HEAVY ION RESEARCH AT CYCLOTRON ENERGIES

P. S. Fisher

Nuclear Physics Laboratory
University of Oxford
England

Abstract

Some of the criteria which will influence the demand for improved heavy ion beams from cyclotrons are discussed in relation to aspects of nuclear research.

One technical aspect of this Conference is concerned with the production of heavy ion beams from cyclotrons. It is therefore appropriate to ask in what ways the availability of high energy heavy ion beams is likely to lead to advances in the understanding of nuclei and nuclear matter. I propose to do this by very briefly indicating the influence which the availability of such beams is likely to have on some existing fields of research.

For convenience I classify collisions between a heavy-ion projectile and a target nucleus according to the impact parameter. Ions which approach with rather large impact parameters make only a peripheral or surface collision. Under these conditions recent work has shown[1] that the ensuing reaction is dominated by the transfer of one or more nucleons from the projectile to the target, or vice versa, the trajectory of the incident and emergent ion being determined by the effective potential between the ions. The single nucleon, or cluster of nucleons transferred excite strongly only those states of the product nucleus which have a large amplitude for decomposition into target nucleus like core plus one or more additional nucleons.

Because the effective interaction region is small, only those nucleons whose motion within the nuclei lie close to the reaction plane are likely to be transferred. As a consequence, when more than one nucleon is transferred, the nucleons enter highly correlated orbits. For example, a cluster of three nucleons (two unlike) transferred to $d_{5/2}$ states are most likely to be coupled to the maximum allowed angular momentum. Behaviour of this kind is beautifully exhibited in the ^{3}He transfer reactions $^{12}C(^{12}C,^9Be)^{15}O$ and $^{12}C(^{11}B,^8Li)$ shown in Fig. 1.

This simple behaviour occurs only if the transferred nucleon may leave the projectile and enter a new state in the target without there being a serious mismatch in the momentum and angular momentum. Any mismatch has to be made good through an interaction between the transferred nucleon and the interacting cores, and the greater this mismatch the more probable is core excitation and the less favoured the simple transfer.

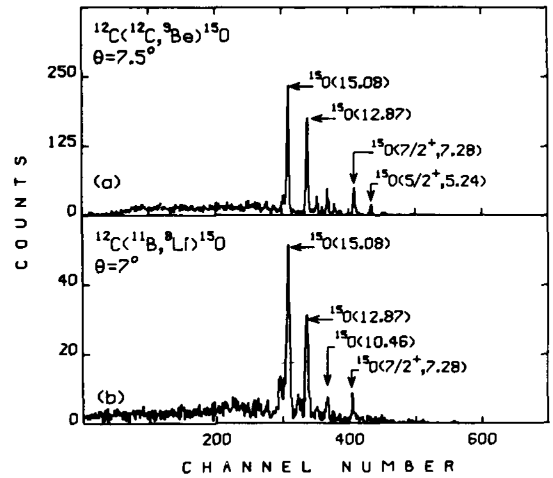

Fig. 1

States in ^{15}O excited by three nucleon transfers. In each case the bombarding ion had an energy of approximately 114 MeV. The state most strongly populated at 15.08 MeV is believed to have $J = {}^{13}/_2{}^+$, the maximum allowed for three d nucleons[1].

These effects result in the excitation of simple states within a well defined range of excitation energies. The region favourable to direct transfer, the Q window, depends upon the spin of the excited state and the bombarding energy. This dependence is illustrated in Fig. 2 for the $(^{12}C,^9Be)$ reaction just mentioned. We see that the excitation of the ${}^{13}/_2{}^+$ state of maximum angular momentum is predicted to be most favoured at a bombarding energy of 120 MeV, or 10 MeV per nucleon.

Since it is the relative velocity of the ions which is the important parameter entering the condition for favourable transfer, this energy of 10 MeV per nucleon for optimization of correlated transfer remains approximately constant as the projectile or target mass is varied. Here we have guidance in the choice of ion energies for this type of work. It remains an open question, though, whether the use of projectiles heavier than ^{20}Ne will add to the power of the method as a spectroscopic tool.

It should be mentioned in passing that the energy separation of the states of interest tends to decrease from several MeV in light nuclei, $A < 20$, to hundreds of keV at higher mass numbers. The

Proc. 7th Int. Conf. on Cyclotrons and their Applications (Birkhäuser, Basel, 1975), p. 571-573

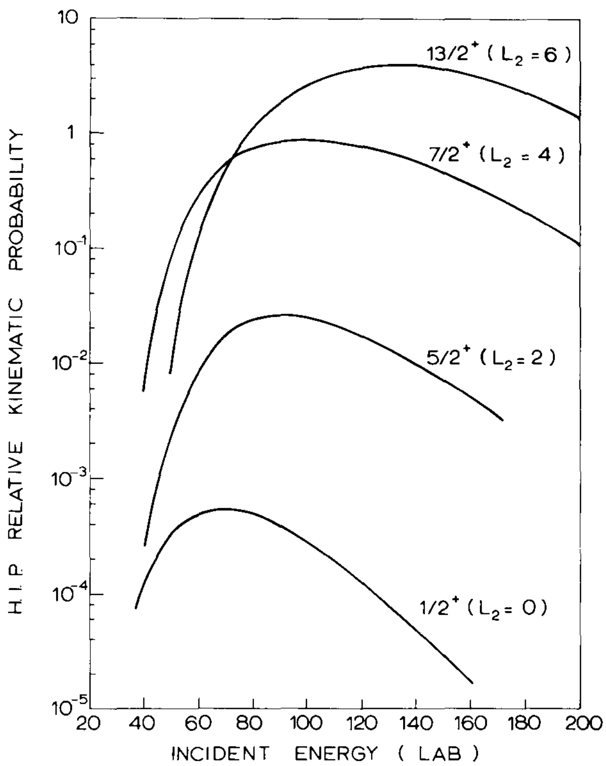

Fig. 2

The transfer probability computed from a semi-classical formulation[2] for the reaction $^{12}C(^{12}C,^{9}Be)^{15}O$ for a range of incident energies and final state spins.

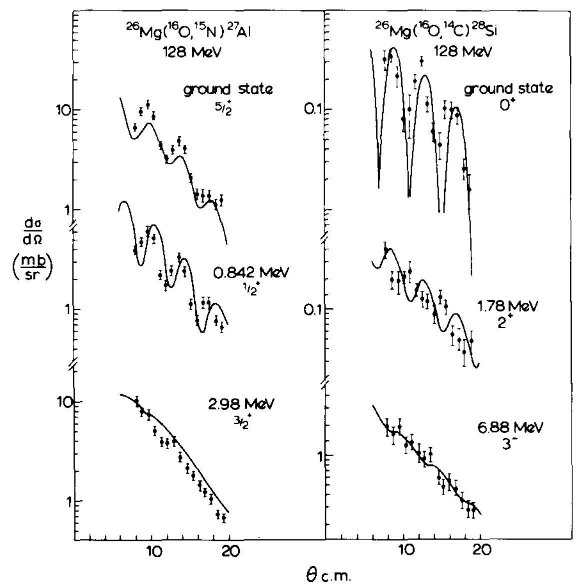

Fig. 3

Angular distributions for the reactions $^{26}Mg(^{16}O,^{15}N)^{27}Al$ and $^{26}Mg(^{16}O,^{14}O)^{28}Si$ at 128 MeV. The reactions all exhibit similar periodicity with a spacing between maxima of approximately 4^{o} in the centre of mass[3].

need to attain energy resolution of less than 100 keV in the particle energy spectra represents a major challenge for the future.

Where angular distributions show structure, whether for elastic and inelastic scattering or for transfer reactions, the periodicity of the structure with angle is the same, being determined by the interference of amplitudes from opposite sides of the nucleus. The angular periodicity in the centre of mass system is $\Delta\theta = \frac{\pi}{kR} = \frac{\pi}{L}$ where k is the wave number of the ion and L the partial wave making the greatest contribution to the reaction amplitude. Examples of this behaviour are shown in Fig. 3. Experiments with heavier ions on heavier nuclei will have smaller values of $\Delta\theta$ and will require control on beam divergence to about 0.1^{o}

For smaller impact parameters, target and projectile may form a compound system. The probability of forming a compound nucleus in the reaction $^{40}A + {}^{208}Pb$ as calculated by Yu Ts Oganessian et al.[4] is shown in Fig. 4. The cross section rises with energy but reaches a plateau at energies of approximately 10 MeV per nucleon. Once formed the subsequent decay of the compound nucleus depends upon its angular momentum and excitation energy. If it is desired to form elements with Z > 100 through fusion, followed by neutron evaporation, the competition between fission and neutron evaporation is crucial. The ratio of these processes is highly dependent upon the excitation energy of the initial compound nucleus, the higher the energy the smaller the fraction of decays by evaporation. However, to interact the ions must have at least sufficient energy to overcome the coulomb barrier, so that the excitation energy of the compound system is $E^{*} > Q + B$, where B is the barrier height. Yu Ts Oganessian et al.[4] have pointed out that for a given compound mass $A = A_I + A_T$, the barrier height B and hence E^{*} exhibits a minimum as a function of A_I. For the case of A in the neighbourhood of 250 a minimum B of 20 MeV occurs at A = 48. As a consequence the cross sections for forming Z = 104 through

$$^{50}Ti + {}^{208}Pb \rightarrow {}^{256}104 + 2n$$

may be a hundred times larger than

$$^{242}Pu + {}^{22}Ne \rightarrow {}^{260}104 + 4n$$

which was first used to synthesise the element, and the prospect for reaching nuclei with Z > 106-108 using similar projectiles with targets of Pb and Bi appear favourable, and this approach may well be useful in attempts to synthesise superheavy elements with Z > 110.

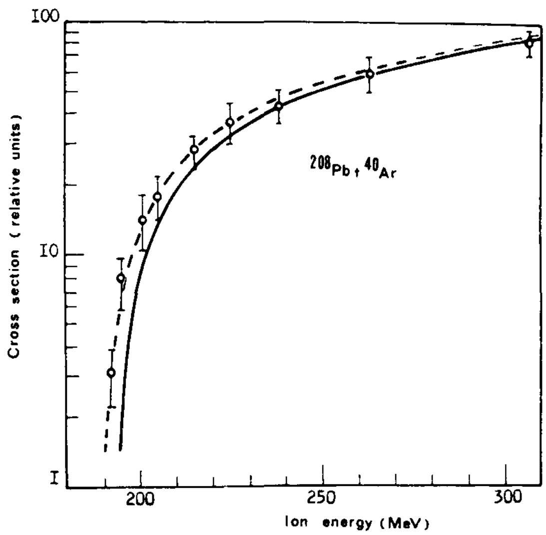

Fig. 4

The cross section for the formation of the compound nucleus ^{248}Fm by the reaction ^{208}Pb + ^{40}Ar as a function of bombarding ion energy from Yu Ts Oganessian et al.[4]

Finally, we should look at the possibility of producing in the small impact parameter collision of two ions, a region of extremely high energy density and a new phase of nuclear matter[5]. For the excitation to remain localized the relative velocity of the ions must be higher than the velocity of compression waves in nuclear matter, which involves bombarding energies in excess of 100 MeV per nucleon. The nature of the phenomena to be expected under these conditions is hotly contested. It seems unlikely that local energy densities will arise comparable with those in GeV nucleon-nucleon collisions, but the bulk material in the strongly interacting region may well exhibit novel and interesting characteristics. The elucidation of the properties of this region will involve the nuclear structure physicist in pi-meson detection, and counter hodoscopes capable of simultaneously capturing and identifying all the products of fragmentation.

References

1) N. Anyas-Weiss, J.C.Cornell, P.S.Fisher, P.N.Hudson, A.Menchaca-Rocha, D.J.Millener, A.D.Panagiotou, D.K.Scott, D.Strottman, D.M.Brink, B.Buck, P.J.Ellis and T.Engeland, Physics Reports 12C (1974) 203.

2) D.M.Brink, Phys. Lett. 40B (1972) 37.

3) D.Sinclair, Phys. Lett. 53B (1974) 54.

4) Yu Ts Oganessian, A.S.Iljinov, A.G.Demin and S.P.Tretyakova, Nucl. Phys. A239 (1975) 353.

5) T.D. Lee, Rev. Mod. Phys. 47 (1975) 267.

DISCUSSION

H.G. BLOSSER: Why does the superdense object have to come to another nucleus before it gives off mesons?

P.S. FISHER: The problem is to find a decay mechanism which indicates the formation of superdense matter. There will be abundant pion production at the visualized bombarding energies. There is speculation that in a collision between superdense nuclear matter and normal nuclear matter the superdense matter will return to normal and emit a meson cluster; it is this process which may provide a signature for the existence of superdense matter.

M. REISER: What are the predicted cross-sections for these collisions that are expected to lead to superdense compound states?

P.S. FISHER: The cross-section for formation of superdense matter would be approximately the geometrical collision cross-section. The decay via a channel giving a clear signature of the reaction would be very much smaller and any estimate of this will have to await more detailed calculations of the properties of the superdense system.

R. WIDERÖE: What do you think would be the best method to reach the supposed stable region of Z = 114 or so?

P.S. FISHER: I do not think I can usefully add to the conclusions of Oganessian et al. who conclude that the acceleration of ions in the region of A = 50 holds good promises for work of this kind.