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INTERMEDIATE ENERGY HEAVY ION REACTIONS

A Program for CELSIUS

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Intermediate Energy Heavy Ion Reactions - A Program for CELSIUS

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The accelerator system under construction in Uppsala with the ECR-source + the K=200 synchrocyclotron + the CELSIUS synchrotron ring for storage, cooling and acceleration opens up possibilities for a very fruitful heavy ion physics program. Some recently obtained results and some recent ideas on intermediate energy reactions are discussed and speculations are made about some experiments where the unconventional qualities of CELSIUS beams could be utilized.

1. The ECR + CLU + CELSIUS Accelerator System for Heavy Ions

The recently funded ion source of ECR- (Electron Cyclotron Resonance) type will have a very favourable impact on the spectrum of heavy ions to be ejected from the synchrocyclotron (subsequently called CLU) and to be injected into the CELSIUS ring. Fully stripped Z/A=1/2 ions (^{12}C, ^{16}O, ^{20}Ne, possibly ^{40}Ca) with 50A MeV are expected at CLU with very high currents (for ^{12}C up to 100 eμA), while heavier ions - perhaps up to Xe - could be produced with 8 MeV/A and a current of 5 enA (accelerated in the 26+ state). Such a spectrum of beams will put the program into a domain of heavy ion reaction physics which has been expanding dramatically after the advent of coupled cyclotron facilities (SARA, GANIL, MSU). Some new results in this field are discussed in section 3.1.

The final performance of CELSIUS beams can of course only be estimated. The electron gun and the power supply for the magnets are initially designed for the acceleration of light ions up to 386A MeV whereas a Xe beam in the 40+ state (possibly obtained with post CLU stripping) could get 160A MeV. The cooling time will be short compared to proton-cooling ($t_C \sim Z/A$, about 1s for ^{12}C beams and a few tenths of a second for the heaviest beams). The strongest limitation on the momentum resolution will be set by intra-beam scattering, the expected resolution being $\Delta p/p \approx 1 \cdot 10^{-4}$ for 10^9 circulating ^{12}C ions or $\Delta p/p \approx 2 \cdot 10^{-4}$ for 10^{10} ions [1]. As stated in section 3.2 the luminosity with 10^9 ions on a typical gas target ($\leq 10^{14}$ atoms/cm^2) will be high enough for many experiments. The injection + acceleration time is perhaps the most difficult parameter to predict due to the uncertainty in the ramping time for the magnets. With an efficient field-reshaping procedure this time may become 10s out of a typical storage time of 1 minute, thus resulting in a reasonable final duty cycle. Finally we want to mention that the limit in beam energy for future upgrading will be set by the maximum possible field in the magnets. Possibly this is 1.5 T (0.89 T presently) which gives rise to light ions with 900 MeV/A. Some exciting perspectives on experiments at the CELSIUS facility are presented in section 3.2.

2. The Behaviour of Nuclear Matter in Heavy Ion Reactions

Although true conditions for a statistical description of nuclear matter - equilibrium in an infinite system - are reserved for certain astrophysical objects such a description may still be useful also in the imperfect situation of a nucleus-nucleus collision. Describing nuclear matter properties with the canonical variables temperature (T) and density (ρ) one may expect a phase diagram of the kind shown in Fig 1a.

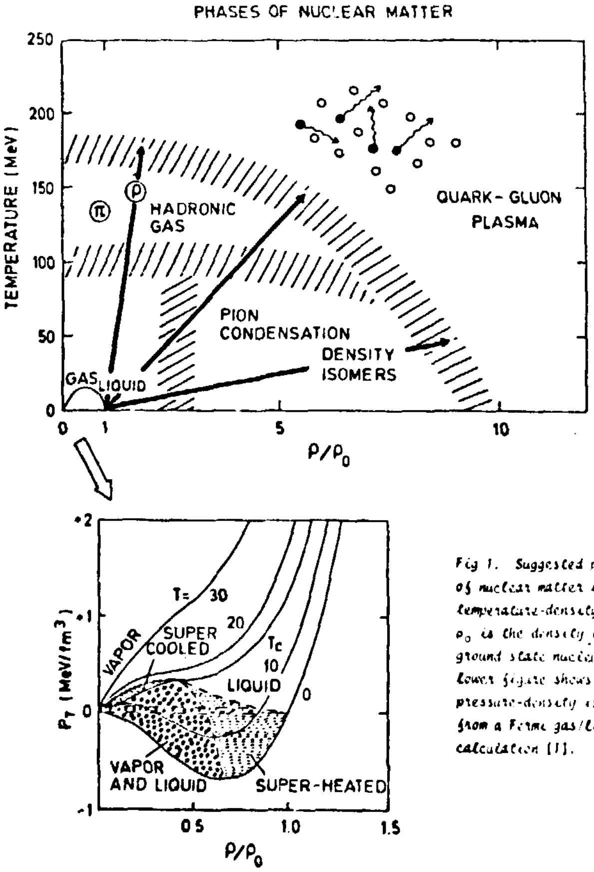


Fig 1. Suggested phases of nuclear matter in a temperature-density diagram. ρ_0 is the density in a ground state nucleus. The lower figure shows the pressure-density isotherms from a Fermi gas/liquid calculation [1].

In normal nuclei, matter is at the ($T=0,\rho=\rho_0$) state and the way the system evolves in the T-ρ plane when excitation energy is introduced depends essentially on how this energy is divided between compressional energy (E_C) and thermal energy (E_T). In order to find this way one must introduce an equation of state (i e $E_C(\rho)$) a task which requires knowledge about the mean-field as well as the importance of two-body collisions. Some early attempts to describe the equation-of-state within the liquid drop model [2] gave the following suggestions:

$$E_C(\rho) = K_1 (\rho-\rho_0)^2 / 18\rho\rho_0 \quad \text{or}$$
$$E_C(\rho) = K_2 (\rho-\rho_0)^2 / 18\rho_0^2 \qquad (1)$$

where $K_{1,2}$ is the compressibility constant (perhaps about 200 MeV).

In the low T - low p region, which may be reached after expansion of the interaction volume, the classical conditions for a van der Waals gas is fulfilled (repulsive short-range force + attractive long-range force), and the equation of state, e g $P(\rho)|_{T=const}$, could be estimated [3] (Fig 2b). Here we find a critical isotherm ($T_C \approx 18$ MeV) predicting a liquid-vapour transition. It is indeed an exciting experimental challenge to search for signatures for such a transition particularly in intermediate energy heavy ion reactions where the temperature never reaches the hadronization region. The latter region is reached when T approaches the meson masses (Fig 1a) and will give rise to a strong production of π, p etc. If compression is favoured abnormal states of matter - like density isomers [4] - may be produced or a direct Bose Condensation may be reached [5]. The latter effect should be directly observable in the pion spectra [6]. Finally the quark-gluon plasma phase has been predicted in the high T-large p region but this definitely requires much larger beam energies than are obtainable with the CELSIUS ring.

In order to describe realistic heavy-ion reaction scenarios we must consider finite nuclear volumes and thus all kinds of surface effects. An impact parameter (b) - energy "phase" diagram could look like the one in Fig 2 [7] with broad transition borders between peripheral and central collisions and between low energy (binary) reactions and high energy (multifragmentation) reactions. The dominating importance of the nucleon mean-field at lower energies which produces central fusion and peripheral deep inelastic collisions (represented by the TDHF calculation) is reduced when the beam energy gets higher. Here we find instead the growing importance of two-body collisions in a limited volume for peripheral collisions (spectator-participant picture) and in the total volume for central collisions (explosion-like collisions). The intermediate energy region - say between a few tens of MeV per nucleon to a few hundreds of MeV per nucleon - is obviously a transitional region and it is therefore very important to study the energy and mass dissipation here in order to find answers to fundamental questions about the behaviour of nuclear matter in heavy ion reactions.

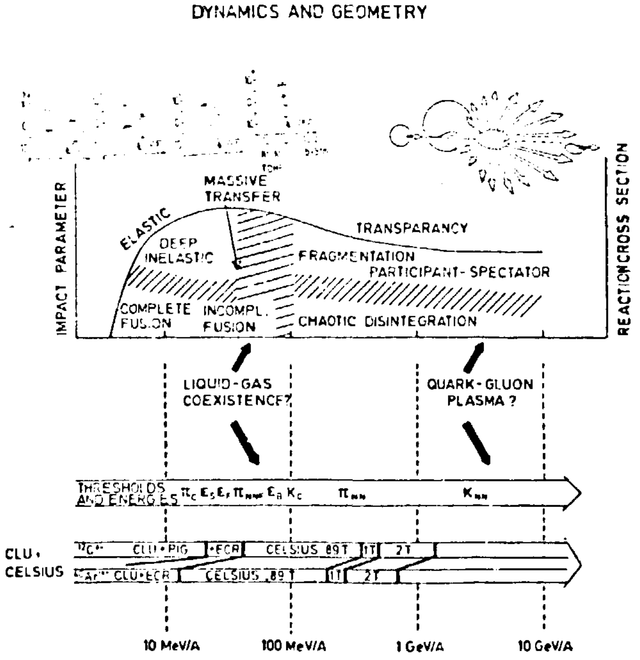


Fig 1. An impact parameter - energy "phase diagram" of heavy ion reactions. Collective (c), Fermi boosted (NNc) and non-boosted (NN) nucleon-nucleon production of π and K mesons as well as the sound energy (ε_S) and the Fermi energy (ε_F) are indicated on the energy axis below together with the predicted CLU-CELSIUS energies.

Meson production will of course have a dramatic cooling effect and below the scenario picture in Fig 2 we show the energy thresholds (collective, nucleon-nucleon scattering with and without Fermi boosting). We also show the energies corresponding to the first-order speed of sound and the Fermi velocity which may play an important role. With the exception of the "normal" K-production process all these energies fall into the CLU/CELSIUS region and we stress that also collective "subthreshold" K-mesons are available. These may turn out to be very important probes for the conditions in the interior of the interacting volumes since they are little affected by final-state interactions.

3. An Experimental Program for the CLU/CELSIUS Facility

3.1. Studies at CLU-Energies

The well-established knowledge that the binary reaction types at low energies turn into violent breakup of the active reaction region at high energies is now being complemented by studies of the mass- and energy-distributions of the products at intermediate energies. The slowest heavy component in asymmetric (heavy target) reactions has so far been measurable only with methods where the target and detection system is integrated like with track detectors [8] or with radiochemical methods [9.10]. Fig 3a gives a very dramatic example [9] of the disappearance of the (quasi-)fusion process (both fusion+fission and fusion+evaporation) between 27A and 44A MeV for an ^{40}Ar+^{124}Sn reaction.

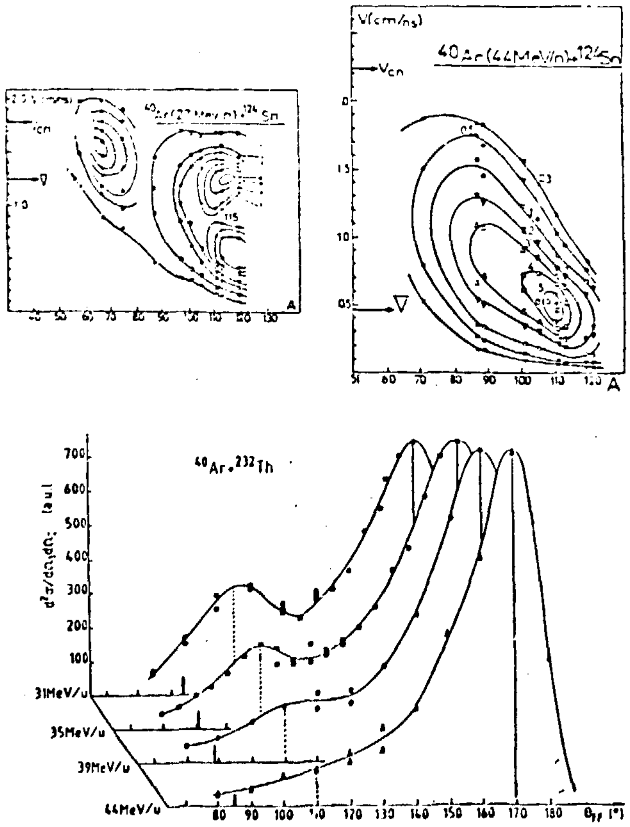


Fig 3. Production cross-section contour plots in the velocity-mass plane of heavy fragments in Ar + Sn reactions at 27A and 44A MeV [9]. Lower: Fission opening angle distribution in Ar + Th reactions at 31A - 44A MeV [11].

The slowest component - interpreted as the peripheral component - remains with a very stable (small) momentum-transfer but with an increasing deviation in mass from the target mass. A confirmation of the disappearance of the fusion-fission process is clearly demonstrated in the fission opening angle experiments of Pollaco et al [11] (Fig 3b). Here it is also shown that the disappearance takes place gradually between 30A and 40A MeV while the dominant peripheral low momentum transfer fission process remains unaffected.

The slow target-like component has been investigated in more energetic reactions only in emulsion experiments [8] and here again one finds the same recoil velocities.

In counter experiments one has instead investigated the projectile-like fragment component. Fig 4 shows how the velocity distribution of ^{34}S emanating from an ^{40}Ar projectile evolves with increasing beam energy [12,13].

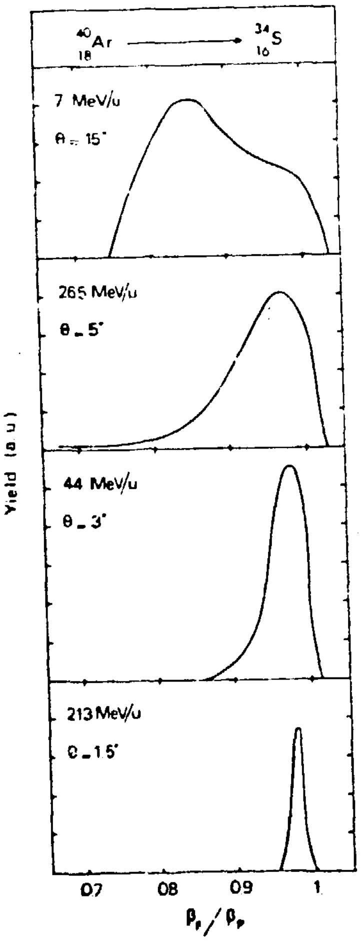


Fig 4. Velocity distribution of ^{34}S fragments emitted in ^{40}Ar induced reactions in ^{58}Ni (three upper) and in ^{12}C (lowest) [12,13].

We observe the gradual reduction of the width of the velocity distribution again indicating the decreasing importance of large momentum transfer processes. In fact all data on (peripheral) fragmentation at high energies support the idea of a sudden liberation of a part of a Fermi-gas system. For the momentum widths this means [14]:

$$\sigma^2 = (p_F^2 / 5) \cdot A_{FR} (A_B - A_{FR}) / (A_B - 1) \qquad (2)$$

where $A_{FR(B)}$ is the fragment (beam) mass number and p_F the Fermi momentum.

Thus we have seen that the active (participant) volume evolves from the total system at low energies to the impact parameter dependent geometrical overlap volume at high energies. The creation of pions must be intimately related to this active volume. Recent experiments [15] show that pions are produced with measurable probabilities (Fig 5) very close to the true coherent threshold, i e:

$$\varepsilon_{th}^2 = \left[(M_{B+T}^* + m_\pi)^2 - (M_B + M_T)^2\right]/2M_T \qquad (3)$$

where M_{B+T}^* stands for the rest energy of the first isospin conserving state of the fused system. For the reaction $^{12}C + ^{12}C \rightarrow \pi^0 +$ .... this threshold is about 17A MeV and we see in Fig 5 cross-sections in the nb-region 10A MeV above the threshold.

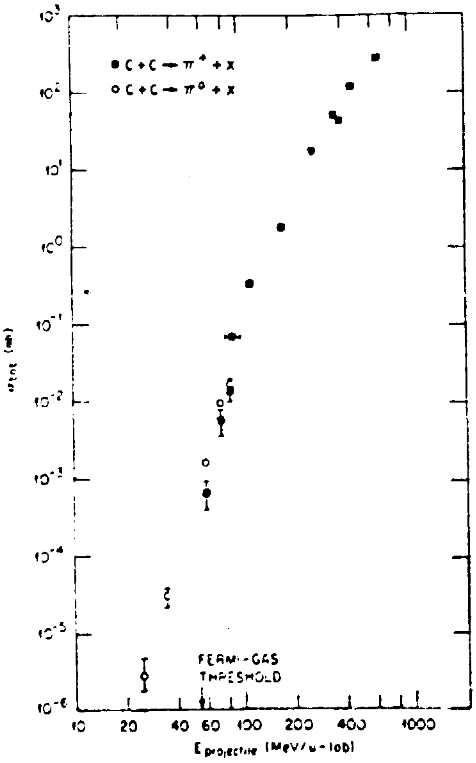


Fig 5. Inclusive pion production cross-section in $^{12}C + ^{12}C$ collisions as a function of the beam energy [15].

Several models assuming more or less collectivity have been applied.

Above 100A MeV both collective thermal participant (fireball) models and nucleon-nucleon scattering (cascade) models roughly explain the cross-sections, but both these models fail. Not even Fermi boosting is enough to reach the cross-section with individual scattering between nucleons [16] whereas cooperative interactions between multi-nucleon systems [17] as well as a compound formation model [18] may explain the data. Even the compound model fails at energies below 50A MeV [18] where one would normally expect such a model to be relevant. The way to save such a description is to push it towards the fully coherent limit of pionic fusion [19]. Selective experiments where pions are measured in coincidence with heavy fragments seem to be urgently needed. So far there are some results only for projectile-like fragments in coincidence with pions [20] showing a surprisingly high degree of breakup (central collisions?) even at 48A MeV.

Even inclusive macroscopic parameters, like the equilibrium temperature, are still controversial [21] but in order to learn more about the fundamental processes in the active region one must probably concentrate on experiments on two- or many-particle correlations. From large-angle proton-proton correlation spectra [22] one has observed an increasing deviation from the expected results of pure quasi- elastic scattering with decreasing energy (not only the trivial one from the enhanced relative importance of the internal motion). Since back-to-back correlations are also observed for heavier particles at these energies one must think in terms of other momentum-conservation effects which favours in-scattering-plane correlations. Emission from a thermal participant source (or quasi-fusion at low energies) may be the answer! Here we want to call the attention to recent data on the azimuthal angle (Φ) distribution of the two-particle cross-section (non-evaporation particles) which indicates a significant difference between 25A MeV [23] and 85A MeV [24]. Fig 6 shows that the shift from a clean back-to-back peak for light targets to a structure where $\Phi=0$ has as strong a correlation peak as $\Phi=\pi$ for heavy targets has disappeared completely at 85A MeV. If the shadowing volume explanation of the low energy results [23] is correct then we must believe that the increasing relative velocity between the non-active parts of the nuclei must cause the disappearance of the effect at the higher energy. Thus we see an example of dynamical effects which could be important to follow up.

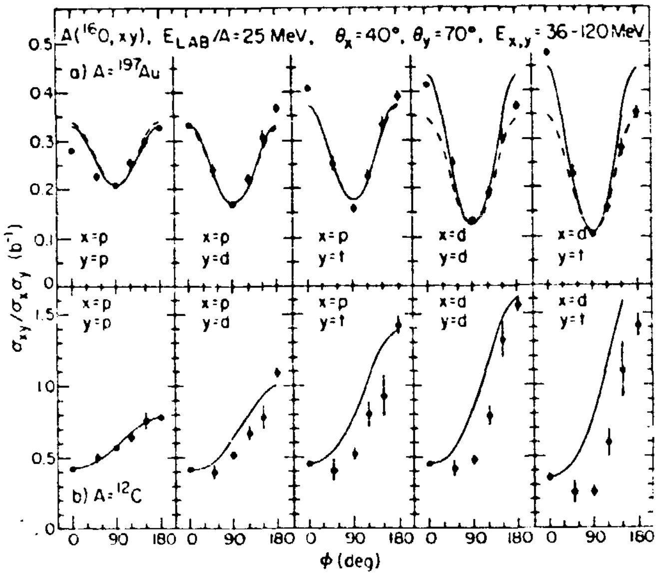
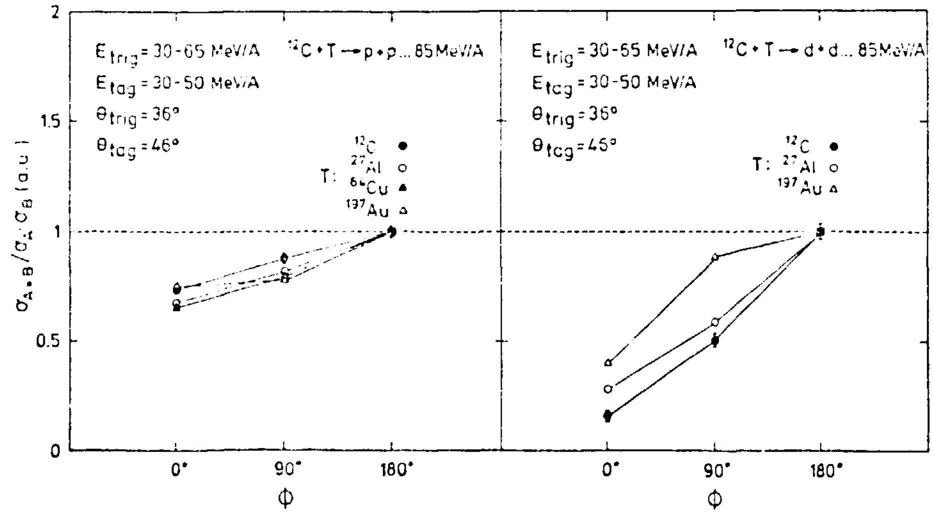


Fig 6. Azimuthal angle correlations between non-evaporation light particles in ^{16}O [25] and ^{12}C [24] induced reactions at 25A MeV and 35A MeV respectively.



Another kind of correlation phenomenon which shows (Fig 7) a remarkable similarity for all energies is the strong 2-proton peak for small relative momenta ($\Delta p \sim 20$ MeV/c) [24-26]. Originally this phenomenon was interpreted as a second order wave-interference effect (the Hanbury-Brown Twiss effect [27]) which should give information about the hot, active source size. The remarkable similarity for various energies have however caused some doubt about this explanation and it has later been shown that the decay of the particle unstable diproton (^{2}He) could give similarly good fits to data (see the fit for 25 A MeV). Further experiments on correlations between heavier systems, like those shown in Fig 8 [25] have been performed to see whether the ground state or excited states of other particle unstable systems can be observed. The results are only partly understood. Some obvious resonant states of ^{4}He and ^{5}He are observed the d,d system shows no such peaks. Naturally the p,t decay channel is favoured because the separation energy is smaller but should it really be

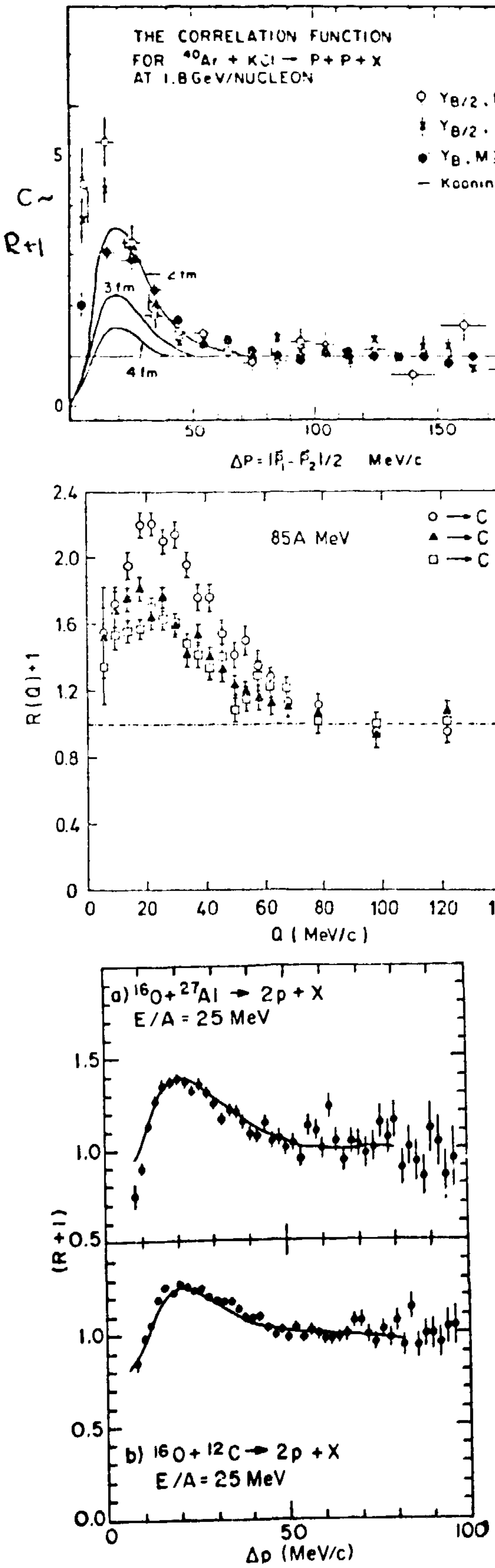


Fig 7. Two-proton correlation function ($R \sim \sigma_{xy}/\sigma_x \cdot \sigma_y$) versus $\Delta p = |\vec{p}_1 - \vec{p}_2|/2$ in 1.8A GeV Ar induced [25], 0.085A GeV C induced [24] and 0.025A GeV [26] O induced reactions.

absent? If deuterons behave like good bosons then the correlation spectrum should peak at $\Delta p=0$ from quantum interference point of view. Clearly there is a minimum for $\Delta p \approx 20$ MeV/c as expected, but experiments with smaller angular spacing between the detectors are urgently needed.

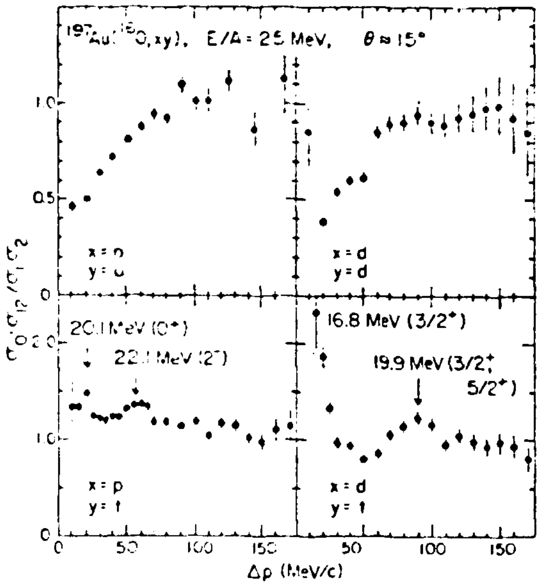


Fig 8. Light particle correlations for ^{16}O+^{197}Au reactions at 25A MeV. The location of well known particle unstable resonance states is indicated [26].

The discussion above provides all needed justification of the CLU-synchrocyclotron program and therefore we switch now to the question of what can be learned with the unique conditions at the CELSIUS ring.

3.2. Some Suggested Experiments for CELSIUS

The unique qualities of CELSIUS-beams contain; i) high resolution and precision of the energy, ii) rapid changes of the beam energy in large or very small steps, iii) a DC time structure, iv) very thin targets and still high luminosity and v) very low background. Naturally these qualities have to be met by the detector systems and by experiments where one can really extend the knowledge because of these qualities.

The high resolution should particularly be taken advantage of in investigations of very peripheral reactions where specific excited states are reached. The beam energy resolution must then be less than the average level distance $\Delta E \lesssim d_E$, or if the resonances are overlapping we should have $\Delta E \lesssim \Gamma$ where Γ ($=\hbar$/life-time) is the average width. The value of d_E and Γ depend on the excitation energy of the system and its angular momentum and in the low CELSIUS-energy region these values are well-known ($\Delta E \lesssim 100$ keV)[28]. Since the target straggling is negligible (thickness < 10^{14} atoms/cm^2) we state that a beam energy resolution of a few tens of keV is useful. A 43A MeV ^{12}C beam is predicted to have $\Delta p/p \approx 1 \cdot 10^{-4}$ corresponding to $\Delta E \approx$ 100 keV which means that there is a point in pushing the resolution even further. Some well-suited high resolution experiments, like investigations of the fine structure in elastic and inelastic resonant scattering and in giant resonances as well as experiments on quasi-molecular states and threshold pion production, are discussed in [29]. No detailed suggestions about such experiments have yet been presented possibly because they must be connected with the construction of high resolution spectrometers. The experiments which have been presented in two letters-of-intent [30] are instead based on the combination of very thin targets, high luminosity, DC structure and a rapid change of the beam energy. A common goal for the two programs is to develop a detector system for the registration of the slow target-like fragments (possibly in the range 30A to 200A keV) which become available with gas-jet targets. The first program (C5) is focused on detailed inclusive information about these recoils in order to get a better knowledge about the transition from the binary reaction types to the multifragmentation reactions (section 2). The other program (C2) is focused on correlation studies where the heavy recoil information is used mainly to determine the reaction plane and the impact parameter. The reaction plane information is essential for the complete understanding of the particle production processes but it is important to remember that the recoil angle as a carrier of reaction plane information is limited by the dispersion in the momentum transfer process [31]. The impact parameter information is fundamental for heavy ion reactions (Fig 2) and in experiments where only incomplete multiplicity information is available it is likely that the mass of the heaviest fragment is the most reliable parameter. Several measurements of single-particle hadron spectra, at several energies , in combination with heavy recoil registration could be very informative. In particular we stress measurements of pion emission from the threshold to the maximum CELSIUS energy. Also two- and many-particle correlation experiments are realistic and we want to finish this presentation by giving one such example. The example is a 4-fold coincidence registration of two protons (both with fixed emission angle and one with fixed azimuthal angle), the heaviest projectile-like fragment(PF) and the heaviest target-like fragment(TF). In two-proton experiments one has found an in-scattering-plane excess of coincidences (back-to-back correlations) as well as the small Δp correlations discussed in section 3.1. Impact parameter information in these correlation events would certainly help in understanding the processes and in particular for the large-angle correlations one is eagerly waiting for the answer to the question whether the scattering plane is the same as the reaction plane or not. With such information one could e g distinguish between the two most fundamental explanations for the in-plane excess - quasi-elastic scattering of nucleons or sequential emission from a recoiling equilibrized(fireball) source. Below we present a table which shows the realism of such an experiment at CELSIUS. The estimations are based on empirical information and an experimental setup of a two-proton experiment [32] and from conservative figures of the CELSIUS performance as compared to those presented at this meeting [33].

Number of stored ions (s^{-1})	Single count. rate (s^{-1})	Random count. rate per det. comb. (s^{-1})	True p*p coinc. rate per det. comb. (s^{-1})	p*p*PF*TF coinc. rate with 10 det. comb. (s^{-1})
$1 \cdot 10^8$	310	$3.8 \cdot 10^{-3}$	$9.4 \cdot 10^{-2}$	0.12
$1 \cdot 10^9$	$3.1 \cdot 10^3$	0.38	0.94	1.18
$1 \cdot 10^{10}$	$3.1 \cdot 10^4$	38	9.4	11.8

Table 1. Expected counting rates in a 4-fold p*p*PF*TF correlation experiment (C + Xe at 100A MeV) with the following input:

- $\lesssim 10^{10}$ ions can be stored for 50s with a Xe target of thickness $1 \cdot 10^{14}$ atoms/cm^2 (2% fractional loss).
- Dumping + reinjection of beam in 10s.
- DC- time structure.
- Inclusive proton cross-section ($\theta = 45^o$ $E > 30$ MeV) $d\sigma/d\Omega$ =2000 mb/sr.
- Two-particle cross-section ($\theta_1 = \theta_2 = 45^o$ $E_{1,2} > 30$ MeV) $d^2\sigma/d\Omega_{1,2}$ = 50 mb/sr^2 (= 10 mb/sr^2 for the in-plane excess).
- Solid angle = 10 msr per telescope.
- Coincidence gate ≈ 40 ns.
- The PF telescopes register 50% and the TF telescope 25% of all fragments.

Optimal conditions should be obtained for between 10^9 and 10^{10} stored ions producing 10^6 useful coincidences in a day!

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FÖRFATTARE B Jakobsson

DOKUMENTTITEL OCH UNDERTITEL
Intermediate Energy Heavy Ion Reactions - A Program for CELSIUS

SAMMANFATTNING
The accelerator system under construction in Uppsala with the ECR-source + the K=200 synchrocyclotron + the CELSIUS synchrotron ring for storage, cooling and acceleration opens up possibilities for a very fruitful heavy ion physics program. Some recently obtained results and some recent ideas on intermediate energy reactions are discussed and speculations are made about some experiments where the unconventional qualities of CELSIUS beams could be utilized.

NYCKELORD Heavy Ion, Medium Energy Reactions, Storage- and Cooling Ring Physics

DOKUMENTTITEL OCH UNDERTITEL – SVENSK ÖVERSÄTTNING AV UTLÄNDSK ORIGINALTITEL
Tungjonsreaktioner i mellanenergiområdet - Ett program för CELSIUS

TILLÄMPNINGSOMRÅDE
Tungjonsexperiment vid synkrocyklotronen och CELSIUS-ringen i Uppsala

TILLÄMPNINGSNYCKELORD Tungjonsreaktioner, Mellanenergiområdet, Lagrings- och kylningsringexperiment

UTGIVNINGSDATUM år 86 mån 02	**ANTAL SID** 15	**SPRÅK** ☐ svenska ☒ engelska ☐ annat

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