of the q distribution.

The angular dispersion introduced by this distribution necessitated the use of three adjacent detector positions and some variation of the electric field strength in order to detect all the principal charge states of the compound nucleus. Each measurement required from 3 to 5 h beam time with a beam intensity of ~10^{10} particles/sec, the sensibility of the measurement varying between 10 and 500 nb according to beam quality.

Special precautions were required in setting up the beam optics since it was necessary to minimize the presence of contaminants with E/q near that of the compound nucleus under study. The principal problem in this respect was the presence of low energy ^{14}N ions produced by slit scattering in the beam handling system. By limiting the beam emittance at the exit of the cyclotron and minimizing the use of slits after this point, it was found to be possible to reduce the low energy ^{14}N component observed, with the target removed, to ~10^2 particles for an incident beam intensity of 2×10^{10} particles/sec (13 nA of $^{14}N^{4+}$).

Before setting up the beam the detection was tested at 0° using a collimated Cm α source (E_{α_1} = 5.81 MeV, E_{α_2} = 5.76 MeV) placed 1 m in front of the deflection plates. Since the angular position of the detection system had been separately verified using the kinematic energy difference for ^{14}N ions scattered from Au and C, the use of this source permitted the calibration of the high voltage supplies. Furthermore, absolute energy and time scales were established using the α source and the mass identification was verified. The beam divergence and direction were then verified by placing the detection system at 0° and, with no deflecting voltage, observing the beam spot on a phosphor placed 1 m in front of the target and on a similar phosphor mounted on a retractable arm just in front of the E detector with the target removed. Finally with the voltage on the deflecting plates and the target in position it was verified that the deflection of the beam particles (completely stripped in the target) was correct and that the angular straggling introduced by the target was within the detection acceptance limits.

Measurements were carried out using ^{14}N beams on a carbon target 100 μg/cm^2 thick at 59 and 70 MeV, on a 75 μg/cm^2 ^{30}Si target at 59 and 70 MeV, and on a 100 μg/cm^2 Al target at 59 MeV. All targets were self-supporting. Raw data consisting of energy and time-of-flight signals were coded, transferred on-line to a PDP 9 computer, and stored on magnetic tape. Simultaneously, a biparametric display of $[E,t]$ was generated in which evaporation residue masses can be easily distinguished (Fig. 2). Masses were identified using the previously established calibration of time and energy scales and the calibration rechecked using the parasitic low energy ^{14}N ions. To determine the locus of the compound nucleus in the E-t plane, the average energy losses in the target and in the 20 μg/cm^2 carbon foil in the channel plate were taken into account. In the case of the ^{14}N + ^{30}Si reaction at 59 MeV, for example, the compound nucleus ^{44}Sc looses ~600 keV in the target and ~540 keV in the channel plate.

The biparametric representation of the data shows that our method of detection does not depend critically on a precise energy or time calibration.

III. RESULTS AND DISCUSSION

As can be seen in Fig. 2 the region of E-t space corresponding to mass 26 in the experiment ^{14}N

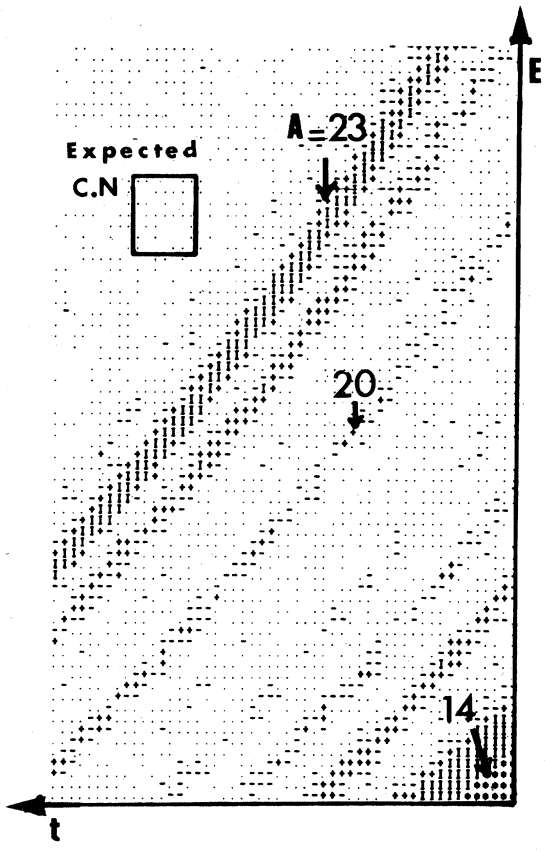

FIG. 2. Portion of the biparametric spectrum $N=f(E,t)$ for events detected at $\theta_{lab}=4°$, in the case ^{14}N(70 MeV) + ^{12}C. The dots represent a number of counts $1\leq N<4$. The symbols −, +, and I represent $4\leq N<8$, $8\leq N<16$, and $16\leq N<400$ respectively.

$+ {}^{12}C$ at 70 MeV contains mainly background counts.

The E-t plots for all cases studied were very similar in that

(1) no peak corresponding to the mass of the compound nucleus was observed, and

(2) no well defined line corresponding to the evaporation of one nucleon could be distinguished.

In the case of compound nucleus formation an upper limit on the cross section was determined by taking into account the background count density in the appropriate region of E-t space. For one nucleon emission it was considerably more difficult to make an estimate of the upper limit cross section since the detection system did not cover an angular range compatible with the expected angular distribution. However, in the case $^{30}Si + {}^{14}N$ at 70 MeV an estimate was made by assuming a uniform angular distribution out to the angle $\theta = \tan^{-1} P_t / P_{c.m.}$ where P_t is the momentum obtained from the expected average nucleon energy and $P_{c.m.}$ the momentum associated with the center of mass movement.

This estimate together with the results for radiative capture cross sections are presented in Table I. As can be seen from the table, our estimated limits are in total disagreement with the measurements of Ref. 1 for the system $^{14}N + {}^{30}Si$ (where cross sections 100 to 1000 times larger were reported). We suggest that the reason for this discrepancy has its origin in the experimental technique used by the authors of Ref. 1, i.e., thick natural Si target, off-line γ-ray counting. Under these circumstances ^{44}Sc can be produced by double reactions such as

$$^{14}N + {}^{28}Si \rightarrow {}^{18}F + {}^{24}Mg\,,$$

$$^{18}F + {}^{28}Si \rightarrow {}^{46}V \rightarrow pp + {}^{44}Sc\,.$$

We can estimate roughly the contribution produced in the above reactions by assuming that the cross sections associated with the direct and fusion evaporation processes in the above sequence are constant from the initial energies down to the Coulomb barriers. To simplify the discussion we further assume that the Coulomb barriers and ranges in the two reactions are identical and that the masses of targets for the primary (^{30}Si) and secondary (^{28}Si) processes are about equal (A). We then obtain a ratio for the primary (radiative capture) events to the secondary (production of ^{44}Sc by the two-step process) of

$$\frac{N_{sec}}{N_p} \approx \left(\frac{6\times 10^{-7}}{A}\right) \frac{R}{2} \frac{\sigma_d \sigma_f}{\sigma_c F}\,,$$

where σ_d, σ_f, and σ_c are the direct reaction, fusion evaporation, and radiative capture cross sections, respectively, in mb, R is the range down to the Coulomb barrier in mg/cm^2, A is the mass of the targets in the primary and secondary processes, and F is the isotopic ratio of target particles for the primary process to that for the secondary mechanism. In natural silicon $F \approx \frac{1}{30}$. Using rough estimates of σ_d obtained from Ref. 12, $\sigma_d \simeq 10$ mb, and the value of σ_c reported in Ref. 1 ($\sim 10^{-2}$ mb) and making the reasonable assumption that the cross section for the reaction $^{28}Si + {}^{18}F \rightarrow {}^{46}V \rightarrow pp + {}^{44}Sc$ is $\sigma_f \approx 200$ mb, we find a ratio $N_{sec}/N_p \approx 1$. Since other similar mechanisms may also contribute to the production of ^{44}Sc we are led to conclude that there is a strong possibility that the ^{44}Sc nuclei observed by the authors of Ref. 1 were produced by double mechanisms of the type cited above. Our limit for ^{43}Sc production would indicate that similar mechanisms may also have contributed to the value ~ 70 μb reported in Ref. 1.

TABLE I. Radiative capture results.

Reaction	Energy	Measured cross section
$^{12}C(^{14}N,\gamma)$	59 MeV	<500 nb
$^{12}C(^{14}N,\gamma)$	70 MeV	<50 nb
$^{27}Al(^{14}N,\gamma)$	59 MeV	<25 nb
$^{30}Si(^{14}N,\gamma)$	59 MeV	<25 nb
$^{30}Si(^{14}N,\gamma)$	70 MeV	<25 nb
$^{30}Si(^{14}N, p \text{ or } n)$	70 MeV	<17 μb

The results of our measurements at first sight would seem to indicate that the maximum angular momenta in the compound nuclei studied are considerably smaller than the yrast angular momenta at the excitation energy obtained. However, such a conclusion should be treated with caution since, as mentioned in the Introduction, the situation is complicated by the decrease of nucleon binding energies with increasing angular momentum (Ref. 9). Reasonably realistic calculations of this effect would need to be incorporated into an evaporation calculation before meaningful comparison between experiment and theory could be made.

Note added. We recently became aware of an experiment (Ref. 13) which, for the $^{27}Al + {}^{16}O$ system, gives an upper limit of the radiative capture cross section commensurate with our results.

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