PHYSICAL REVIEW C VOLUME 48, NUMBER 1 JULY 1993

Total nuclear reaction probability of 270 to 390 ^{14}N ions in Si and CsI

R. E. Warner, C. L. Carpenter, J. M. Fetter, and W. F. Waite*
Oberlin College, Oberlin, Ohio 44074

H. W. Wilschut and J. M. Hoogduin
Kernfysisch Versneller Instituut, 9747 AA Groningen, The Netherlands
(Received 24 February 1993)

A magnetic spectrograph and position-sensitive detectors were used to measure the total nuclear reaction probability η_R for α+CsI at 116 MeV, ^{14}N+CsI at 265 and 385 MeV, and ^{14}N+Si at 271 and 390 MeV. From these η_R's, average reaction cross sections σ_R were deduced for α and ^{14}N on CsI; these agree with optical and strong absorption model predictions. These same models predict σ_R's for ^{14}N+Si which vary by nearly a factor of 2; our measurement favors the smaller predictions.

PACS number(s): 25.55.−e, 25.70.−z

I. INTRODUCTION

The total nuclear reaction cross section σ_R provides information about the radii and transparency of nuclei and gives clues regarding their structure. σ_R is predicted by several nuclear models, including the optical and strong absorption models, but these models are in substantial disagreement for some systems. There is a shortage of direct measurements of this important quantity.

New methods for measuring σ_R are therefore worth pursuing. Earlier, we measured [1] σ_R for 74–112 MeV α particles in CsI by using a magnetic spectrograph to focus monoenergetic α particles on a CsI detector located in the focal plane. At each bombarding energy, the total nuclear reaction probability η_R (i.e., the total probability for the α particle to have any nuclear reaction before stopping) was determined from analysis of the detector's energy spectrum. The energy-averaged σ_R was then determined from the dependence of η_R upon bombarding energy. More recently, measurements [2] of σ_R for light neutron-rich radioactive nuclei in Si were made by a similar method.

Here we report new measurements of η_R for ^{14}N ions of about 270 and 390 MeV, ions incident upon both Si and CsI detectors. It is useful to know which of these detector types (if not both) will serve best for η_R measurements on light radioactive ions at the new radioactive beam facilities currently being planned. This method is quite appropriate for such ions produced in transfer or fragmentation reactions, since it requires only a small flux of the projectiles of interest. The ^{14}N+Si measurements are of particular interest, since optical model parameters obtained [3] in recent elastic scattering measurements on nearby system (^{12}C+^{27}Al) predict a σ_R well above the geometric value.

*Present address: Physics Department, University of Colorado, Boulder, CO 80309-0390.

II. EXPERIMENTAL PROCEDURE

The procedures, similar to those used earlier to measure σ_R for α+CsI from 74 to 112 MeV, are described elsewhere [1] in greater detail.

To verify that the apparatus worked properly, we first remeasured η_R for α+CsI. An α-particle beam of energy 117.2 MeV (as determined from the analyzing magnet B field) was scattered at 8° from a 500 μg/cm^2 Au target. Scattered particles entered at the Kernfysisch Versneller Instituut (KVI) spectrograph through an entrance slit whose horizontal and vertical openings were 3.4° and 2.9°, respectively. They were detected by a two-counter telescope in the focal plane, whose Si position-sensitive transmission detector (PSD), 115 μm thick with an active area 8 mm wide and 27 mm high, measured both energy loss and vertical position. The stopping detector was a 1-cm^3 CsI scintillation crystal, read by a photodiode and covered by a 25-μm Al foil. The α particles entered the latter detector with 116 MeV, and η_R was determined from the summed energy spectrum of the two counters. The spectrograph produced a line image about 2 mm wide and 2 cm high. Field adjustment centered this image on the telescope entrance slit, which was 5 mm wide and 8 mm high, thereby preventing illumination of the sides of this slit. Particles too far above or below the axis were rejected by their position signals; in particular, the vertical edges of the spectrograph entrance slit are projected outside the accepted vertical range. Thus, particles degraded in energy by the spectrograph and detector entrance slits were excluded from the event sample.

The Si+CsI telescope was then used to measure η_R for ^{14}N ions at two energies. These ^{14}N beams traversed the spectrograph with energies of 297 and 410 MeV, as was found by comparing the spectrograph NMR frequencies needed to focus them with those for the 117-MeV α particles. Their energy losses in the PSD and the CsI detector's 25-μm Al cover were determined from α-particle energy loss tables [4] and the scaling law $dE/dx = Z^2 f(v)$. Thus they were known to enter the CsI stopping detector with energies of 265 and 385 MeV, respectively.

0556-2813/93/48(1)/245(5)/$06.00

The $^{14}N+Si$ measurements utilized two crossed Si PSD's: a transmission counter identical to that in the CsI telescope, and a stopping counter 2 mm thick with active area 8×47 mm. ^{14}N ions entered the stopping counter, which measured a horizontal position, with either 271 or 390 MeV. A vertical position gate, set during analysis, rejected particles which could have struck the top or bottom edges of the stopping counter or entrance slit.

III. RESULTS AND DISCUSSION

A. $\alpha+CsI$

Figure 1 shows the recorded energy spectrum of 116 MeV α particles in CsI. Those events selected were among (a) the 60% of all events which passed closest to the detector axis, and (b) the 50% of all events whose energy losses in the PSD were closest to the mean energy loss. The anomalously small pulses are attributed to nuclear reactions, since all $\alpha+{}^{127}I$ and $\alpha+{}^{133}Cs$ reactions have negative Q values. This spectrum yields $\eta_R=(1.624\pm0.035)\%$. This result includes an estimated contribution [1] of $(0.027\pm0.004)\%$ from inelastic scattering and other low-Q reactions masked by the total ionization peak. This η_R, with those measured previously [1] at slightly lower energies, is shown in Fig. 2. From all data in this figure we obtain $\sigma_R=2210\pm50$ mb, averaged [1] over the interval 74–116 MeV, in agreement with our previous value of 2220±50 mb.

In Table I, we present the measured σ_R, an optical model (OM) prediction which uses the ^{140}Ce parameters of Baker and Tickle [5] and agrees well with the measurement, and the predictions of some strong absorption (SA) models. We previously reported [1,6] that several SA models [7] greatly overpredict σ_R for α particles of these energies. Table I shows, however, that the models of Kox *et al.* [8] give good results for σ_R; their predictions, with and without the neutron excess term included, bracket the measured value. However, at lower energies the models of Kox *et al.* predict much lower σ_R's than the other models; thus they underpredict η_R (see Fig. 2).

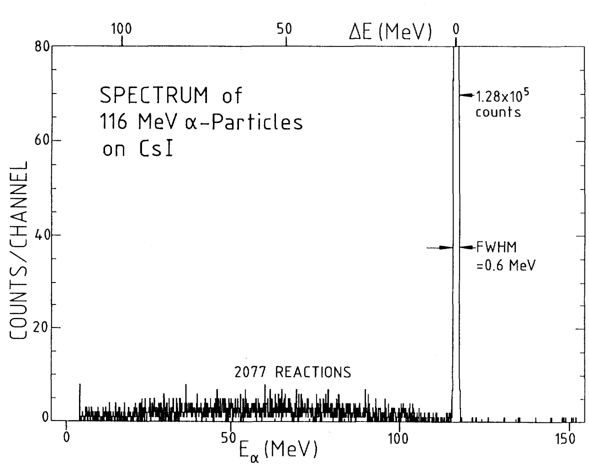

FIG. 1. Recorded energy spectrum of 116-MeV α-particles incident upon a 1-cm-thick CsI scintillation detector. Upper scale shows missing energy ΔE due to nuclear reactions of negative Q.

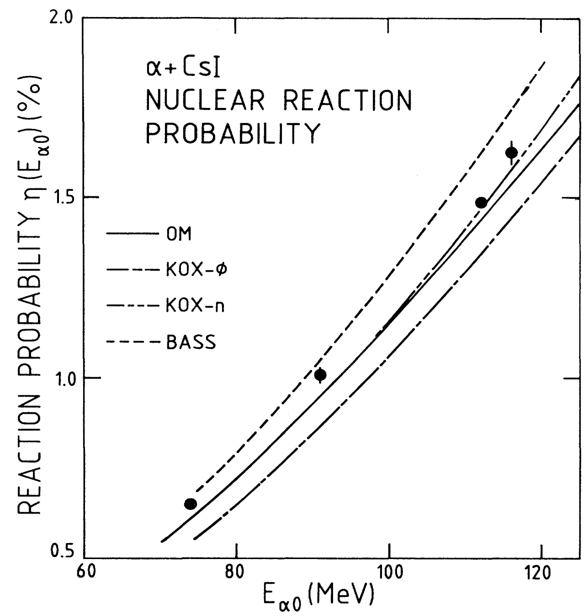

FIG. 2. Measured nuclear reaction probabilities η_R for 74- to 116-MeV α particles incident upon CsI, plotted vs their initial energy, are compared with optical model [5] and strong absorption [7,8] calculations. For the Kox [8] models, predictions including the neutron excess term (dash-double-dotted) and neglecting it (dash-dotted) are given.

B. $^{14}N+CsI$

The cyclotron injected either 297- or 410-MeV ^{14}N ions into the spectrograph. They entered the CsI stopping detector with residual energies of 265 or 385 MeV, respectively, after passing through the Si PSD and the Al cover of the CsI detector.

For several reasons, $^{14}N+CsI$ reactions can give anomalously large signals in CsI. Some reactions have positive Q; e.g., $Q\simeq+2.7$ MeV for $^{127}I(^{14}N,^{12}C)^{129}Xe$ and $^{133}Cs(^{14}N,^{12}C)^{135}Ba$. More frequently, the ^{14}N breaks into lighter nuclei. Such events, despite their negative Q values, give larger signals than stopping ^{14}N ions since light projectiles have greater luminous efficiency in CsI [9]. This effect (large E signals, for normal ΔE signals) is clearly shown in Fig. 3. However, the upper right qua-

TABLE I. Measurement and predictions of σ_R for $\alpha+CsI$ system, averaged between 74 and 116 MeV.

	σ_R (mb)	Reference
Measurement	2210±50	Present work
Optical model	2210	5
Kox (no neutron excess)	2140	8
Kox (with neutron excess)	2340	8
Bass	2570	7
Gupta	2730	7

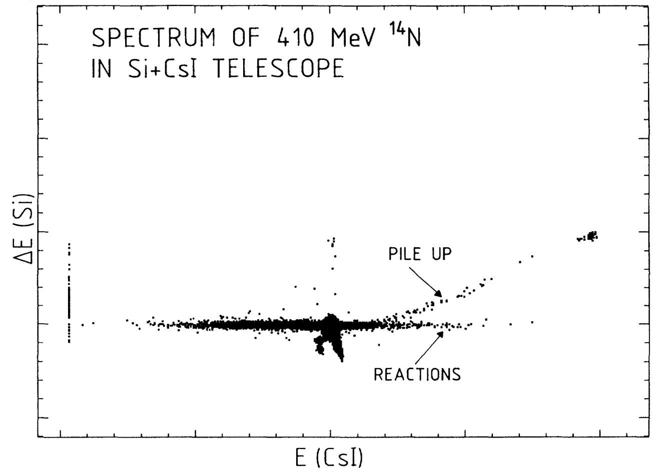

FIG. 3. Two-dimensional energy spectra for 410-MeV ^{14}N ions. ΔE is measured in a Si transmission detector, and E in a CsI detector. Events on the curved locus in the upper right quadrant represent pileup of two particles. Those labeled "REACTIONS" are attributed to reactions in which ^{14}N breaks up into smaller particles; anomalously large E signals then result from the greater luminous efficiency of the fragments, despite the negative Q value.

drant of Fig. 3 also shows pileup due to two particles entering the telescope together. Since this pileup locus extends into the region of the ΔE-E plane where events were accepted, the background of pileup signals had to be subtracted from the large reaction signals. This was done by plotting pileup rate versus ΔE for large ΔE (i.e., in the region where the two loci were well separated), and extrapolating this rate into the ΔE window used for event acceptance. Neglect of this correction would have increased the measured σ_R by about 4%.

As in the $\alpha+$CsI analysis, the reaction events were obtained from ΔE- and y-gated E spectra. At 385 MeV, the y-gate accepted events from about the central half of the slit; further broadening this gate increased the apparent η_R, indicating that slit-scattered events were being counted. At 265 MeV, acceptance had to be limited to the central quarter of the slit, as was expected since, at lower energies, the mean multiple-scattering angle increases. η_R's of $(0.268\pm0.016)\%$ and $(0.536\pm0.014)\%$ were obtained for 265- and 385-MeV projectiles, respectively; these values include interpolated contributions for reaction events lying under the total ionization peaks. From them, we obtain $\sigma_R=2750\pm220$ mb for this energy region.

The closest system for which optical model (OM) parameters are available is $^{12}C+^{90}Zr$, which has been analyzed at both 300 MeV [10] and 344 MeV [3]. Our data are compared with the OM predictions and some strong absorption (SA) calculations in Table II and Fig. 4. Our σ_R value, by itself, is consistent with the OM predictions and both the Kox (with neutron excess) and Gupta SA calculations. However, η_R is determined by integrating

TABLE II. Measurement and predictions of σ_R for $^{14}N+$CsI system, averaged between 265 and 385 MeV.

	σ_R (mb)	Reference
Measurement	2750±220	Present work
Optical model (Sahm)	2670	10
Optical model (Jarczyk)	2975	3
Kox (no neutron excess)	2340	8
Kox (with neutron excess)	2550	8
Gupta	2910	7
Bass	3170	7
Schröder-Huizenga	3290	7

σ_R over energy, and the data (see Fig. 4) favor the predictions from the OM parameter set of Jarczyk *et al.* [3] over those from the OMP's of Sahm *et al.* [10]; therefore, the latter must predict too little σ_R at lower energies.

C. $^{14}N+$Si

The previously described ^{14}N ion beams emerged from the transmission Si detector and entered the stopping Si detector with energies of either 271 or 390 MeV. These two detectors had one-dimensional position sensitivity in perpendicular directions. After focusing by the spectrograph, the secondary beam width parallel to the long axis of the stopping detector (i.e., the x direction) was smaller than the widths of the slit and transmission detector. Two-dimensional (x vs E) spectra from the stopping

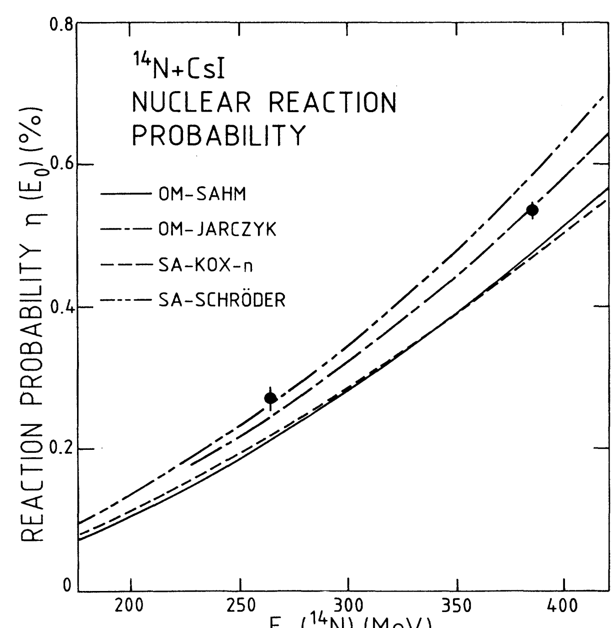

FIG. 4. Measured total nuclear reaction probabilities for 265- and 385-MeV ^{14}N ions incident upon CsI, plotted vs initial energy. Predictions are shown for two OM parameter sets (Jarczyk *et al.* [3] (dash-dotted curve), and Sahm *et al.* [10] (solid curve)) and two SA models (Kox *et al.* [8], neutron excess term included (dashed curve) and Schröder-Huizenga [7] (dash-double-dotted curve)).

detector revealed that, in one run, the beam had struck a vertical edge of the slit or transmission detector; these data were discarded. Other runs were analyzed with tight gates set on ΔE and the y coordinate, but without restriction on the x coordinate.

Of the transfer reactions from $^{14}N+Si$, only $^{28}Si(^{14}N,^{12}C)$ has a positive Q value, which is too small (+1.57 MeV) to resolve the group from the ionization peak. No significant background, from either reactions or pileup, appeared above the peak. Therefore, η_R was found from the event yield below the peak in the gated energy spectra, including interpolation of this yield to the peak center to allow for reactions of small negative Q. The values (0.388±0.010)% and (0.815±0.015)% were obtained for η_R at 271 and 390 MeV, respectively. These give $\sigma_R = 1445 \pm 60$ mb for this energy region.

The data and predictions are presented in Fig. 5 and Table III. The predictions vary widely, by nearly a factor of 2 for both optical and strong absorption models. The closest systems for which OM parameters are available are $^{12}C+^{27}Al$ at 344 MeV [3], $^{12}C+^{12}C$ at 300 MeV [10], and $^{16}O+^{28}Si$ at 215 MeV [11]. The measured σ_R agrees with the $^{12}C+^{12}C$ OM prediction and is somewhat larger than the Kox *et al.* [8] SA prediction. Other predictions from models of both classes are far too large.

We present this measurement with caution since it is at the lower range of such widely varying predictions. Probably the only systematic experimental error which could reduce σ_R is the failure to count reactions of such low Q that their signals lie under the total ionization peak. Good energy resolution enabled us to count all reactions with $|Q|>3$ or 4 MeV in the 271 and 390 MeV measurements, respectively. Thus the $^{14}N+^{28}Si$ transfer reactions producing $^{12}C+^{30}P$, $^{13}N+^{29}Si$, and $^{16}O+^{26}Al$ in their ground states, all of which have $|Q|<2.1$ MeV,

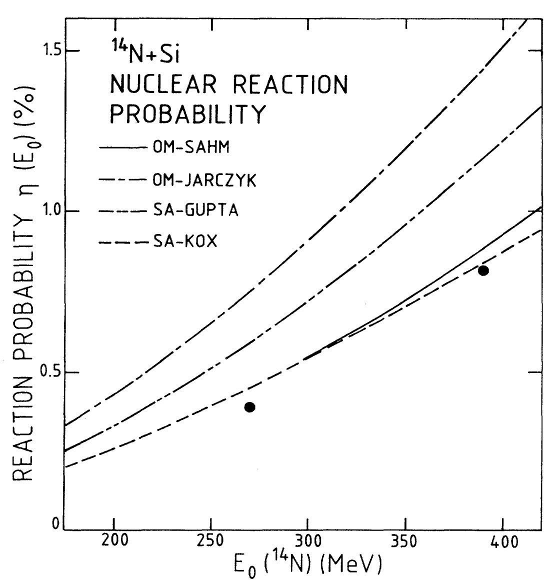

FIG. 5. Measured total nuclear reaction probabilities for 271- and 390-MeV ^{14}N ions incident upon Si. Predictions are for the same models as Fig. 4, except that the Gupta rather than the Schröder-Huizenga SA model is used.

TABLE III. Measurement and predictions of σ_R for $^{14}N+Si$ system, averaged between 271 and 390 MeV.

	σ_R (mb)	Reference
Measurement	1445±60	Present work
OM-Sahm	1480	10
OM-Cramer	1860	11
OM-Jarczyk-165	1915	3
OM-Jarczyk-80	2365	3
Kox	1290	8
Gupta	1960	7
Bass	2160	7

were not counted. However, other intermediate-energy heavy-ion studies [12] suggest that integrated cross sections for such reactions are at most a few mb. A σ_R measurement [2] similar to ours, but with a 4π NaI detector array added to detect low-Q quasielastic reactions, found that such events are only a few percent of the total yield. Thus it seems unlikely that the present measurement has missed a large fraction of the true σ_R.

It seems significant that the Kox *et al.* [8] SA model slightly *underpredicts* this measurement since, as shown earlier, it alone among the SA models fits the $\alpha+Si$ data. The simplest classical model, which allows for Coulomb deflection of the orbits, gives for the geometric cross section

$$\sigma_R = \pi R^2 (1 - V/E_{c.m.}) ,$$

where V is the Coulomb potential energy at the interaction radius R, the latter being given by

$$R = r_0 (A_1^{1/3} + A_2^{1/3}) .$$

A radius parameter $r_0 = 1.3$ fm then reproduces our σ_R. This value seems small (but perhaps not unreasonably so) since a smooth-cutoff analysis [13] of elastic scattering in heavier systems finds the *maximum* r_0 at which absorption occurs to be 1.49 fm. However, the widely used Bass model [7] predicts (see Table III) $\sigma_R = 2160$ mb.

IV. CONCLUSIONS

The average σ_R for $\alpha+CsI$, obtained from the new 116 MeV η_R measurement and earlier data [1], agrees with both OM predictions and those of the Kox *et al.* strong absorption model; indeed, the model of Kox *et al.* appears to be the only SA model which can fit α-particle data.

The average σ_R for $^{14}N+CsI$, between 265 and 385 MeV, agrees with several OM and SA predictions [3,7,8,10]. However, since the reduced luminous efficiency of CsI for heavy ions places some reaction events above the peak, the usefulness of this technique for measuring heavy-ion σ_R's on CsI may be impaired.

Silicon detectors seem better suited than CsI for heavy-ion σ_R measurements; in general, larger detectors than those used in this experiment are desirable, for increased efficiency and assured freedom from slit scattering. Their use in the $^{14}N+Si$ measurement provided easy discrimination between the available OM and SA predictions. However, since the predictions differ so dramatically, both confirmation of our measurement and further studies in this region are needed. The latter could usefully focus on both systematics and energy dependence.

ACKNOWLEDGMENTS

We deeply appreciate the advice of G. R. Satchler and J. B. Ball on optical model parameters, and the assistance of A. G. Drentje and H. Leegte with the KVI cyclotron and associated equipment, D. R. Stinebring in reading the event tapes, and J. S. Winfield and A. Nadasen with the optical model program ECIS79. Financial support came from the National Science Foundation (Grant No. PHY-9122067), the BP America Undergraduate Assistantship Program (W.F.W.), The Oberlin College Research and Development Committee (J.M.F.), and the Nederlandse Organisatie voor Wetenschappelijk Onderzoek (NWO) through the Stichting voor Fundamenteel Onderzoek der Materie (FOM).

---

[1] R. E. Warner, H. W. Wilschut, W. F. Rulla, and G. N. Felder, Phys. Rev. C **43**, 1313 (1991).
[2] A. C. C. Villari *et al.*, Phys. Lett. B **268**, 345 (1991).
[3] L. Jarczyk, B. Kamys, A. Magiera, R. Siudak, A. Strzalkowksi, B. Styczen, J. Hebenstreit, W. Oelert, P. von Rossen, H. Sehfarth, and G. R. Satchler, Nucl. Phys. **A518**, 583 (1990).
[4] C. F. Williamson, J.-P. Boujot, and J. Picard, Commissariat d'Energie Atomique Report No. R3042, Saclay, 1966 (unpublished).
[5] F. T. Baker and R. Tickle, Phys. Rev. C **5**, 182 (1972).
[6] R. E. Warner and G. N. Felder, Phys. Rev. C **42**, 2252 (1990).
[7] S. K. Gupta and S. Kailas, Z. Phys. A **317**, 75 (1984).
[8] S. Kox *et al.*, Phys. Rev. C **35**, 1678 (1987).
[9] E. Valtonen, J. Peltonen, and J. J. Torsti, Nucl. Instrum. Methods Phys. Res. A **286**, 169 (1990).
[10] C.-C. Sahm *et al.*, Phys. Rev. C **34**, 2165 (1986).
[11] J. G. Cramer, R. M. De Vries, D. A. Goldberg, M. S. Zisman, and C. F. Maguire, Phys. Rev. C **14**, 2158 (1976).
[12] M. C. Mermaz *et al.*, Z. Phys. A **326**, 353 (1987).
[13] Yu. Ts. Oganessian, Yu. E. Penionzhkevich, V. I. Manko, and V. N. Polyansky, Nucl. Phys. **A303**, 259 (1978).