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Q-VALUE DEPENDENCE OF MULTINUCLEON TRANSFER REACTIONS

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Q-VALUE DEPENDENCE OF MULTINUCLEON TRANSFER REACTIONS

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It has been shown by Volkov et al. that multinucleon transfer reactions between heavy ions are a very effective way to produce neutron-rich light isotopes /1/. Nuclei A are shot on a target B (for example ^{16}O with E_{lab} = 137 MeV on ^{232}Th). During the collision x protons and y neutrons are exchanged and pairs of nuclei $A' = (A - xp - yn)$, $B' = (B + xp + yn)$ are produced and identified by applying the $E, \frac{dE}{dx}$ - method to the A' . The various outcoming A' have very similar angular distributions $d\sigma / d\theta$, which are typical for a direct interaction in a surface collision. They are peaked around $\theta = 40^{\circ}$ with a width of about 20°.

Thus the values of $(d\sigma / d\Omega)_{40^{o}}$ represent also the total cross sections. If one plots the logarithms of these cross sections for the production of various pairs A', B' as a function of the Q -values Q_{gg} for the ground state transitions $B(A, A')B'$, one obtaines a family of parallels, where every line is characterized by a fixed value $x \geq 1$ of transferred protons (Fig. 1).

Fig. 2 shows (for the similar case $^{15}N + ^{232}Th$) the energy loss spectra for the variuos A' : While in every channel a characteristic energy Q_{gg} is needed for the construction of the new ground states of the pair A' , B' the spectra of excitation energy E^* are very similar for all produced pairs, regarded of the number of exchanged nucleons.

It has been shown, that the linear dependence of log $(d\sigma/d\Omega)$ on Q_{gg} can neither be explained by final state density arguments nor by employing the usual DWBA theory /2/.

On the other hand concepts familiar from ion-atom scattering like molecular wave functions /4/ is proposed. The relative motion of the nuclei takes place on potential energy surfaces (PES) $E(\vec{R})$, which are given by the energy of the nucleons moving in molecular orbits $\phi(\vec{R},\vec{r})$ in a shell model with two centers in a distance $\vec{R}$ /5/.

$$H_{Mor}(\vec{R})\,\phi(\vec{R},\vec{r}) = E(\vec{R})\,\phi(\vec{R},\vec{r}) . \tag{1}$$

Different channels are coupled by the usual cross terms between internal and relative motion and by the residual interaction between the nucleons. In the two-state approximation one has to solve the coupled system

$$\begin{aligned} -ih\dot{\psi}_i &= [\,\ni - E_i(\vec{R})\,]\,\psi_i + \langle\phi_i|H_{int}|\phi_f\rangle\psi_f \\ -ih\dot{\psi}_f &= [\,\ni - E_f(\vec{R})\,]\,\psi_f + \langle\phi_f|H_{int}|\phi_i\rangle\psi_i \end{aligned} \tag{2}$$

for the relative motion of nuclei in the channels $\{i\}$ and $\{f\}$. $\ni$ is the total energy. In the deduction of (2) has been neglected the lack of true orthogonality between ϕ_i and ϕ_f which is due to the different molecular Hamiltonians and residual interactions in both channels. The cross terms between internal and relative motion are small for distances $R \geq R_0$, where $R_0 = R_A + R_B$ is the distance, where the nuclei begin to overlap each other, and can be included into H_{int} for $R < R_0$.

The Q-value of the reaction is given by the asymptotic difference between the PES.

$$Q = Q_{gg} - E^* = \Delta(\infty) = E_i(\infty) - E_f(\infty). \qquad (3)$$

Unless the Coulomb interaction changes through transfer of protons this difference between the PES will be constant also for finite distance between the nuclei, until the difference of the polarization effects due to Coulomb and nuclear forces in the different channels becomes important in the immediate neighbourhood of R_0.

Microscopically the multinucleon transfer reaction consists of a large number of "elementary" collisions between the nucleons of A and B, leading to 2p–2h states describing as well the transfer of nucleons as the excitation of the nuclei.

$$\langle \phi_f | H_{int} | \phi_i \rangle = \sum_{\substack{\text{elem.} \\ \text{coll.}}} [\langle jk | V_{res.} | lm \rangle - \langle jk | V_{res.} | ml \rangle]. \qquad (4)$$

For $R > R_0$ the radial behaviour of the interaction matrix elements is governed by the slowliest decreasing term in (4), which behaves like the exponential tail of the stronger bound one of the two nucleons least bound in A and B

$$H_{fi} = \langle \phi_f | H_{int} | \phi_i \rangle = V_0 e^{-kR}; \qquad (5)$$

Due to the compression of nuclear matter when the nuclei are overlapping one expects the matrix elements of the residual interaction to become large for $R < R_0$.

It has been shown by Demkov in an application to ion-atom scattering that under such conditions the system (2) can be solveed analytically /6/. The transition probability becomes

$$w = |\psi_f(\infty)|^2 = \{ \operatorname{sech} [\frac{\pi \Delta}{2k\hbar} (\frac{dR}{dt})^{-1}] \sin (\frac{1}{\hbar} \int_{-\infty}^{\infty} H_{if} \, dt) \}^2 , \qquad (6)$$

$\frac{dR}{dt}$ describes quasi-classically the radial velocity of the nuclei in the region around R_0, where the transition takes place. In the reactions leading to the results shown in Fig. 1 there is always

$$-\Delta \gg \frac{2k \cdot \hbar \frac{dR}{dt}}{\pi} \qquad (7)$$

so that eq. (6) becomes

$$w = \{ 2 \exp [\frac{\pi \Delta}{2k\hbar} (\frac{dR}{dt})^{-1}] \sin (\frac{1}{\hbar} \int_{-\infty}^{\infty} H_{if} \, dt) \}^2 . \qquad (8)$$

After integration over the excitation energy E^*, of which the spectrum is known experimentally to be the same in all channels (Fig. 2) one gets

$$w = \text{const.} \exp . \frac{\pi \cdot Q_{gg}}{k \cdot \hbar \cdot \frac{dR}{dt}} , \qquad (9)$$

where the variation of the second factor in (8) has been neglected in comparison to that of the exponential. This may be justified since similar angular distributions correspond to similar classical trajectories. Therefore the average number of elementary collisions contributing to the second factor in (8) does not vary rapidly in the different channels.

Eq. (9) gives the required linear behaviour between log $(d\sigma/d\Omega)$ and Q_{gg}. Inserting a value of k corresponding to an average separation energy of 8 MeV and taking the velocity at R_0, eq. (9) gives a slope of 0.48 for the parallels while the experimental values range between 0.40 and 0.60 (Fig. 1).

Properly not the asymptotic values Δ and Q_{gg} have to be inserted in eqs. (6) and (9) respectively, but those values at R_0: $\Delta \to \Delta + \delta Q$, $Q_{gg} \to Q_{gg} + \delta Q$. As stated above δQ is mainly due to the change in the Coulomb field, when protons are transferred. In the Dubna experiments one obtains therefore parallels splitted by characteristic values δQ_{xp} for the production of different chemical elements.

In an earlier experiment in Berkeley however, a number of different incident nuclei A and different targets B were used and the yield ratios $Y(A+p)/Y(A-p)$ were plotted as a function of both Q_{gg} and $Q_{gg} + \delta Q$ /7/. In this case to every measured point belongs a different δQ, so the δQ -correction must necessarily be applied before in order to get the linear behaviour of eq. (9).

It should also be noticed that if the condition (7) is not fulfilled, which is often the case when more particles are stripped from the target than picked up by it, the integration over E^* must be performed in eq. (6). Then the cross sections will turn out smaller than those predicted by eq. (9).

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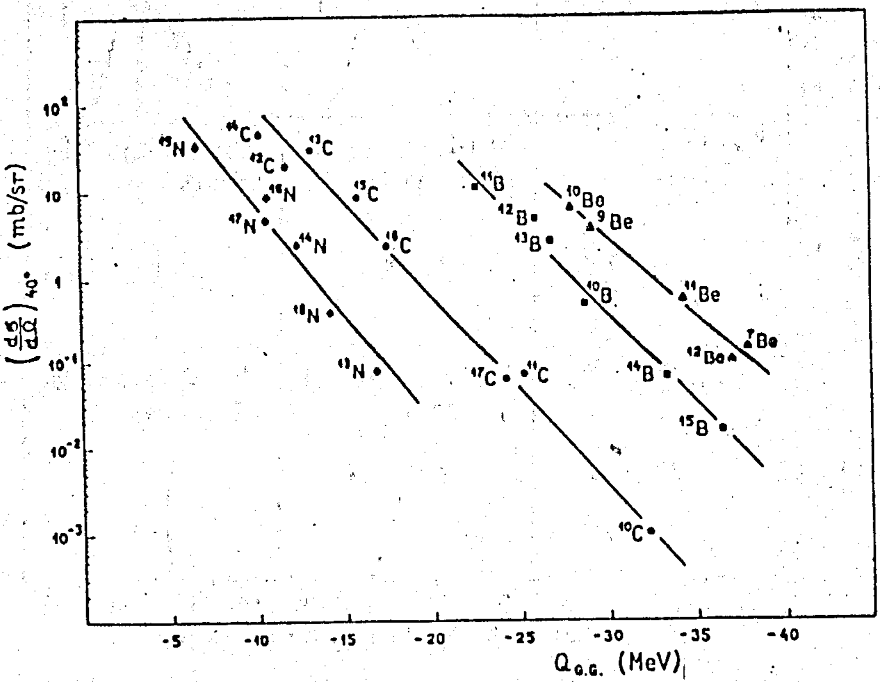

Fig. 1. Differential cross sections $(d\sigma/d\Omega)_{40^\circ}$ for production of Be , B , C and N isotopes in the $^{232}Th + ^{16}O$ interaction as function of Q_{gg} .

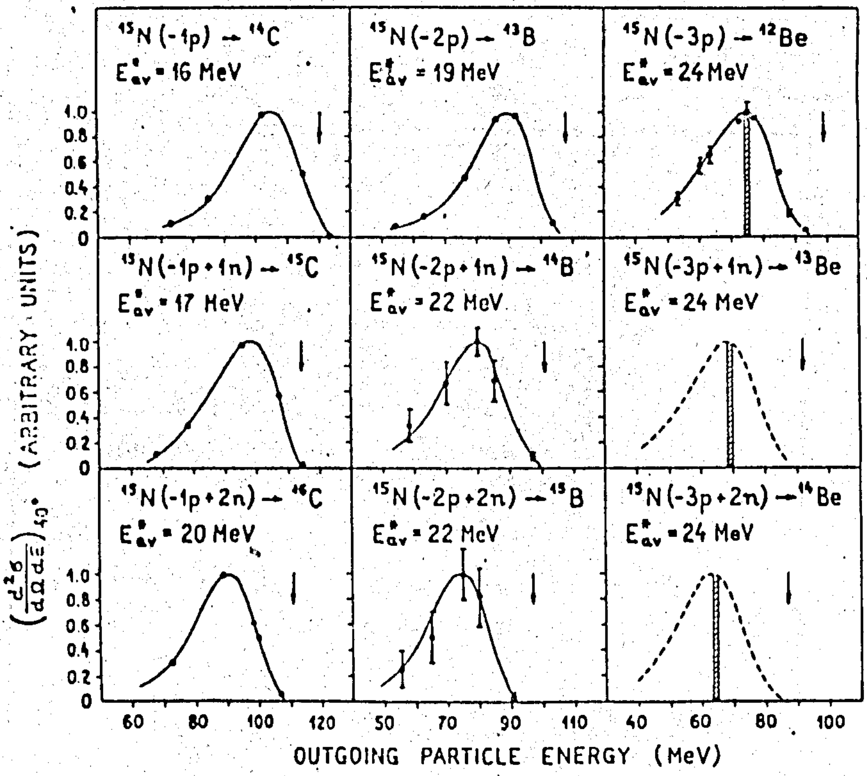

Fig. 2. Energy spectra of ^{14}C , ^{15}C , ^{16}C , ^{13}B , ^{14}B , ^{15}B and ^{12}Be produced in the nucleon exchange reactions (projective-x protons + y neurtons) in bombardment of ^{232}Th target with ^{15}N 145 MeV ^{15}N ions. The dashed curves show the predicted spectra of ^{13}Be and ^{14}Be . The arrows denote the energy values corresponding to the formation of both reaction products in the ground states.