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Production Rates of Excited Fragment Isotopes from the ^{36}Ar + Ag Reaction at 35 MeV/nucleon

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Abstract. Previous studies showed that the binding energy plays a systematic and important role in the production of ground-state fragments in intermediate energy, heavy ion reactions. The production rates were measured as a function of fragment kinetic energy at angles of 15°, 30°, 45° and 60° for excited fragments of ^{7}Li, ^{8}Li, ^{11}Be and ^{12}B. Using a thermal model the total production of neutron unbound excited states was determined, and it was found that their production rates correspond to the previous systematic behaviour using the binding energies corrected by the excitation energies.

1. Introduction

The investigation of fragment production in heavy ion collisions in the intermediate energy range (30 MeV/nucleon $< E/A <$ 500 MeV/nucleon) has attracted wide interest since several years [1–5]. Several possible mechanisms for the production of fragments, e.g. evaporation, incomplete fusion and fragmentation, have been suggested. Questions of the interplay between individual nuclear properties of the produced fragments, some combinatorial effects and the role of multifragmentation are still to be answered.

The proper time evolution of the highly excited nuclear matter is not yet solved. The models of evaporation and multifragmentation lead to different mass distributions of the resulting nuclei. An exponential dependence on A is expected if evap-

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oration is the dominant fragment production mechanism, and multifragmentation leads to a power-law rule [1] in high energy collisions. In our energy range the free energy per nucleon of the excited nuclear matter is close to the Fermi energy of the nucleons. Therefore, the features of the individual nuclei play an important role. In a previous paper [6] it was shown that for ground-state nuclei the binding energy is the decisive property for explaining the production cross section. A thermal model was a good framework to find a systematic behaviour in spite of the fact that there were signs of non-equilibrium behaviour.

For excited fragments experimental data have been presented [4] on the kinetic energy and angle dependences of the internal excitation of the fragments. The data were obtained by measuring both fragment singles and fragment–neutron coincidences in collinear geometry. These data enable the determination of production rates, for some excited state nuclei. The experiment was optimized for neutron unbound excited states of ^{12}B, but as in the earlier study [7], other fragments, especially Li, Be, and C isotopes, where excitation of neutron-unbound states could be observed, were evaluated as well.

For the production of ground-state fragments, binding energy is the decisive parameter. In this paper we ask whether the production of excited fragments is also governed by binding energy or if a thermal model is not valid for their production and non-equilibrium features play an important role in their formation.

2. Experimental Methods

The experiment was performed at the K500 cyclotron of the National Superconducting Cyclotron Laboratory of Michigan State University. The heavy ion beam was ^{36}Ar^{11+} at 35 MeV/nucleon kinetic energy with 10^9 ions/sec intensity. Natural silver targets of 2.2 mg/cm^2 and 2.57 mg/cm^2 areal densities were put into the center of the scattering chamber. The fragments were detected with $\Delta E - E$ silicon detector telescopes. The ΔE detectors were 30 μm and 100 μm thick silicon detectors. The thicknesses of the E silicon detectors were adjusted to stop all intermediate mass fragments up to at least 40 MeV/nucleon. The detector telescopes were placed at angles of $15°, 30°, 45°$ and $60°$ in a collinear geometry with four closed-packed arrays of neutron detectors which were set 3–5 m far from the target [4,6]. The solid angles of the detector telescopes and the solid angles of the neutron arrays were optimally matched to each other. These were about 10 msr for each group.

In the intermediate energy range experimental work generally measures cross sections for producing different elements. Cross sections can also depend on the specific mass number. In order to investigate this dependence we measured spectra of individual isotopes. Double differential cross sections of the isotopes produced from ^{36}Ar + Ag collision at 35 MeV/nucleon were determined. These spectra are reliable sources of reaction characteristics. We focused on the low energy part of these spectra because the isotopes could be separated and because the fragments are produced in central collisions. In order to eliminate the kinematic effects we calculated the total production integrated over energy and angle.

In a previous paper [6] a parametrization was given of the total production of individual isotopes. We created "corrected" values

$$\sigma^*(Z,A) = \sigma(Z,A)/\exp(E_{binding}/T_S)$$

using the known values of the binding energies [8] and 7.2 MeV for the nuclear temperature T_S.

Other points of view of this experiment allow us to determine the cross sections for collinear neutron-fragment coincidences. These coincidence spectra depending on the relative velocity of the neutron and the fragment show interesting structure. There are double peaks (symmetric about relative velocity = 0) if the fragment and the neutron are coming from a given particle unbound state of a nucleus [9]. Using this relative velocity technique we determined the production rates of some neutron unbound states of ^{7}Li, ^{8}Li, ^{11}Be and ^{12}B as functions of the fragment kinetic energy and the lab angle. Then in the same way as for the ground-state fragments [6], we calculated the total production of these excited nuclei.

The energy resolution of these spectra was not so detailed to separate the low energy part. Therefore we used the energy integrated production of ground-state fragments from central collisions and it was multiplied by the energy independent ratio individually at every angle. The angle distribution was handled and the total production was determined exactly in the same way as for the ground-state fragments.

3. Experimental Results and Conclusion

Figures 1, 2, 3 show the production rates for the first neutron unbound excited states of ^{7}Li, ^{8}Li and ^{12}B, respectively. The shapes of these spectra are the same as for their ground-state nuclei but the amplitudes are smaller. The ratios at different energy values were determined and were found to be independent of the kinetic energy [2,3,10].

The total productions were corrected in the previously described way for the binding energy, but in these cases the binding energy of the ground-state was added to the excitation energy. The "corrected" productions obeyed an exponential behaviour for ground-state nuclei. The points for excited states in addition to the ground-state points are on Fig. 4. These points are on the same line which was found for ground-state nuclei.

The "corrected" cross sections can therefore be explained in one model for ground-state and excited-state nuclei. This shows that thermal models are applicable in these collisions and the non-equilibrium features of the intermediate energy, heavy ion collisions do not appear at 35 MeV/nucleon.

3.1. Figures

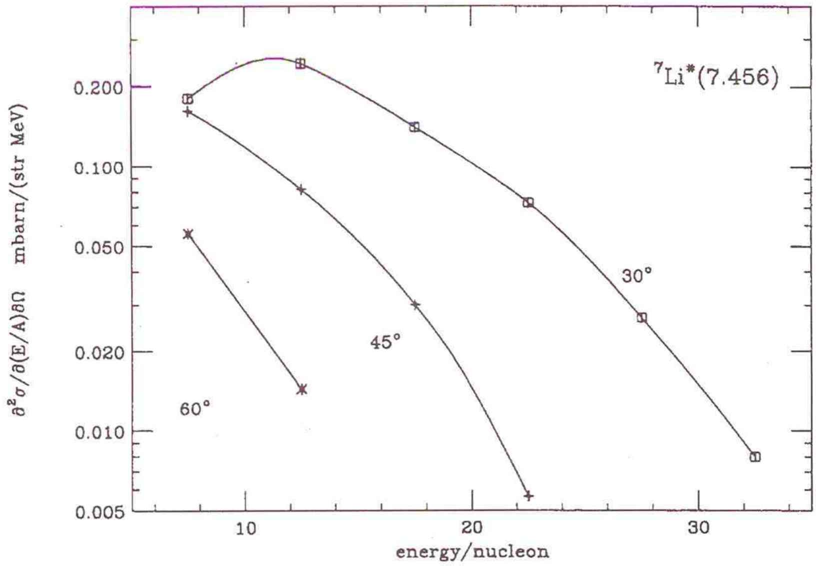

Fig. 1. Energy distribution of the 7.25-MeV excited state of ^{7}Li at 30°, 45° and 60° lab angle

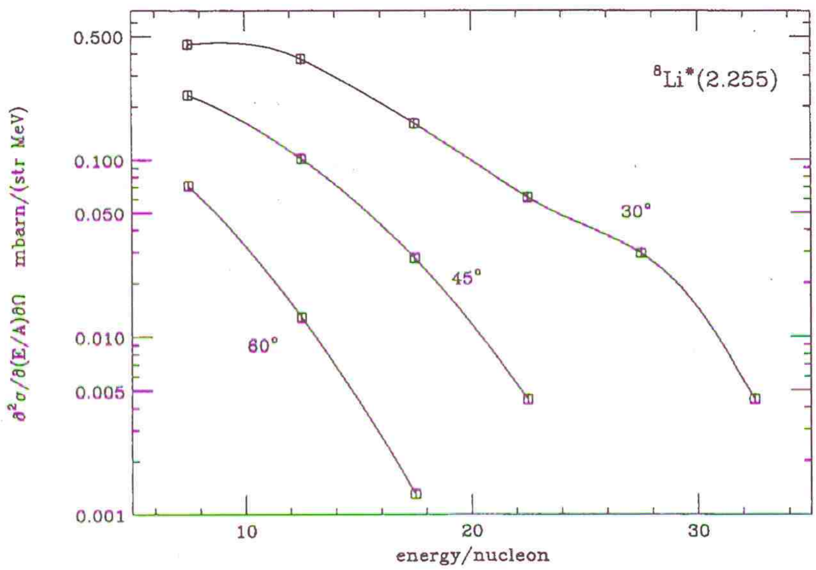

Fig. 2. Energy distribution of the 2.255-MeV excited state of ^{8}Li at 30°, 45° and 60° lab angle

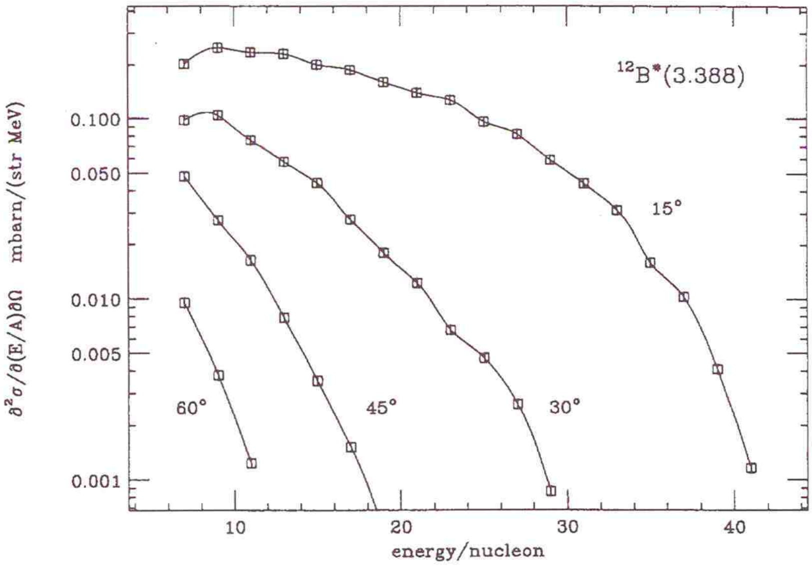

Fig. 3. Energy distribution of the 3.388-MeV excited state of ^{12}B at 15°, 30°, 45° and 60° lab angle

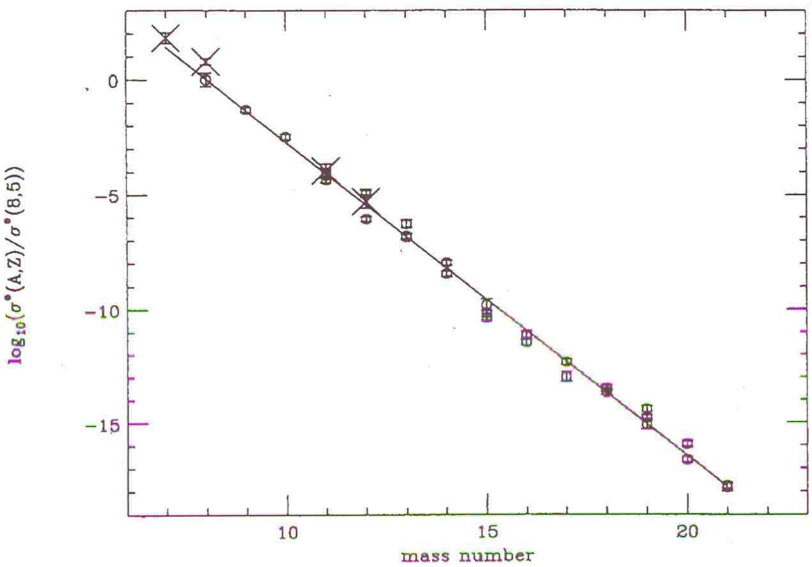

Fig. 4. The dependence of the "corrected" total production σ^* of fragments relative to σ^* for ^8B. The circles represent the values for ground-state nuclei and the big size crosses show the four new values for excited states.

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Dedicated to G. Marx and K. Nagy on the occasion of their 70th birthdays

Notes

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