Impact Parameter Dependent X Ray Investigations in Heavy Ion Heavy Atom Collisions

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Abstract— The discovery of x-rays in 1895 marked the beginning of quantitative studies of atomic collisions. These investigations have made important contributions in formulation of modern concepts and theory of atomic physics. It is well known that x-rays emitted during heavy-ion collisions stem from the innermost shells of a quasi-molecule formed during the collision. These x-rays and impact parameter dependence of their emission probability holds crucial information about molecular orbital x-ray emission or charge exchange during interaction with solid targets. These super heavy quasi-molecules can be approached in relatively slow heavy ion-atom collisions which are slow compared to the orbital velocity of innermost electrons of concern. In order to probe the inner shell levels, vacancies have to be provided there. Since the vacancy production probability is primarily determined by electron emission into final states at the Fermi surface of the united atom, the energy transfer is essentially given by the binding energy of the bound state considered. In our investigations it has been calculated that to achieve the above desired system, an impact parameter range of (0.016-0-.023) a.u. is required. The experimental work has been planned to be done at Inter University Accelerator Center, India. ^{127} I-ions will be bombarded on heavy solid targets of $_{53}$I, $_{79}$Au and $_{83}$Bi. Targets of different thickness will be used to extrapolate to near "zero target thickness" (thinnest to 250 μg/ cm^2) which are approximately the conditions under single collision conditions. The characteristic x-rays from the collision partners as well as MO x-rays will be detected by available x-ray detectors (a Si (Li) and a low energy Ge detector) to cover the entire energy range of K and L x-rays of the collision partners. For measurement of recoils at backward angles SBD/ (gas or annular) proportional counter will be used. A coincidence will be set up between the backward angle particle detectors and the x-ray to extract the impact parameter dependency of x-ray emission. Experimental data will then be compared with the data from correlation diagrams drawn on the basis of Self Consistent Field-Dirac Fock Slater (SCF-DFS) calculations for these systems for interpretation. Such a type of comparison will give a concrete idea about the couplings of the inner shells during such a slow ion-atom collision. A part of the investigations were presented as M.Sc. dissertation work of the second author.

Key words: Heavy Atom Collisions, X Ray Investigations

I. AIM OF THE EXPERIMENT

The purpose of planning an impact parameter dependent ion atom collision experiment was to study the dependency of impact parameter on x-rays emitted during heavy ion heavy atom collision. This dependency holds crucial information about the inner shell couplings and hence vacancy transfer in a quasi-molecule (atomic energy levels of projectile and target overlap and hence the system behaves as a united atomic system) during a slow ion-atom collision. A detailed literature survey of similar experiments done in the past across the globe showed that for studying the above mentioned collisions, an impact parameter range of (0.016-0.023) atomic units was required. Thus a suitable experimental set up has been planned keeping the desired impact parameter range in mind at Inter University Accelerator Centre (IUAC). To examine the impact parameter of scattered projectile and emitted x-rays in coincidence (observing the scattered projectile and x-rays emitted from the target simultaneously) a particle detector (parallel plate avalanche counter available at IUAC) will be used to detect the scattered projectile and Low energy germanium detectors (LeGe) will be used to detect the x-rays. As a part of pre-experimental preparations a detailed theoretical analysis was done for the planned experimental set up. Correlation diagrams for the chosen projectile target combinations have been drawn which will be used to analyze the results after performing the experiment. After performing the experiment we would be able to get a concrete idea about how superheavy systems (combined atomic number of target and projectile should be greater than 130) behave under the conditions of single ion-atom collisions.

II. PHYSICS BACKGROUND OF THE EXPERIMENT

A. *Ion-Atom Collision*

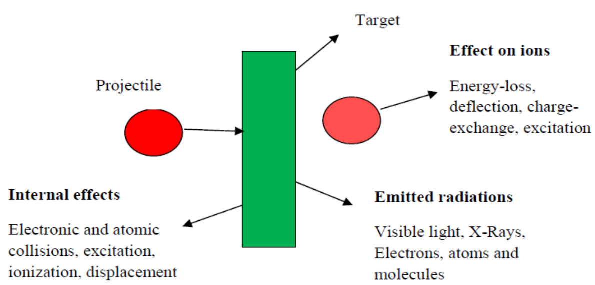

Fig. 1: Schematic representation of an ion-atom collision

When a projectile of atomic no Z_1 collides with a target material of atomic number Z_2 there are different possibilities that would happen after their interaction (shown in Fig.1). In such an interaction every projectile has some energy and thus capable of exerting forces on other particles in its way through particle interactions.

B. Production of X-Rays in an Ion-Atom Collision

During an ion-atom collision, production of X-Rays (shown in Fig.2) may occur due to following reasons:

- Direct ionization: It occurs due to direct transfer of momentum to the bound electrons of the target by the incident projectile due to coulomb interaction. It is independent of projectile charge state and is the principal mechanism of ionization for $Z_1 << Z_2$
- Electron capture: It occurs due to capture of a bound state electron of the target atom to an unoccupied state of the projectile ion. The electron capture contribution to the target inner shell ionization is dependent upon projectile charge state and becomes significant for $Z_1 < Z_2$.

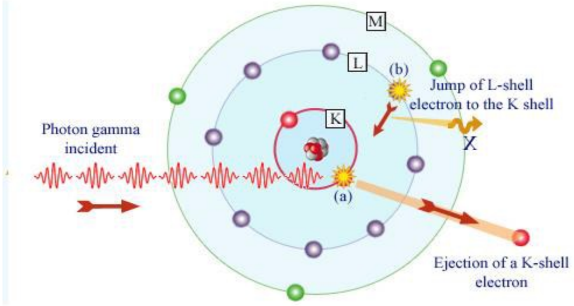

Fig. 2: Production of X-Rays

C. Impact Parameter

The impact parameter is the perpendicular distance between the target and the projectile if the projectile goes undeflected.

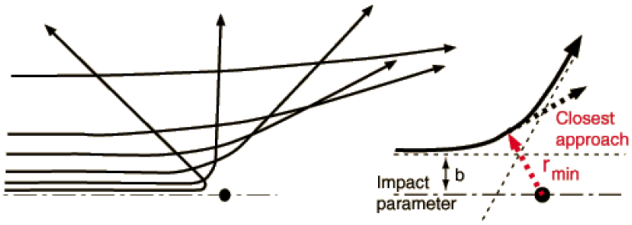

Fig. 3: Scattering of projectile by target at different scattering angles

For coulomb scattering of a small projectile off a massive nucleus, the impact parameter is related to the scattering angle by

$$b = \frac{1.44 Z1Z2 \cot(\Theta/2)}{2E}$$

where , b is the impact parameter (in fm), Z_1 is the atomic no. of projectile, Z_2 is the atomic no. of target, E is the energy of projectile (Million electron Volt), Θ is the angle of scattering of projectile.

III. HISTORICAL ASPECTS OF THE EXPERIMENT

A. Literature Survey: Summary of Research Papers Studied

S.No.	System Projectile $^{q+}$-target	Energy (MeV)	MeV/u	Impact Parameter (b) (fm)	Author	Year
1	Proton- Al, Ca, Ni, Ag	0.3-3	0.3-3	<1000	Brandt *et al.*[1]	1973
2	H^+,Be^{4+},C^{5+},$O^{6+,8+}$	2- 32	2	<4000	Andersen *et al.*[2]	1976
3	S^{q+} -Na(Cl)	32	1	84 , 700	Schmidt-bocking *et al.*[3]	1976
4	P-,α-,Li^{q+} -,O^{q+} - Ni	1.25-32	1.25-2.19	100-10000	Schmidt-bocking *et al.*[4]	1977
5	Xe ,U- Pb	4.7	640 118	<40	Greenberg *et al.*[5]	1977
6	$O^{5,8+}$ Ne, Ar, Kr, Xe	10-30	0.6-1.9		Rosner *et al.*[6]	1977

7	Kr^{24+}- Ge		1.4	52.9-740.6	Liesen *et al*[7]	1978
8	Nb –Mo	143	1.5	b<1000	Schuch *et al.*[8]	1980
9	Au-U	768.3	3.9	b<100	Banda *et al.*[9]	1984
10	Ar^{6+} Au	70	1.75	b <1000	Notle *et al.*[10]	1984
11	Pb^{q+} -Pb	890 994	4.3 4.8	b<400	Stiebing *et al.*[11]	1984
12	α – Dy	5.02	1.26	b ~1000	Schuch *et al.*[12]	1985
13	U^{44+} Sn, Ag	332	1.4	b <200	Warczak *etal.*[13]	1986
14	S^{16+} Ar	16MeV	1	b <11000	Schulz *et al.*[14]	1986
15	Pb^{26+} Sn, Xe	745	3.6	b <200	Liesen *et al.*[15]	1987
16	He^{+} -Ca, Cr, Cu	4.04	1.01	500-6000	Schuch *et al.*[16]	1987

Table.1: Details of various parameters used in experiments done on impact parameter dependent ion atom collision

B. Graphs Plotted Using Literature Survey

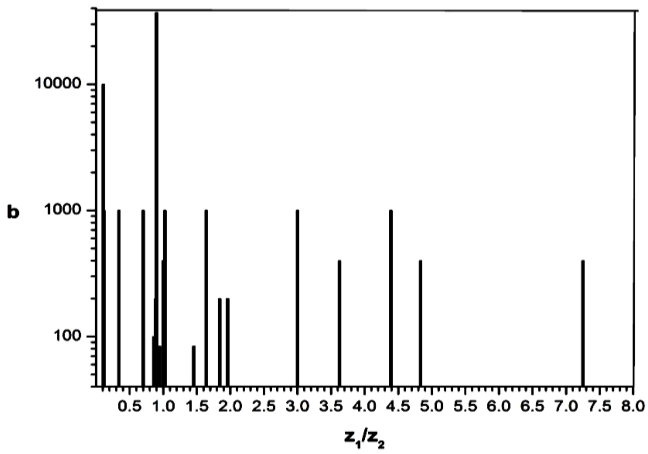

Fig. 4: Variation of impact parameter with definite Z_1/Z_2 ratio

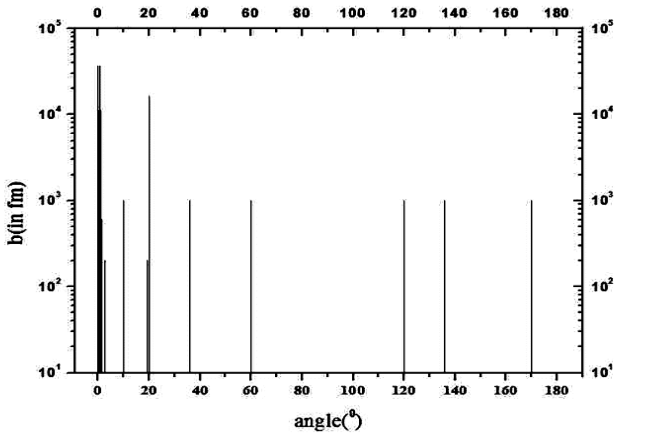

Fig.5: Variation of impact parameter, b with scattering angle

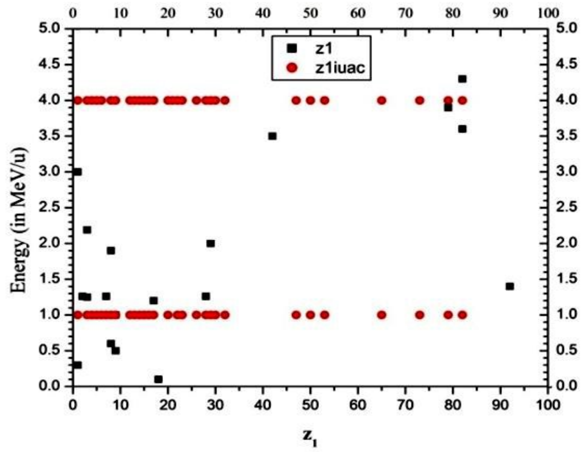

Fig. 6: Variation of energy of projectile with Z_1

C. Inference from Literature Survey

Fig.4 shows that for heavier systems (i.e. systems having $Z_1/Z_2<1$), impact parameter has larger magnitude as compared to lighter systems. Fig.5 shows ranges of impact parameter that had been investigated for different scattering angles and also gives an idea about order of impact parameter for a particular value of scattering angle. From Fig.4 and Fig.5 it has been concluded that for investigating impact parameter dependent study of heavy systems scattering angle has to be as small as possible in forward direction of beam. Fig.6 shows range of the projectile energy that has been covered for projectiles having atomic number Z_1. It also shows the feasible energy range for available beams at IUAC.

D. Conclusions from Literature Survey

After the literature survey was done it was concluded that heavier targets i.e. 47Ag, 79Au and 83Bi would be the most appropriate targets for the experiment. It was also observed that impact parameter varies in inverse proportion with the forward scattering angle of the projectile. Thus it was finalized to use parallel plate avalanche counter as the particle detector (detector with minimum least count available at IUAC) for measuring scattering angles of projectile.

IV. PLANNED EXPERIMENTAL SET UP

A. Pelletron Accelerator

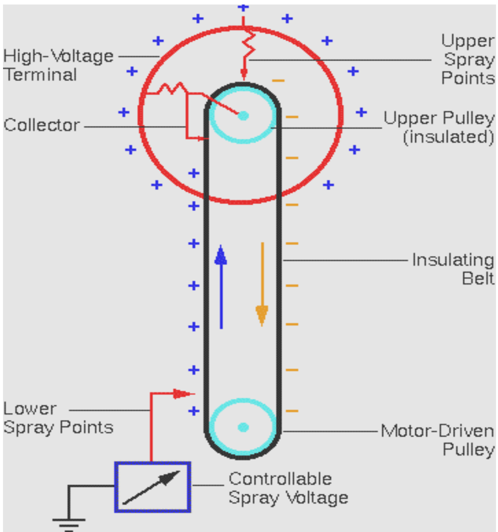

Fig. 7: Schematic diagram of the principle of a pelletron accelerator.

It is a 15 (UD) MV accelerator working on the principle of van de graff generator (Fig.7). It is used to accelerate both light and heavy ions for all atomic and nuclear physics experiments at IUAC.

B. General Purpose Scattering Chamber

Fig. 8: Picture of General Purpose Scattering Chamber

It is a stainless steel chamber of 1.5 m diameter, 0.6 m height and 1100 liter volume. Several ports are provided to the chamber, for viewing as well as for attaching additional equipment [17]. This chamber will be used for placing the target and the detectors. Fig. 8 shows a photograph of the chamber.

C. Detectors to be used for the experiment

1) Parallel Plate Avalanche Counter (PPAC) for detecting projectiles at forward scattering angles

PPAC is a gas detector which works in the proportional region that is detector output is proportional to the incident radiation. The gas of the chamber is an inert gas. An ionizing particle collides with a molecule of the inert gas to produce an ion pair. The chamber geometry and the applied voltage are such that in most of the chamber the electric field strength is low and the chamber acts as an ion chamber. Particles are detected in proportion to ion pairs generated. [18]

Fig. 9: Picture of cathode

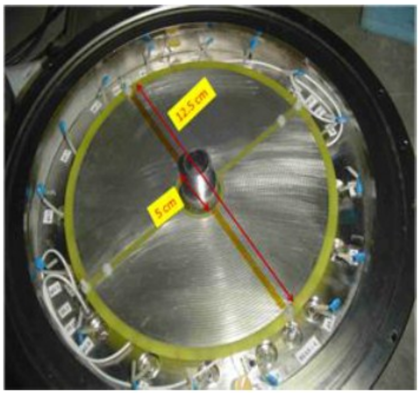

Fig. 10: Picture of anode

Detector specification:

Cathode of PPAC (Fig.9)
Aluminized Mylar- 2 micron thickness
Resolution (22.5 degree) –16 segments
Anode of PPAC (Fig.10)
Circular PCB
Active area ~ 420 sq. cm

2) Low energy germanium detectors for detection of x-rays

These detectors are basically semiconductor detectors which work on the principle that electron hole pairs are generated in the band gap of semiconductors whenever ionized radiation such as x-rays falls on it. For x-ray detection, germanium is preferred over silicon because of its much higher atomic number (Si = 14, Ge = 32).The photoelectric cross section is the thus about 60 times greater in Ge than Si. Germanium however must be operated at low temperatures because of its smaller band gap. This inconvenience is offset, however by its greater efficiency.

Specifications of the detectors

The two used LeGe detectors manufactured by Canberra (shown in Fig.11):-

– Model no. GUL0035 coined the name “vertical LeGe (LeGe-1) detector” and
– Model no. GUL0055 coined the name “horizontal LeGe (LeGe-2) detector”.

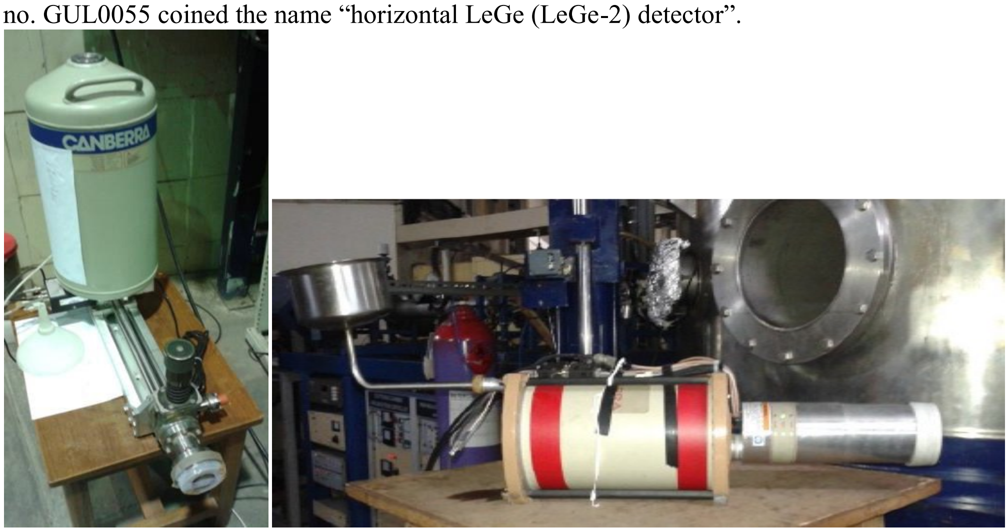

Fig. 11: Pictures of LeGe detectors, vertical on the left and horizontal on the right.

Detector	Vertical	Horizontal
Bias Supply	-500 V (dc)	-500 V(dc)
Active area	30 mm^2	50 mm^2
Active diameter	6.2 mm	8 mm
Sensitive depth	5 mm	5 mm
Detector to window distance	5 mm	5 mm
Beryllium window thickness	0.025 mm	0.025 mm

Table 2: Specifications of the two detectors

3) Silicon surface barrier detector for detection of projectile at backward scattering angles

A SSBD is a solid state detector that has a p-n junction which is formed by placing an n-type semiconductor (Si) in contact with a metal (Au). Using the principles of solid state physics, Silicon Surface Barrier (SSB) detectors operate on principles analogous to those used in gas ionization chambers. In gas ionization chambers, incoming ionizing radiation creates electron-ion pairs which are collected by an electric field. In SSBs, the energy lost in the detectors by ionizing radiation ultimately results in the creation of electron- hole pairs which are collected by an electric field. Fig. 12 sows a schematic diagram of its working principle. By using electrical contacts that are placed in the SSB, a current proportional to the ionization can be detected. This current can then be converted to a collection of electric pulses for analysis.

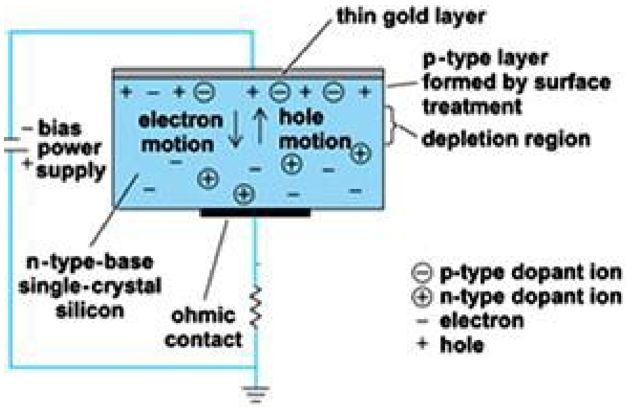

Fig. 12: Diagram showing principle of operation of a SSBD

D. Position of Detectors inside the Chamber

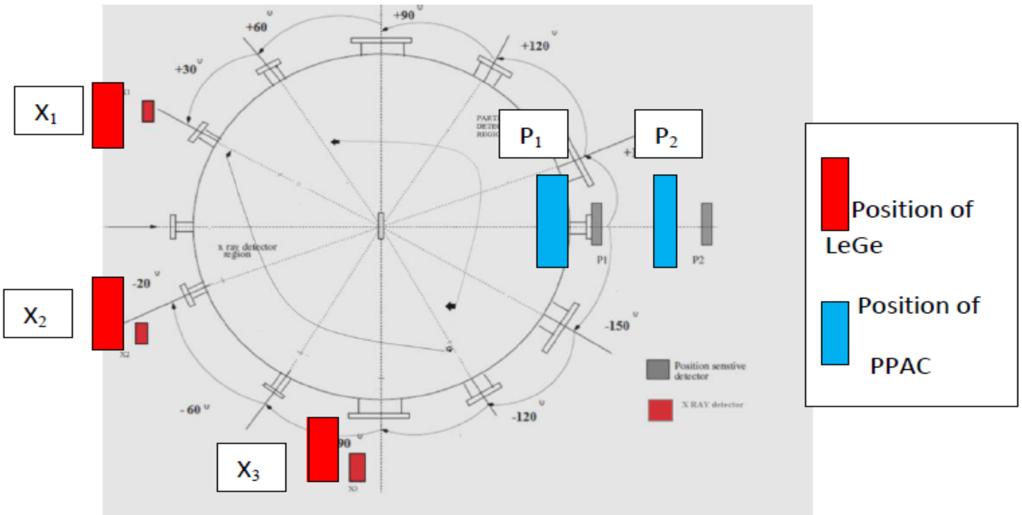

Fig. 13: Diagram shows the position of the detectors while performing the experiment.

The possible positions of the detectors while performing the experiment are shown in Fig. 13.

1) Annular Parallel Plate Avalanche Counter will be placed at the exit port of GPSC chamber. Its position can be varied from P 1 to P 2 where

- P_1=75 cm from centre of the chamber
- P_2=175 cm from centre of the chamber

This detector will be used to detect the scattered projectile. It will be placed in forward direction of the ion beam to detect projectiles in scattering angle range of 1^0 to 5^0.

2) Three Low Energy Germanium Detectors will be used to detect X-Rays coming out of target when energetic projectile collides with it.

These detectors can be placed at the three ports shown as X1, X2 and X3 in Fig.13.This covers all the possible ports of the chamber which can be used for x-ray detection. X-ray detectors cannot be placed at backward scattering angles because the carbon backing in targets leads to attenuation of x-rays in the carbon backings at those angles.

3) Silicon surface barrier detectors will be placed on rotating arms of GPSC chamber for detecting the scattered projectile.

These detectors will be placed at backward scattering angles of the chamber to detect the scattered projectile to cover all the possible scattering angles of the projectile to cover a wider range of impact parameter which is crucial for desirable results of the experiment. Fig. 14 shows a photograph of the inside of the GPSC chamber with rotatable arms.

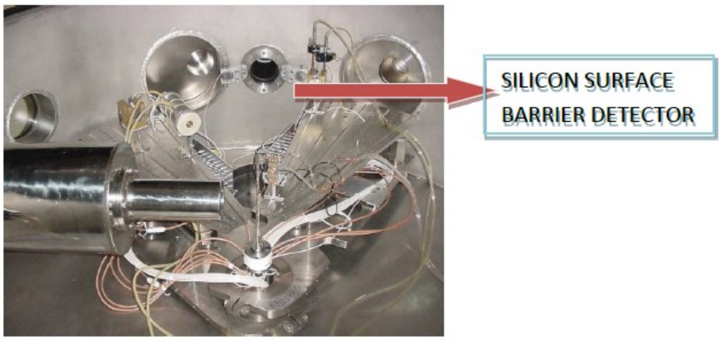

Fig. 14: Silicon surface barrier detectors are placed on the rotatable arms of the chamber to detect the scattered projectile.

V. THEORETICAL ANALYSIS OF EXPERIMENTAL PARAMETERS

A. Calculations of Impact Parameter for Different Positions of PPAC

Radius of chamber=75 cm
Inner Diameter of PPAC= 5.08 cm
Outer Diameter of PPAC=22.86 cm
Diameter of exit port=10.16 cm

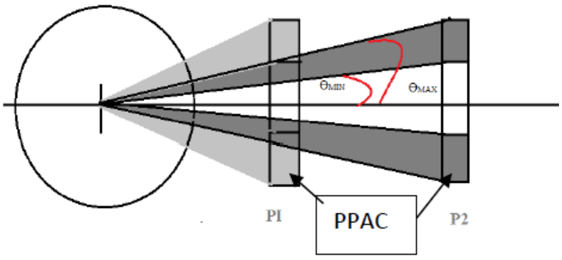

Fig.15: Change in measurable scattering angle with change in position of PPAC.

Distance between PPAC and target x (cm)	Θ min (degree)	Θ max (degree)
0	1.93	3.87
25	1.45	2.91
50	1.16	2.32
75	0.97	1.93
100	0.83	1.66

Table 3: Value of scattering angle for different distances between PPAC and target

As can be seen from the above table, as we change the position of PPAC the value of scattering angle that can be measured from PPAC also changes. As mentioned before scattering angle depends on impact parameter of the scattered projectile and hence we can vary the position of our particle detector according to the desired impact parameter.

Detailed calculations were done to see the range of impact parameter that can be achieved under the restraints of experimental setup and already prevailing lab conditions at IUAC. It was concluded that if we measure our scattering angle in the range of 1.380-4.230, the desirable range of impact parameter i.e. (0.016-0.023) atomic units can be achieved. Table4 shows the variation of impact parameter with change in projectile-target combinations and projectile energy, keeping the maximum measurable scattering angle and minimum measurable scattering angle fixed. The range of impact parameter came out to be (0.005-0.099) atomic units which cover the desirable range of impact parameter.

Projectile-target combinations have been finalized on the basis of availability of targets in the target lab of IUAC.

Projectile	Z_1	Target	Z_2	E (MeV)	b (in a.u.)	
					Θ_{max} 4.23	Θ_{min} 1.38
I	53	Bi	83	50	0.032408	0.099424
I	53	Au	79	50	0.030845	0.094632
I	53	Bi	83	170	0.009532	0.029242
I	53	Au	79	170	0.009072	0.027833
Ag	47	Bi	83	50	0.008454	0.025932
Ag	47	I	53	50	0.005395	0.016558
Ag	47	Bi	83	170	0.008454	0.025932
Ag	47	I	53	170	0.005395	0.016558

System P/T	Angle(in °)	b(in a.u.)	Energy(in MeV)
I/Bi	4.24	0.016-0.023	101-70
I/Ag	1.38	0.023	122
I/Au	4.24	0.016-0.023	57-39.7
Ag/Bi	4.24	0.023	138.7

Table. 4: Range of impact parameter that can be investigated at IUAC finalized values of experimental parameters.

B. Correlation diagram

Correlation diagrams are required to be drawn in order to see the inner shell couplings and hence the transfer of vacancies for the collision systems. Correlation diagrams are drawn as per the binding energy values given by Fricke. Correlation diagrams have been drawn for all the projectile target combinations shown in Table 5. Correlation diagram drawn for gold as target and iodine as projectile is shown in Fig.16.

These correlation diagrams will be used to analyze the experimental results and interpret how vacancies are transferred between projectile and target which ultimately lead to generation of x-rays. And hence study the dependence of impact parameter on x-ray emission in slow ion-atom collision experiments.

VI. SUMMARY

Investigations tend to get information about the inner shell couplings in quasi atoms which can be studied only in slow heavy ion atomic collisions. All the pre experimental preparations have been done at Inter University Accelerator Center. After performing the experiment and analyzing the projectile scattering angles in coincidence with emitted x-rays, we would be able to comment on the vacancy creation and inner shell couplings during super heavy ion atom collisions (ZUA>130). To analyze the results correlation diagrams would be used.

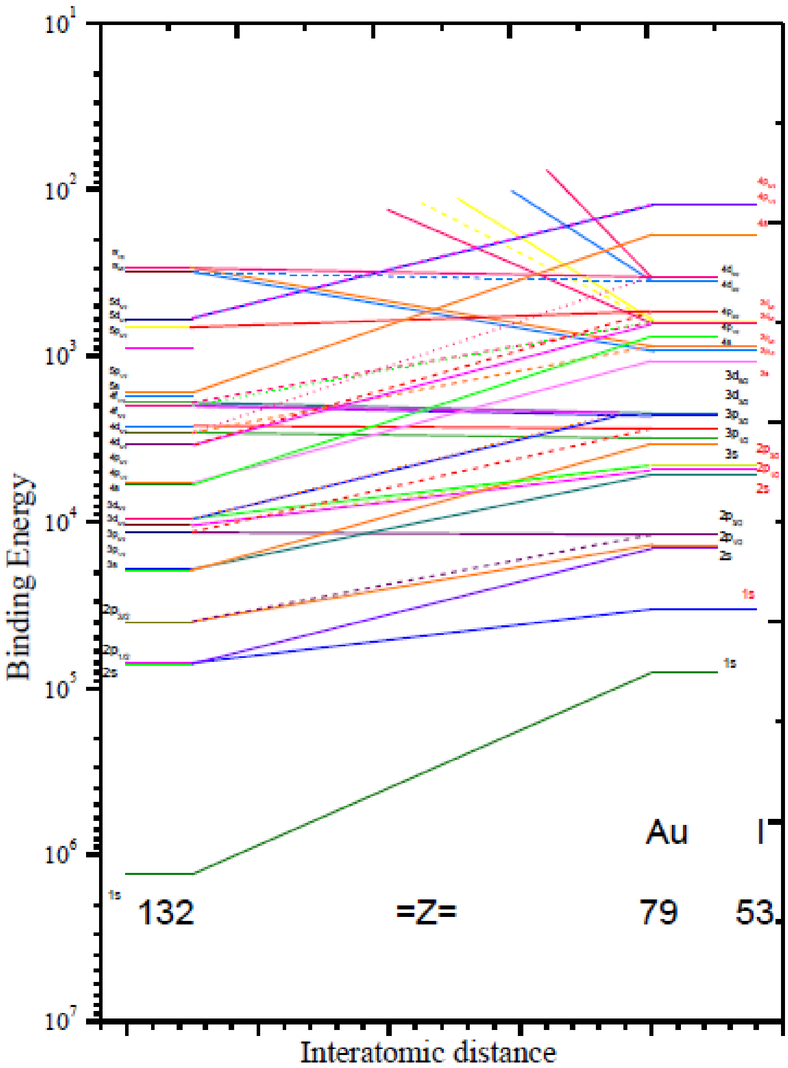

Fig. 16: Correlation diagram of Iodine (I) projectile and Gold (Au) target

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