Measurement of Total Reaction Cross Sections of Exotic Neutron-Rich Nuclei

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Total reaction cross sections of neutron-rich nuclei from C to Mg in a thick Si target have been measured by the detection of the associated γ rays in a 4π geometry. This cross section strongly increases with neutron excess, indicating an increase of as much as 15% of the reduced strong-absorption radius with respect to stable nuclei.

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High primary beam intensities and production rates of exotic nuclei at Grand Accélérateur National d'Ions Lourds (GANIL) allow the measurement of properties of nuclei far from stability. Recently, we reported on the mass measurement[1,2] of neutron-rich nuclei. The present work reports the measurement of total reaction cross sections of some of these nuclei. Tanihata and coworkers have recently measured[3,4] total reaction cross sections for He, Li, and Be isotopes. These results have stimulated considerable interest, and were quite well reproduced by theoretical calculations[5,6] with the Glauber model and a Hartree-Fock–type variational calculation for the nuclear structure. An important difference, however, was observed for ^{11}Li.

The experimental arrangement used for mass measurements[1,2] suits well the simultaneous measurement of total reaction cross sections. A Ta target (350 and 500 mg/cm^2) near the exit of the accelerator was bombarded with a 60-MeV/nucleon ^{40}Ar beam of 1 μA*e*. Part of the secondary particles produced were transported to the magnetic spectrograph SPEG.[7] At the focal plane, a nondispersive doubly achromatic tuning of the line ensures a maximum beam-envelop entent of about 2×2 cm^2. Hence, all the particles hit a telescope consisting of two 300-μm ΔE and a 6000-μm E solid-state Si detectors. The telescope was surrounded by an array of six hexagonal NaI(Tl) detectors 13.1 cm thick and 23.5 cm long, covering a solid angle of 87% of 4π. Behind the solid-state detectors, a smaller NaI(Tl) detector (7.5 cm thick and 10 cm long) permitted detection of γ rays and charged particles in a close-up geometry (Fig. 1). The particles were identified by the energy-loss signal of the first ΔE detector and the time of flight T between this detector and a microchannel plate device positioned 80 m upstream. For a given $B\rho$ value, T and $\sqrt{\Delta E}/T$ are essentially proportional to A/Z and Z, respectively.

The raw uncorrected reaction probability $P_{\rm reac}^{\rm nc}$ is given by the number of coincidences between the ΔE counter and any set of NaI detectors divided by the singles in the ΔE detector. The reaction probability $P_{\rm reac}^{\rm nc}$ was of the order of several percent in the present measurements.

Several corrections were applied in order to obtain the reaction cross section: correction for random coincidences (about 2%), correction for ambiguous identification—background due to tails in the identification functions was subtracted (about 1%), and efficiency correction.

The last one is the most important. A detection efficiency of the six-detector array of 70% for a single photon was measured with a calibrated ^{60}Co source. A geometrical calculation and the measured multiplicity lead to a probability of 84% that at least one detector fires. The coincidence probability between this array and the smaller NaI(Tl) was found to be around 70%; thus the combined detection probability was about 95%, with an estimated uncertainty of 5%. This uncertainty contributes mainly to the uncertainty of the absolute value

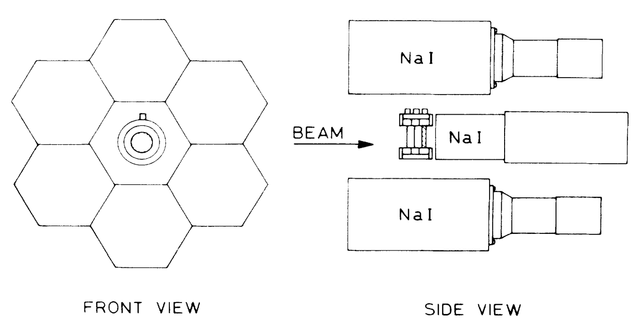

FIG. 1. Schematic view of the experimental setup for the detection of the associated radiation around the Si telescope that serves as target. The six-detector array is mainly sensitive to γ rays and, with less efficiency, to neutrons, whereas the smaller NaI detector behind the telescope will register, too, charged particles produced in the forward-angle cone with high enough energy to leave the last Si detector.

of the cross section. No dependence of this correction on mass or atomic number is expected.

Applying these corrections, we obtain the corrected reaction probability $P_{\rm reac}$. The total reaction cross section is obtained with the relation

$$\sigma_R = P_{\rm reac} \times 28.085/N_A\, R. \quad (1)$$

N_A is the Avogadro number, 28.085 g/mol is the weight of the unenriched Si of the detectors that constitute the target, and R is the range of the incident particles in Si. R was taken from the tables of Hubert *et al.*,[8] which are in good agreement (1.4%) with recent measurements.[9] The incident energy of the particles is well known by the $B\rho$ value of the beam line. Two values of $B\rho$ were used, 2.611 and 2.876 T m. The thickness of the first ΔE detector must be subtracted from the total range since a correct identification implies that no reaction has occurred in this detector.

The measured cross sections correspond to thick-target yields, and represent a mean value over energy from $E_{\max}$ at the exit of the first ΔE counter to the Coulomb barrier energy $V_{\rm Cb}$. Because of the selection by the magnetic rigidity, the energy $E_{\max}$ varies from one nucleus to the other and is typically 40 to 60 MeV/nucleon. Here we are mainly interested in the variation of the nuclear properties as a function of neutron excess. It is then necessary to reduce the experimental $P_{\rm reac}$ to a quantity independent of the energy. Such is the reduced geometrical strong-absorption radius r_0, as defined by

$$\sigma_R(E) = \pi r_0^2 f(E), \quad (2)$$

where the energy dependence $f(E)$ can be estimated in appropriate models. Then

$$P_{\rm reac} = \frac{N_A}{28}\int \sigma_R(E)\, dR = \frac{N_A}{28}\pi r_0^2 \int_{E_{\max}}^{V_{\rm Cb}} f(E)\frac{dR}{dE}dE, \quad (3)$$

where dE/dR is the stopping which was approximated by $dE/dR \propto E^{-0.73}$.

We used for $f(E)$ the empirical formula of Kox *et al.*[10]

$$f(E) = \{A_1^{1/3} + A_2^{1/3} + aA_1^{1/3}A_2^{1/3}/(A_1^{1/3}+A_2^{1/3}) - C(E)\}^2(1 - B_c/E_{\rm c.m.}). \quad (4)$$

This formula reproduces very well[10] the experimental data over a large energy domain and for many systems. It contains a correction for asymmetry proportional to $a = 1.9$, an energy-dependent transparency term $C(E)$, and a correction for the Coulomb barrier. We have used a linear dependence for $C(E)$, based on the results of Kox *et al.*[10]

$$C(E) = 0.14 + 0.015E/A. \quad (5)$$

One finally obtains at first order

$$P_{\rm reac} = \pi r_0^2 D^2[1 - 2.37B_c/E_{\rm c.m.} - 0.0190(E/A)/D]N_A R/28, \quad (6)$$

where

$$D = A_1^{1/3} + A_2^{1/3} + aA_1^{1/3}A_2^{1/3}(A_1^{1/3}+A_2^{1/3}) - 0.14 \quad (7)$$

takes into account the normal A dependence of the cross section and the reduced radius r_0 is expected to be independent of energy and of the system. It is important to note that the influence of the energy dependence of Eq. (6) is small in the present experiment. This comes from the fact that mainly high energies contribute where dR/dE is big [Eq. (3)]. The total reaction cross section is practically energy independent for high incident energies and essentially the same result is obtained even if we completely neglect this energy dependence.

The comparison of the measurements done at the two $B\rho$ values, therefore at two energies for each nucleus, provides a check of the validity of the energy dependence (4). The two values of r_0^2 agree within error bars. Note that r_0^2 should not depend on the atomic number because the expected A dependence is already taken into account explicitly [Eqs. (2) and (4)].

Kox *et al.*[10] obtained a value of $r_0 = 1.05$ fm. The values obtained in the present measurements are shown in Fig. 2. A strong dependence as a function of neutron excess is observed. For nuclei near stability, the value of r_0 is in good agreement with the one of Ref. 10, that corresponds to stable nuclei.

Possible sources of experimental artifact were carefully checked. No correction was found to depend significantly on the nuclear species. For example, the correction of detection probability due to γ multiplicity varies by 2% from ^{15}N to ^{19}N, as can be estimated from the measured change of multiplicities. The relative coincidence probabilities with the six-detector array, with the central NaI detector, and with both of them may be used to check an isotopic dependence of the detection probability. The six-detector array is essentially triggered by γ's and, with less efficiency, by neutrons. The central NaI detector has a very high efficiency for light charged particles. No dependence higher than (2–3)% was found. The energy dependence of Eqs. (4) and (6) gives only a difference of 3% for the same example going from ^{15}N to ^{19}N. Thus no significant isotope dependence is

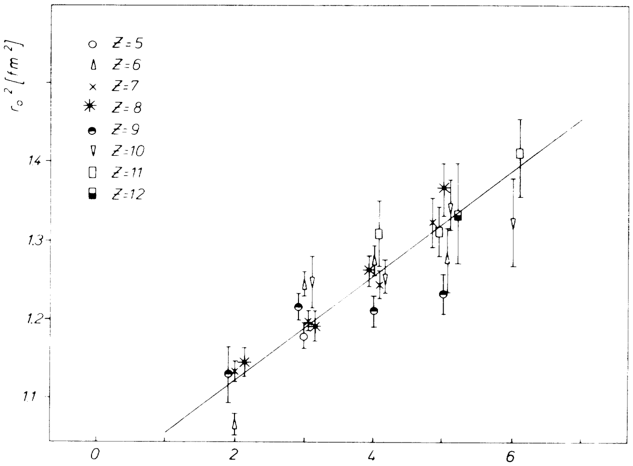

FIG. 2. Square of the reduced strong-absorption radius r_0^2 as a function of neutron excess for various atomic numbers. The errors shown correspond to the statistical error only. The error of the absolute value is estimated to be about 5% (see text).

expected from this effect.

Such a strong dependence is surprising. A long-range tail of the nuclear-matter distribution may produce such an effect. This could be due to increasing deformation as a function of neutron excess, as was suggested by Tanihata and co-workers[3,4] in order to explain the unexpected large radius observed for ^{11}Li. Our data show this trend for all atomic numbers and it is not likely that such a structure effect will show up independently of the proton number. Hence, it seems more probable that a long-range tail would be due to an increase of the diffuseness or a neutron halo.

In order to have a quantitative estimate of such effects, we have calculated these reaction cross sections following a simplified Glauber approach. The attenuation of the incident flux is calculated from the probability for a collision between a nucleon of the target and a nucleon of the projectile.[11] The nuclei are supposed to move on a classical trajectory calculated in a realistic Coulomb-plus-nuclear potential. The total nucleon-nucleon cross section was taken from the literature.[12] The matter distribution of the nuclei was that of the droplet model.[13]

The results of these calculations are as follows:

(a) The energy and mass dependence of Eq. (4) is very well reproduced by the calculations. Indeed, the r_0 value extracted from calculated σ_R at different energies (and therefore for different nucleon-nucleon cross sections) and various nuclei are very constant, i.e., $r_0 = 1.05 \pm 0.02$ fm. This also excludes a bias due to an improper geometry in Eq. (4).

(b) Higher reaction cross sections can be obtained by our allowing a deformation of the nuclei or, equivalently, an increase of the diffuseness of the mass distribution. In order to obtain a 15% increase of r_0 observed for $N - Z = 6$, it is necessary to use a quadrupole deformation $\beta = 0.7$ or a diffuseness of $a = 0.7$ instead of the standard value $a = 0.55$ fm. However, Hartree-Fock calculations[14] for C and O predict a very small increase of the root mean square radius, which is in contradiction with such a strong increase of the diffuseness or such a strong deformation.

In conclusion, we have measured the reaction cross section for neutron-rich light nuclei on Si. The reduced strong-absorption radius increases rapidly with neutron excess. A striking feature of the present data is that this unexpected increase does not seem to depend on the atomic number, but only on neutron excess. It will be interesting to check if this holds for an even greater range of atomic numbers and what is the behavior of the total reaction cross sections for neutron-deficient nuclei.

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