Low Energy Pion Production at 0° With Heavy Ions

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There has been much speculation in recent years on the possibilities of a variety of qualitatively new nuclear phenomena which may be observable with the pions produced in heavy ion collisions. During the past year we have obtained the first results from an experiment designed for pion measurements in a kinematic regime well suited to observing these effects but not previously investigated in heavy ion experiments, namely, pions emitted at 0° with near-zero kinetic energy in the center of mass and projectile frames.

The experiment was carried out at the LBL Bevalac with a 180° magnetic spectrometer which permitted measurements of both π^+ and π^- emitted with kinetic energy between 34 and 155 MeV in the lab system. At 390 MeV/nucleon this includes pions emitted with energies well below the Coulomb barrier in the center of mass and projectile frame. An unexpected result of these measurements is the very sharp and large anomaly in the π^-/π^+ cross section ratio at E_n = 55 and $E_{projectile}$ = 390 MeV/nucleon. Additional results made possible by this apparatus included qualitative measurements of pion production cross sections at heavy ion beam energies much lower than previously possible, far below the threshold for pion production in free nucleon-nucleon collisions and even below the threshold for nucleon-nucleus collisions. Spectra of π^+ and π^- have been recorded at 0° for Ne + NaF at five beam energies from 100 to 390 MeV/nucleon.

The differential cross section at 0° varies by about four orders of magnitude over the beam energy range studied, and at the lowest energy, 100 MeV/nucleon, the pion yield corresponds to less than one pion per 1000 nuclear interactions. The data are summarized in Fig. 1 and will be discussed further below. Table I gives the cross section averaged beam energies in the targets. They have been corrected for the very large fall off of cross section with decreasing beam energy.

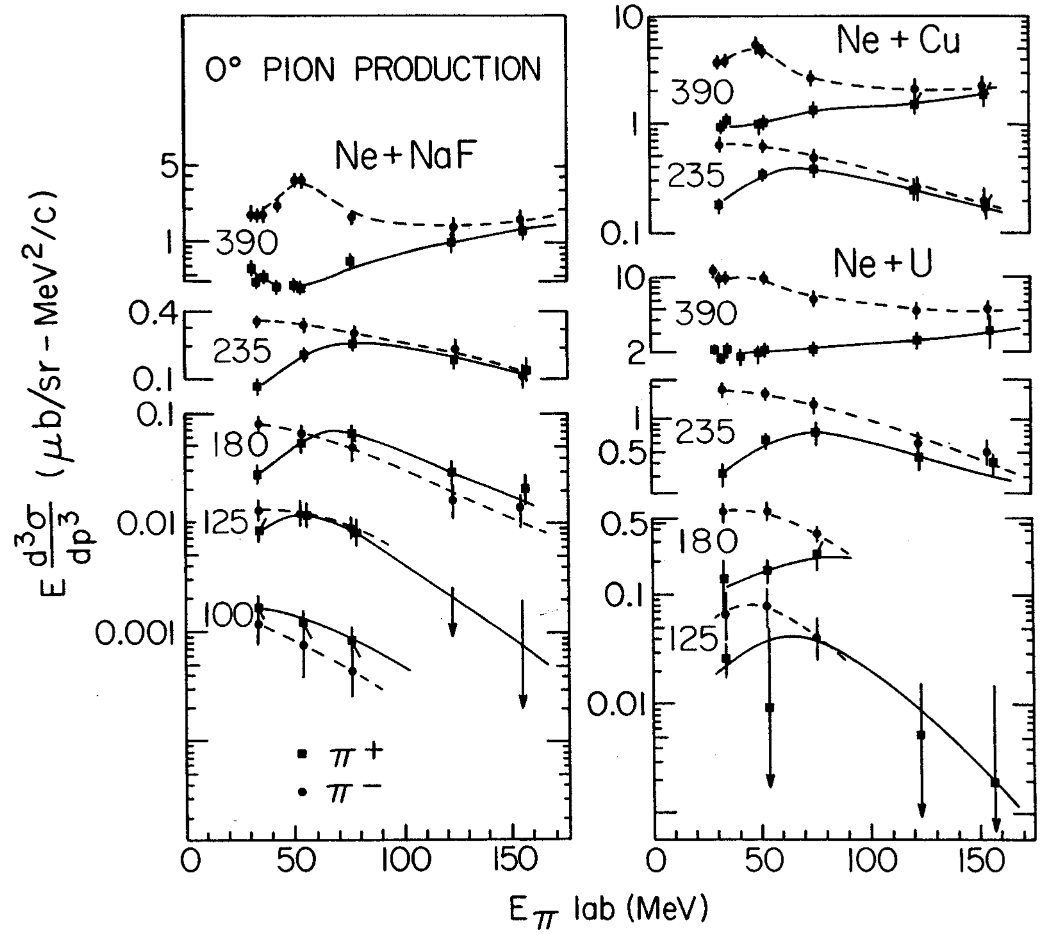

Fig. 1. 0° pion spectra for various targets and incident Ne beam energies in MeV/nucleon. The corresponding average beam energies in the target are given in Table I.

Table I. The incident beam energy (in MeV/nucleon) and its average value in the targets.

Incident Beam Energy	Average in the target NaF	Cu	U
101 ± 5	80 ± 10	--	--
130 ± 4	110 ± 7	--	118 ± 7
182 ± 3	164 ± 8	--	172 ± 8
235 ± 3	219 ± 5	214 ± 5	226 ± 5
388 ± 2	383 ± 3	377 ± 3	381 ± 3

Angular distributions were measured in 7.5^{o} steps between 0^{o} and 30^{o} at 235 MeV/nucleon on NaF and U targets and are quite isotropic. The target mass dependence of the data is approximately $A^{2/3}$ but differs somewhat at the lower pion energies. The absolute cross sections indicated in Fig. 1 are believed accurate within a factor of two at present, with the error bars indicating only statistical and relative cross section uncertainties. Ratios of cross sections are better determined because several uncertainties cancel in the ratio.

The ratio, R, of the π^- to π^+ cross sections is plotted in Fig. 2 for the Ne + NaF data at 0^{o} for all five beam energies studied. The ratios are plotted as a function of the pion kinetic energy relative to the projectile. There is an unexpectedly large and narrow peak in the 390 MeV/nucleon data. For the 235 MeV/nucleon data the lowest pion energy point recorded in the lab (34 MeV) corresponds very nearly to zero energy in the projectile system, and there is a large ratio at this point also.

The data seem to indicate that a large fraction of the pions created with zero kinetic energy in the projectile frame probably results from peripheral collisions. In this case the peak observed in the π^-/π^+ ratio can be qualitatively explained in terms of Coulomb distortion of the pion wave functions in the vicinity of the projectile charge. The Coulomb wave for the π^- is enhanced near the positive charge of the nucleus, while that of the π^+ is reduced. A calculation using a charge and radius appropriate for the projectile ignoring the Coulomb effects of the target gives a reasonable representation of the data for R.

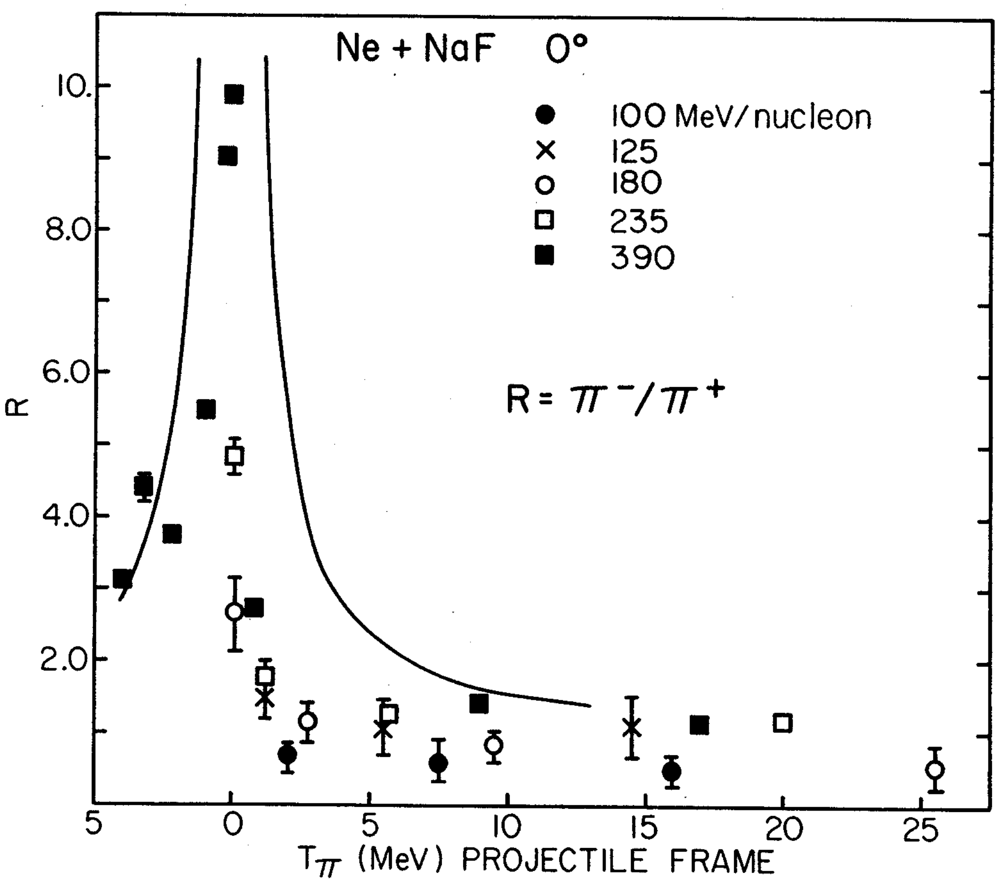

Fig. 2. The ratio of π^-/π^+ at various beam energies plotted versus pion K.E. in the projectile frame. The curve is a calculation of the ratio described in the text.

While this mechanism appears to offer a feasible qualitative explanation of the peak, a more precise treatment will be necessary to explain it in detail. More complete pion spectra at lower beam energies and additional higher beam energies, as well as other beam-target systems, are necessary to develop a real understanding of this structure. Furthermore, there is presumably a similar, but less well defined Coulomb effect for pions created at rest in the center of mass system by central collisions. The heights, widths, and positions of these Coulomb phenomena may yield valuable information on the relative amounts of central and peripheral collisions, as well as being sensitive to the microscopic details of the spatial size and time scale of the interaction.

Other features of the data which we would like to mention here are the absolute pion production cross sections and the rapid rate of decrease of the yields with decreasing beam energy. The original purpose of this experiment was to look for deviations from the predictions of a simple Fermi-gas production mechanism at the lowest possible beam energies. This model cannot account for the absolute pion yields at even the lowest beam energy. The thermal fireball model can nearly account for the pion yields at 235 MeV/nucleon and above but gives a very marked underprediction of the data at the lower energies.

The experiments at the Bevalac have been continued with a much improved apparatus. Very recent runs at 300, 400, 500, and 575 MeV/nucleon have shown that the peak in the π^-/π^+ ratio does move with projectile velocity and is dramatically sharp for thin, low A targets. This data was taken in July 1979 and is currently being analyzed.

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Light Particle Spectra Observed in Central and Peripheral Collisions of $^{16}O + ^{238}U$ at 20 MeV/nucleon

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The emission of energetic light particles in heavy ion reactions at non-relativistic energies has attracted renewed interest both experimentally and theoretically. At present, however, little is known about the relative importance of peripheral and central collisions for the production of these particles. We have addressed this problem by measuring the angle between two coincident fission fragments[1,2] to discriminate between central and peripheral collisions.

The experiment was performed at the 88 inch cyclotron of the Lawrence Berkeley Laboratory. A ^{238}UF target of 200 $\mu g/cm^2$ thickness mounted on a 50 $\mu g/cm^2$ carbon backing was bombarded with $^{16}O^{6+}$ ions of 315 MeV energy. The experimental setup is described elsewhere in this report.[2]

The energy spectra of light particles (p, d, t, α) observed at 14° in coincidence with central and peripheral collisions are shown in Fig. 1. We have denoted reactions with fission fragment folding angle, θ_{AB}, greater than 160° as peripheral and reactions with $\theta_{AB} \leq 160°$ as central (see Fig. 1 of Ref. 2). Although there are differences in the low energy regions, it is most remarkable that very similar slopes are observed in the high energy region of the spectra. Within the present statistics these slopes show little variation for p, d, t, and α-particles or for central and peripheral collisions. This surprising similarity of the spectral shapes on the type of collision was checked to be independent of the particular choice of θ_{AB} used to distinguish between central and peripheral reactions. Even by subdividing the folding angle distribution into four equally wide regions, no significant differences in the exponential fall-off of the coincident light particle spectra could be detected. Recently, it has been suggested[3] that the "prompt emission" of energetic light particles should become an important aspect of heavy ion reactions at energies of a few tens of MeV per nucleon. These "promptly emitted particles" should be produced at a very early stage of the reaction which could yield energy spectra rather independently of the final fate of the colliding nuclei.

There is a sizable probability for the emission of light particles both in central and in peripheral collisions. Substantial cross sections, differing by less than a factor of two, are observed for the emission of all three hydrogen isotopes at 14°. (Note that deuteron and triton emission are generally of minor importance for the statistical decay of equilibrated nuclei as compared to the emission of neutrons, protons,

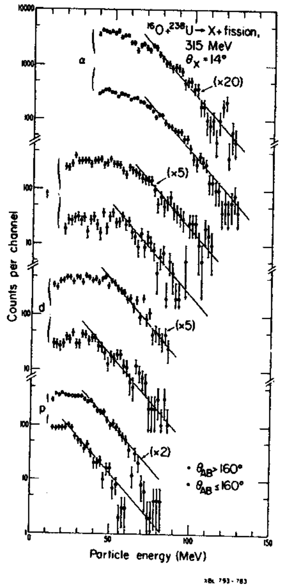

Fig. 1. Light particle spectra measured at the laboratory angle of 14° in coincidence with central ($\theta_{AB} \leq 160°$) and peripheral ($\theta_{AB} > 160°$) reactions. The solid lines correspond to the spectral shape exp(-E/T), with T = 13 MeV.

and alpha particles.) The relative contribution of peripherally produced alpha particles decreases rather substantially with increasing detection angle from 14° to 30° (see Fig. 1 of Ref. 2).

The shape of the proton spectra measured in this experiment is very similar to the shapes of the inclusive proton spectra measured[4] at slightly larger angles for the reaction $^{16}O + ^{197}Au$ at 315 MeV (the solid lines in Fig. 1 correspond to an exponential shape $e^{-E/T}$, with T = 13 MeV). These inclusive spectra could be rather well described[4] in terms of a preequilibrium model,[5] the fireball model,[6] or, even better, as resulting from the isotropic emission from a hot system of nucleons moving with half the beam velocity. The fireball model assumes that the target nucleus acts as a mere spectator to which only a negligible amount of momentum is transferred. Although this model gives satisfactory agreement with the inclusive data at 20 MeV/nucleon, the large momentum that we have observed to be transferred to the target nucleus (see Fig. 1 of Ref. 2) clearly refutes such a hypothesis which, incidentally, has not been subject to experimental scrutiny at higher energies where it has been advocated.

It is observed[2] that the emission of only the detected energetic light particle into the forward direction is a most probable reaction mechanism. The motion of the center of mass of target nucleus. In Fig. 3c the fission probability was obtained from Fig. 3b by making corrections for the fission angular distribution and normalizing to $^{236}U(t,pf)$ data.[3] Due to the strong energy dependence of the fission probability the identification of resonance and background is highly uncertain for the coincidence spectrum. However, even by adopting the extreme simplication of a smooth background (see dashed lines in Fig. 3a) we find that the resonant structure observed in the coincidence spectrum must be associated with an integral fission probability of at least half the fission probability of the underlying continuum. This is in disagreement with the results of Ref. 2.

We are currently investigating the dependence of the total kinetic energy release of the fissioning ^{238}U on its excitation energy to determine whether there is any unusual behavior in the region of the giant quadrupole resonance.

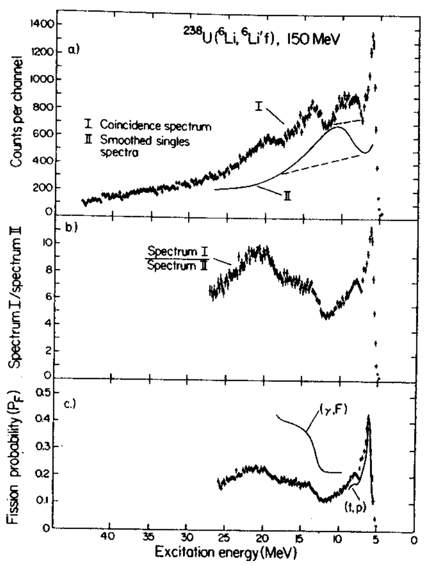

Fig. 3. Comparison between the singles and coincidence energy spectra.

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1. A.C. Shotter, D. Branford, J.C. McGeorge, and J.M. Reid, Nucl. Phys. A290, 55 (1977), J.D.T. Arruda Neto, S.B. Herdade, B.S. Bhandari, and I. Nasimento, Phys. Rev. C18, 863 (1978), A.C. Shotter et al., to be published.

2. J. van der Plicht, M.N. Harker, A. van der Woude, P. David, and J. Debrus, Phys. Rev. Lett. 42, 1121 (1979).

3. J.D. Cramer and H.C. Britt, Phys. Rev. C2, 2350 (1970).

Momentum Transfer to Target Residue in ^{16}O Induced Reactions at 20 MeV/nucleon

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At bombarding energies below about 10 MeV/nucleon the reactions between ^{16}O and heavy nuclei are dominated by fusion, deeply inelastic, and grazing collisions. For much higher energies, different reaction mechanisms such as nucleon-nucleon collisions and fragmentation become important.[1] A transition is then expected to occur at intermediate energies of a few tens of MeV/nucleon. To study the reaction mechanism for the production of energetic light particles that are observed already at the lower energies, a method to discriminate between central collisions and peripheral collisions is desired. By measuring the angle between the outgoing fission fragments from the reaction of 20 MeV/nucleon ^{16}O on ^{238}U one can infer the momentum transferred to the heavy nucleus prior to fission and discriminate central and peripheral collisions, or, more precisely, reactions that are accompanied by small and large momentum transfer.

The experiment was performed at the 88-inch cyclotron of the Lawrence Berkeley Laboratory. A $^{238}UF_4$ target of 200 $\mu g/cm^2$ thickness mounted on a 50 $\mu g/cm^2$ carbon backing was bombarded with $^{16}O^{6+}$ ions of 315 MeV energy and also with 140 MeV ions in a short calibration run. Light particles (p, d, t, α) were detected at 14° with a ΔE-E telescope consisting of a 350 μm thick ΔE-detector and a 1 1/2 inch thick NaI E-detector. An aluminum absorber of 1 mm thickness was placed in front of the telescope to stop heavy particles ($Z > 3$). In addition, two solid state detector telescopes were installed to detect alpha particles at 30° and heavy ions (Li,...,O) at 15°. Two fission fragments emitted in coincidence with light particles were detected by two position sensitive solid state detectors, each subtending the angular range of 62°-98° and mounted in a plane with the light particle telescope.

The momentum balance for the emitted fission fragments can be written as

$$\vec{P}_R = \vec{P}_A + \vec{P}_B \qquad (1)$$

where the indices R, A, and B denote the target residue and the two primary fission fragments, respectively. If we denote the detection angle between two coincident fission fragments by θ_{AB}, we obtain by taking the square of eq. (1)

$$P_R^2 = (P_A - P_B)^2 + 4P_AP_B \sin^2(\Delta\theta/2) \qquad (2)$$

where $\Delta\theta = \pi - \theta_{AB}$. The momentum transfer is mainly determined by the folding angle θ_{AB} and depends only slightly on the energies and unknown masses of the fission fragments since, within a good approximation, $P_A = P_B$.

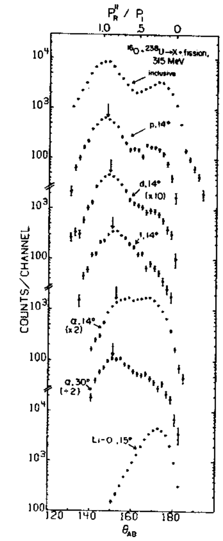

Fig. 1. Folding angle distributions between two outgoing fission fragments. The kind of additional coincidence condition is given in the figure. Symmetric fission of ^{254}Fm has been assumed to calculate the ratio of the parallel recoil momentum P_R to the beam momentum P_1.

The fission yields as a function of θ_{AB} are shown in Fig. 1. The data have been corrected for the dependence of the coincidence efficiency on geometry. The momentum scale was obtained from eq. (2) by assuming symmetric fission of the compound nucleus ^{254}Fm. Slightly varying momentum scales are obtained by using different mass and energy distributions. However, these variations are minor for the above stated reasons. The inclusive distribution shows two groups which we associate with central and peripheral collisions. The high momentum transfer group has a maximum at $\theta_{AB} \cong 148°$ corresponding to a momentum transfer to the fissioning nucleus of about 92% of the beam momentum. Since this is close to the value of 100% expected for compound nuclear reactions we associate this group with central collisions. (At the lower beam energy of 140 MeV this group has a maximum that corresponds to 100% of the beam momentum. Our results therefore indicate that processes other than pure compound nucleus formation are significantly more important for central collisions at 315 MeV than at 140 MeV.) The low momentum transfer group of the inclusive θ_{AB} distribution has a maximum at about 173° which is close to the maximum of the distribution observed in coincidence with projectile residues (Li,...,O) at 15°. Since these reaction products are associated with peripheral reactions,[1] the low momentum transfer group is identified with peripheral reactions. Furthermore, as shown in Fig. 2, as the projectile residue becomes more like the projectile, i.e. as the reaction becomes more peripheral, the θ_{AB} distributions peak at lower momentum transfer.

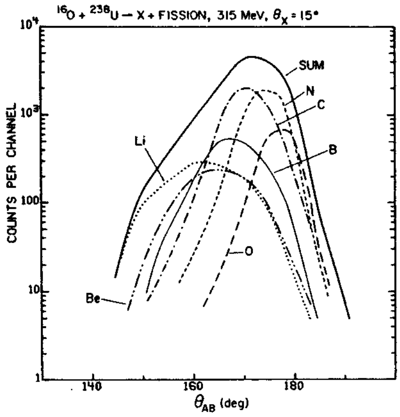

Fig. 2. Smoothed folding angle distributions between two outgoing fission fragments in coincidence with projectile residues.

The mean momentum was determined for the light particles in Fig. 1. The arrows indicate the position at which the recoil momentum is equal to the difference between the beam momentum and the light particle mean momentum. These differences agree very well with the maxima observed in the corresponding folding angle distributions in the region of central collisions. This suggests that the emission of only the one light particle into the forward direction that is detected in coincidence is a most probable mechanism. The forward momentum of the center of mass of any other emitted particles must be small in central collisions.

We hope to obtain additional information about the transfer of kinetic energy to internal degrees of freedom from the mass asymmetries of the fissioning system.

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1. C.K. Gelbke, C. Olmer, M. Buenerd, D.L. Hendrie, J. Mahoney, M.C. Mermaz, and D.K. Scott, Physics Reports 42C, 311 (1978).

An Experiment to Measure Nuclear Lifetimes in the Attosecond Time Range by K X-rays

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A new technique for measuring nuclear lifetimes in the 10^{-18} second range is being investigated. The method involves comparing the nuclear lifetime to that of an atomic K-shell vacancy. If, in a nuclear collision, the projectile produces a compound nucleus it may be possible to observe whether the compound nucleus or the K vacancy decays first. If the atomic vacancy is filled first, the resulting x-ray will be characteristic of the Z of the compound nucleus. The number of these events, relative to the total number of simultaneous nuclear-atomic events, can be used to extract the lifetime of the compound nucleus relative to the well-known lifetime of the atomic K vacancy.[1] The first observation of such events, using a proton-induced reaction, has been reported recently.[2]

We have attempted such a measurement with the reaction 95 MeV ^{14}N + ^{208}Pb, by looking at x-rays in coincidence with fission fragments from the compound nucleus ^{222}Ac. Observation of actinium K x-rays, the strongest line being at 90.9 keV, would indicate that some number of compound nuclei have fissioned after the K vacancy was filled. The atomic lifetime for a Z = 89 K vacancy is 8×10^{-18} sec.

To reduce the background of real coincidence from Compton-scattered gamma rays, an anticoincidence shield was used. Because of the large number of gamma rays produced in the decay of the fission fragments, it is not feasible to surround the x-ray detector entirely with a shield. However, since most of the Compton background in the region of interest comes from gamma rays scattering to a relatively small angle in the Ge detector, it is possible to shield only the solid angle behind the detector, and thus to keep the shield from subtending too much solid angle with respect to the target.

To determine the optimum geometry, a Monte Carlo program has been written to simulate the experiment. The program takes into account vacancy production probabilities, a range of gamma-ray energies, Compton scattering and photoelectric absorption in the Ge detector, Compton scattering angles (and thus deposited energies) weighted by the relevant cross sections, and 3-dimensional geometry. Background reductions in the range of 3 to 20 have been calculated for a totally-absorbing shield (with less than 50% reduction in x-ray yield), where the exact reduction depends on the number of low energy gamma rays ($\lesssim$200 keV) produced in the fission event.

The geometry chosen for the experiment is shown in Fig. 1. A 700 $\mu g/cm^2$ enriched ^{208}Pb target was bombarded with 15 nA of $^{14}N^{5+}$ beam from the MSU cyclotron. Fission fragments were detected by a 600 mm^2 silicon detector 0.8 cm from the target, positioned at 90°. This detector was blocked off forward of 90° (to reduce elastic rate) except for a small hole at 35°, which made possible a simultaneous measurement of the zero-impact-parameter ionization probability (expected to be about 0.002) from ^{14}N elastic--Pb K x-ray coincidences. A small chamber with a special target ladder and re-entrant port for the x-ray detector was constructed. The front of the x-ray detector (a 17 mm diameter, 7 mm thick Ge crystal) was 2.5 cm from the target. Lead was used to shield the anticoincidence detectors over that part of the solid angle not subtended by the x-ray detector. We borrowed 8 plastic scintillators from the Argonne ZGS, each 10 x 25 x 30 cm, and placed these around the Ge detector in order to subtend as much of the solid angle (with respect to the Ge crystal) as possible behind a plane 4 cm from the target. The actual background reduction achieved was less than a factor of 2, presumable because the shield was not 100% efficient over the desired solid angle. Data was acquired for about 40 hours (beam on target) with detection of about 3×10^8 fission fragments. Analysis is in progress.

Interpretation of the result (which will be only an upper limit to the number of coincident x-rays) must involve consideration of a decay sequence, where at each stage neutron and fission widths are calculated, angular momentum being taken into account. Such a program, similar to that of Hagelund and Jensen [3] but not yet as sophisticated in the choice of level density parameters, has been written.

1. P.C. Gugelot, Proc. Conf. on Direct Interactions and Nuclear Reaction Mechanisms, Padua, ed. E. Clementel, C. Villi, 1962, p. 382.
2. J.F. Chemin, Nordic Spring Symposium on Atomic Inner Shell Phenomena, Geilo, Norway, ed. J.M. Hansteen, R. Gundersen, 1978, vol. 1 p. 109.
3. H. Hagelund, A.S. Jensen, Phys. Scripta 15, 225 (1977).

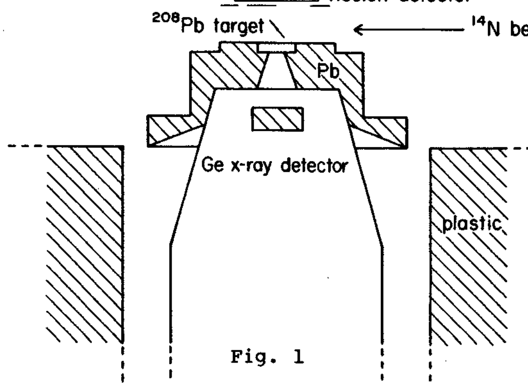

Fig. 1