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EXCITATION FUNCTIONS AND ISOMERIC YIELD RATIOS FOR THE REACTION $C^{12}(N^{14}, 2p)Na^{24m,g}$

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1. Introduction

In reactions involving heavy ions compound systems with very large angular momentum can be formed. Such reactions are, therefore, especially suited to study the influence of angular momentum on the path of nuclear reactions (see for instance[1]).

By measuring the relative production of two isomeric states of the same nuclide formed in the same reaction (the so-called isomeric yield ratio) one can obtain certain informations on the spin dependence of nuclear level densities. This was first shown by Vandenbosch and Huizenga[2]. The method was applied to reactions with heavy ions by Bredel, Fomichev and Gvosdev[3,4], using the isomeric pair $Sc^{44,44m}$. These experiments showed that one can get in this way also informations on the spin distribution of the compound system which is formed in the first stage of the reaction. It is tempting to extend these investigations into the region of lighter target nuclei, because the lower the moment of inertia I of the compound system is, the more pronounced the influence of higher spin states on the reaction mechanism should be. (The energy tied up in rotation is $E_{rot} = \frac{1}{2} J(J+1)/2I$).

All known isomers of elements below Sc have very short half-life and require special experimental techniques, e.g. the method of pulsed activation. The lightest suitable isomeric pair is $Na^{24,24m}$ (fig. 1). Both activities can be observed by γ-spectroscopy. The half-life of the isomeric state is 20 msec, that of the ground state 15h. Some time ago two of the present authors had determined the cross section of Na^{24m} in the reaction $Na^{23}(n,\gamma)Na^{24}$ using a pulsed thermal neutron beam[5]. Applying the method of Huizenga and Vandenbosch[6] on this reaction we were able to determine the spin cutoff parameter and the spin of the capturing state from the measured isomeric yield ratio.

After development of a similar experimental method on the external beam of the heavy ion cyclotron U-150 in Dubna we decided, therefore, first to investigate the reaction $C^{12}(N^{14},2p)Na^{24,24m}$ and to determine the isomeric yield ratio.

2. Experimental method and results

Irradiations of thin carbon targets were carried out in the external beam. The energy of the extracted N^{14} beam after deflection by an analyzing mag-

net was determined by range measurements in Al-foils to 110 MeV. Lower bombarding energies were achieved by passing the beam through calibrated Al foils using the range energy relation given by Northcliffe [7]. To avoid activation of the target backings the maximum beam energy was limited to ~ 70 MeV.

To observe the 20 msec isomeric transition a pulsed beam technique was used. Irradiation bursts of 30 ms duration were followed by an "effect" measuring interval of 8 ms, and after an interval of 50 ms (to allow the induced activity to decay) by a "background" measuring interval of also 8 ms. The γ-activity of the target was observed by a NaJ(Tl) scintillation detector (40 x 25 mm).

Pulse amplitude spectra were stored in 2 x 50 channels of a conventional multichannel analyzer for "effect" and "background" spectra separately. The difference of both spectra is then caused by short-lived activities with half-lifes of the interesting order of magnitude. Targets were made from thick Ta sheet covered by a thin layer of carbon black (made in a very simple way using a gasoline flame). The thickness of the carbon layer was determined by weighing, it amounted for all targets used in this experiment to 0.6 ... 1.0 mg/cm^2. Ta target sheet formed the bottom of Faraday cup which was connected to a current integrator. Reduction of measured intensities to absolute activation cross sections was performed by standard techniques.

The observation of the Na^{24m} activity meets with difficulties because the characteristic 472 keV γ-radiation of this isomer is in the vicinity of the ever present intensive 511 keV annihilation radiation. Therefore, the background amounted to about 75 % of total effect even in the region of maximum cross section. In spite of this, good difference spectra could be obtained from which the Na^{24m} activity was deduced. Fig. 2 shows such a difference spectrum. The high intensity in the lower channels is probably caused by short-lived β-emitters which can be produced in the reaction $C^{12} + N^{14}$. The measured excitation function for the reaction $C^{12}(N^{14}, 2p)Na^{24m}$ is shown in fig. 3.

Measurement of the excitation function for the activity of the Na^{24} ground state was relatively easy because of its long half-life of 15h and the hard γ-rays it emits during decay. For some ion energies the ground state activity was obtained after prolonged irradiation of the targets used for the measurement of the isomer activity (full points). In addition a target consisting of a package of

gold foils (≈ 4,5 mg/cm^2) covered with carbon black (≈ 1 mg/cm^2) was used. After decay of short-lived activities the foils were counted in close geometry. Using the appropriate geometrical corrections both measurements agreed well within limits of error (open points). The excitation function of the $C^{12}(N^{14},2p)Na^{24g}$ reaction is also shown in fig. 3. The isomeric yield ratio σ (high spin)/σ (low spin) gives fig. 4.

As far as we know, the excitation function of the reaction $C^{12}(N^{14},2p)Na^{24g}$ was measured till now only up to ≈ 28 MeV bombarding energy by Fremlin /8/. Our absolute cross section values in this energy region show the same trend and have the same order of magnitude (within a factor of two). Fremlin gives no limits of error, and also the errors of our absolute cross sections are difficult to estimate. It can be supposed, however, that the relative values of the isomeric yield ratio are more accurate.

3. Discussion

The excitation functions for Na^{24g} and Na^{24m} show the characteristic behaviour expected for a compound-nucleus reaction. Surely, there is no other way to form Na^{24} in this experiment as by formation of the compound nucleus Al^{26} which emits in turn two protons.

The isomeric yield ratio exhibits a pronounced maximum at about the same bombarding energy as the two excitation functions. This is somewhat unexpected for a compound reaction because higher bombarding energies should lead to higher mean angular momenta of the compound nucleus and should, therefore, produce after deexcitation a higher ratio σ (high spin)/ σ (low spin).

A simple calculation of the given deexcitation process using a computer program of the type described by Hafner, Huizenga and Vandenbosch /9/ can, therefore, not reproduce the experimental data. Calculations made in this manner using the M-20 machine of the Joint Institute for Nuclear Research were indeed unsuccessful.

For the region of the maximum, however, the right value of the isomeric yield ratio could be obtained in these calculations using a plausible set of parameters.

We will only give here two qualitatively possible physical interpretations of our experimental results, in particular of the decline of the isomeric yield ratio at higher bombarding energies. The first possibility is the existence of a "critical spin" in the formation process of the compound nucleus. If the system of

colliding nuclei has an angular momentum which exceeds this critical value, the formation of a compound nucleus is considered to be impossible because of dynamical instabilities.

This assumption was first used by Bredel et al.[3] who found a similar behaviour of the isomeric yield ratio in some heavy - ion reactions leading to $Sc^{44,44m}$. For the formation of heavier compound nuclei Kuapf and Karnaukhov came to similar conclusions[10].

When we accept this interpretation the critical spin needed is rather low in our case. From the position of the maximum we obtain $J_{crit} \approx 12$. Quasiclassical calculations of the dynamics of a colliding system of two nuclei were made by Kalinkin and Petkov[11]. They confirm the concept of a critical spin. Unfortunately, these calculations do not cover the region of low atomic masses. But an extrapolation of the values for heavier nuclei, including the experimental result of Bredel et al.[3] ($J_{crit} = 25$ for the reaction $Al^{27}(Ne^{20}, 2pn)Sc^{44,44m}$) gives a critical spin of the right order of magnitude.

Our experimental values are in favour of the critical spin concept, but they cannot prove it definitely. For this end it would be necessary to show that in all other reaction channels into which the compound nucleus Al^{26} can decay the same angular momentum cutoff is acting. As such evidence is lacking so far, the following alternative explanation cannot be excluded. The channel which leads to Na^{24} in our reaction contains only a small fraction of the total reaction cross section. The relative weight of the different channels should depend on the spin of the compound nucleus. It could be, then, that in the reaction $C^{12} + N^{14}$ the compound nucleus Al^{26} will be formed also with spin values $J > 12$ but that for higher angular momenta the channel leading to Na^{24} will be practically closed in favour of other channels.

For instance, the reaction $C^{12}(N^{14}, \alpha n)Na^{21}$ has a Q - value which is only 2 MeV lower than for the reaction studied in this investigation. But the reaction products α, n could carry off a considerable larger angular momentum as two protons. A high- spin compound nucleus should, therefore, prefer to decay by α - emission. It seems difficult to decide such questions on the basis of the existing rather limited experimental material.

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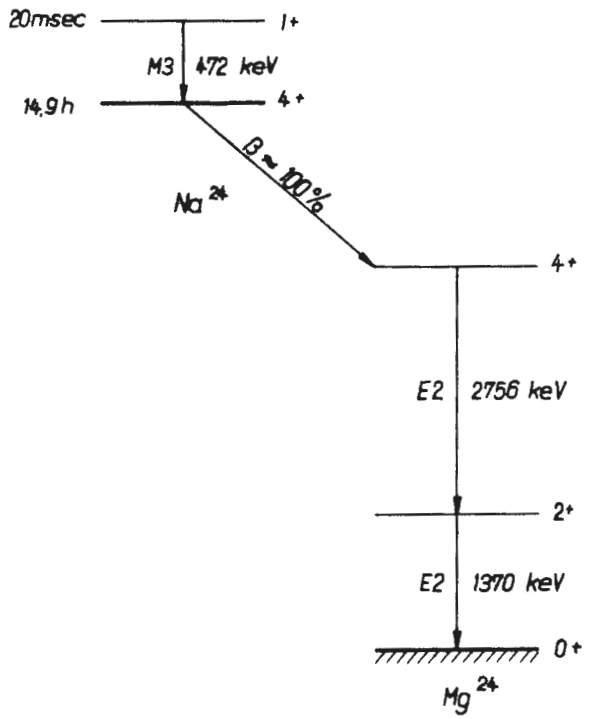

Fig. 1. Decay scheme of Na^{24}.

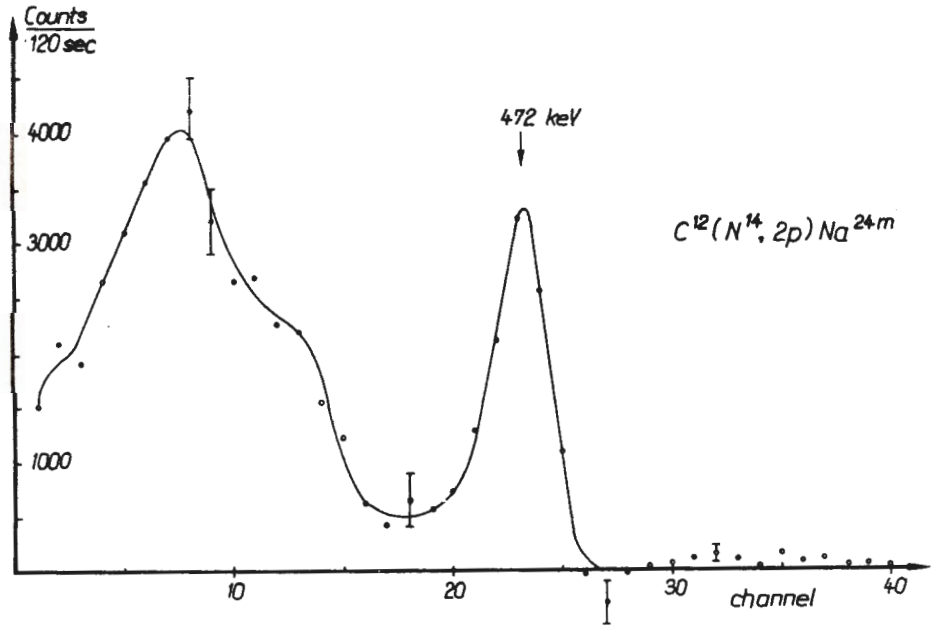

Fig. 2. γ - spectrum of Na^{24m} (background subtracted). Bombarding energy 46 MeV.

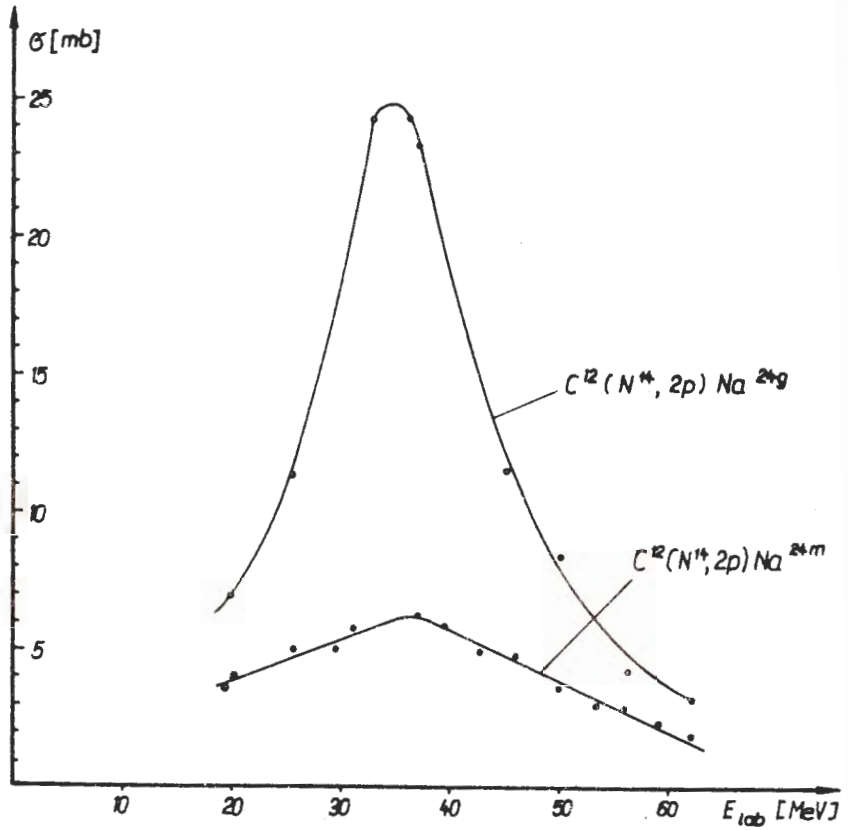

Fig. 3. Measured excitation functions.

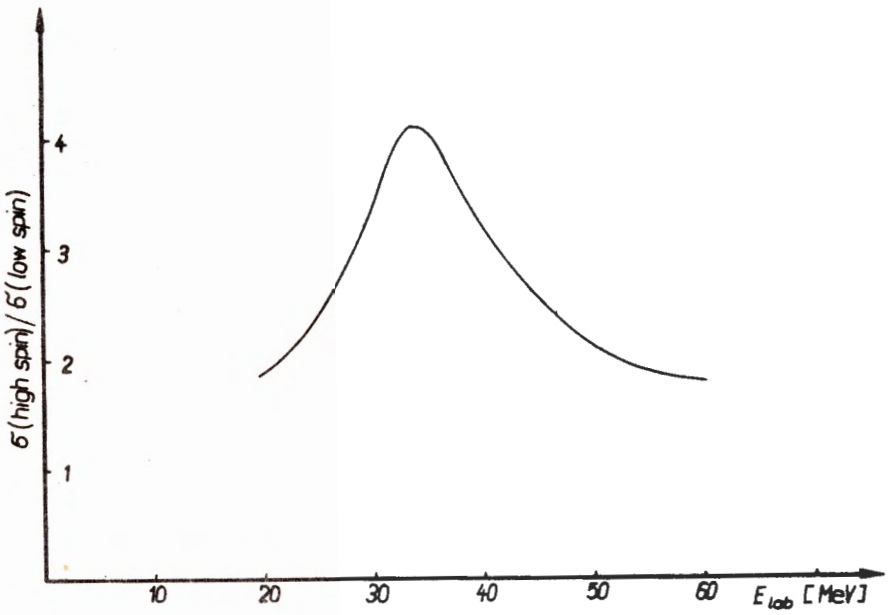

Fig. 4. Isomeric yield ratio.