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INSTRUMENTATION FOR PARTICLE-BEAMS RESEARCH USING LASER 1/1  
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<p>A summary of research performed under AFOSR Grant No. 83-0242 is given. The report is for the period 25 June 1983 - 24 December 1984. The review describes molecular-beam studies of ion-pair production and measurements of the fraction of excited Na atoms, <math>f^*</math>, in a composite beam of ground-state and excited Na atoms. The actual ion-pair production reactions studied are the following: <math>\text{Na} + \text{Br} \rightarrow \text{Na}^+ + \text{Br}^-</math>, <math>\text{Na} + \text{Cl} \rightarrow \text{Na}^+ + \text{Cl}^-</math>, <math>\text{Na} + \text{I}_2 \rightarrow \text{Na}^+ + \text{I}_2^-</math>, <math>\text{Na}(\text{Na}^*) + \text{Na} \rightarrow \text{Na}^+ + \text{Na}^-</math>, and <math>\text{Li} + \text{Na} \rightarrow \text{Li}^- + \text{Na}^+</math>. The reaction <math>\text{Na} + \text{I}_2 \rightarrow \text{Na}^+ + \text{I}_2^-</math> was used to measure <math>f^*</math>. A value of about 6% was obtained. The work was performed using instrumentation provided by the grant.</p>						
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## Research Objectives

Instrumentation purchased under the subject grant will be used to conduct particle-beam research of interest to the Air Force. Molecular beam techniques will be employed to study two-body reactions that will result in an intense, collimated beam of Li atoms at an energy of several hundred keV. Generating such a beam by charge transfer of a  $\text{Li}^{(+)}$  beam is not efficient at this energy. It appears that it can most efficiently be produced by forming a  $\text{Li}^{(-)}$  beam and stripping away valence electrons in a suitable gas. We plan to study reactions associated with the production of a  $\text{Li}^{(-)}$  beam which is formed when a  $\text{Li}^{(+)}$  beam interacts with a vapor of ground and excited (resonance state) Na atoms. One of the reactions (after  $\text{Li}^{(+)}$  has been converted to Li) is  $\text{Li} + \text{Na}^{*} \rightarrow \text{Li}^{(+)} + \text{Na}^{(-)}$ . This will be examined by merging a Li beam with a beam of Na atoms excited with a single frequency dye laser. The instrumentation required to complete this study consists of some laser and optical components, some vacuum equipment, and a laboratory computer system for data acquisition and analysis. This apparatus will supplement as well as rejuvenate an existing merging-beam apparatus.

## Status of the Research

The research accomplished on Grant AFOSR 83-0242 for the period 25 June 1983 - 24 December 1984 is cited below.

1. Absolute and relative cross sections were obtained for the ion-pair production process  $\text{Na} + \text{Br} \rightarrow \text{Na}^{+} + \text{Br}^{-}$  in which the reactants and products are in the ground state. The studies were made by a merging-beams technique in a range of relative kinetic energy  $W$  of the reactants from the threshold of 1.78 eV to 500 eV. Agreement is excellent between the experimental results and calculations of Faist and Levine.

The purpose of conducting this experiment was three-fold. First, the basic physics of this ion-pair production process is interesting and particularly the threshold behavior, which is different from that of other

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resultant spread due to the source  $\Delta v_s = 230$  cm/s, which is equivalent to a frequency change of  $\Delta v_s / \lambda = 230 \div (5890 \times 10^{-8}) = 3.9$  MHz. This Doppler width is well within the 10 MHz natural linewidth of the Na-D<sub>2</sub> line as is the 1 MHz linewidth of the laser beam. Therefore, the laser was capable of exciting all of the g. s. F = 2 atoms in the beam and, in fact, saturating the transition. On this basis, it was calculated from the statistical weights of the hyperfine levels that  $5/8 \div 2 = 5/16$  or 31% of the atoms in the interaction region should be in the upper level.

An experiment was devised to measure  $\Delta v$ , the linewidth of the atomic beam. This width is a composite of  $\Delta v_s$ , a spread due to angular divergence  $\Delta v_a$ , a spread due to power broadening  $\Delta v_p$ , and the natural linewidth of the Na-D<sub>2</sub> line  $\Delta v_n$ . At 5000 eV, the  $\Delta v$  is 45 MHz, which reduces to a spread of 30 MHz for the combined effects of  $\Delta v_s$  and  $\Delta v_a$  (after  $\Delta v_p$  and  $\Delta v_n$  were taken into account). The angular divergence of the experiment, or half angular spread, is about 5 milliradians, and computations indicate that a negligible fraction of the 30 MHz is contributed by this spread.

The significance of the above figures is the following. First, the measured linewidth of 45 MHz is quite large, and instead of exciting 31% of the atoms in the beam, the laser will roughly excited only  $(\Delta v_c / \Delta v) \times 31 = (30/45) 31 \approx 21\%$ , where  $\Delta v_c$  is a composite spread due to power and natural broadening. This fraction can be improved only by decreasing the velocity spread of atoms from the source since the other spreads are near their realizable minimums. It is not clear why the surface ionization source produces a spread of 30 MHz instead of its predicted 3.9 MHz, but presumably the trouble originates from resistivity in the fused, silica glass from which Na<sup>+</sup> emerges and a variable work function of the glass.

Actually, not even 21% excitation can be attained because power broadening allows wing absorption to pump some of the atoms from the g. s. F = 2 level to the g. s. F = 1 level via the excited F = 2 level. These atoms cannot then be re-excited by the laser. We will see later that only about 6% excitation could be reached.

Because of the small percentage of excited atoms, beam-beam experiments would be very difficult, if not impossible, to conduct. We decided instead to confine our efforts to beam-gas methods. Elastic scattering is a bigger problem in beam-gas than in beam-beam experiments, but can be mollified by using larger collision energies, say in the range of several hundred to several thousand electron volts. This presents no problem for the Air Force study of producing negative ion beams since such beams have to be generated at fairly large energies in order to achieve sufficient intensity. Before such experiments could be done completely quantitatively, the actual fraction of excited atoms had to be measured. The next section describes how we accomplished that goal.

4. Actual measurements of  $f^*$ , the fraction of atoms in a beam excited by a laser, are rather rare in the literature. Generally, it is assumed that the laser saturates the excitation, and a calculated value of  $f^*$  is used. If a measurement is made, it is usually of the intensity of the fluorescence associated with the excitation. Rather than trying to measure photon intensities to determine  $f^*$  for our Na beam, we felt we could get a more accurate value through the use of a chemical reaction. We have used a similar technique in the past to determine the fraction of metastable atoms in a composite beam of excited and g. s. rare gas atoms. The trick is to find a reaction which proceeds with g. s. atoms but not with the excited atoms whose fraction is being measured. The  $f^*$  is then determined by measuring reaction products with the source of excitation on and off - in the present case, the laser. In our case of a composite beam of g. s. Na and  $\text{Na}^*$ , we concentrated on ion-pair producing beam-gas reactions, i. e., those reactions which produce a positive and a negative ion. (We had originally planned to use the beam-beam reaction  $\text{Na} + \text{Br} \rightarrow \text{Na}^+ + \text{Br}^-$  for measuring  $f^*$ , but only 6% excited atoms obviated this approach.) Such considerations require that the sodium beam react with a gas which has a relatively large electron affinity (EA). Gases which were tried include  $\text{O}_2$ ,  $\text{NO}_2$ ,  $\text{Br}_2$ , and  $\text{I}_2$ . We settled on  $\text{I}_2$ , which has an EA = 1.72 eV. Ion pairs of  $\text{Na}^+$  and  $\text{I}_2^-$

are formed when the reactant covalent potential curve of g. s. Na and  $I_2$  crosses the product ionic curve of  $Na^+$  and  $I_2^-$ . The covalent curve of  $Na^*$  and  $I_2$  crosses the  $Na^+$  and  $I_2^-$  curve at such a large internuclear distance (and hence with negligible coupling) that no interaction and, hence, no  $I_2^-$  occurs. The  $f^*$  measured with this reaction was about 6%, as mentioned previously. We have published a paper on this technique. The first experiment we conducted using a  $Na^*$  beam is briefly described next.

5. We decided to investigate the ion-pair producing reaction  $Na^* + Na \rightarrow Na^- + Na^+$  before the Li reaction because we had a cell for producing Na vapor and not one for Li. The vapor in such a cell is the gas that is reacted with the fast  $Na^*$  beam. Not only did we measure absolute and relative cross reactions  $Q^*$  for this process but also for  $Na + Na \rightarrow Na^- + Na^+$ , where all species are in the g. s. Figure 1 shows the results of some of these experiments. The graph shows  $Q^*/Q$  versus  $W$ , where  $Q^*$  and  $Q$  are the cross sections for ion-pair production for collisions of  $Na^*-Na$  and  $Na-Na$ , respectively. The results were obtained by measuring  $Na^-$  generated from the fast beam of atoms. It is clear from the figure that ion-pair production is greatly enhanced by exciting the Na, and we anticipate that the same will be true in the case of  $Li-Na^*$  collisions. We are preparing a paper for publication.

6. Another preparation we made for the  $Li-Na^*$  experiment was a study of the reaction  $Li + Na \rightarrow Li^- + Na^+$ , where all the species are in the g. s. Knowledge of this process is necessary because in the  $Li-Na^*$  study only a fraction of the Na beam will be excited. Most of it will be in the g. s., and the contribution to  $Li^-$  from the g. s. atoms must be known. The EA of Li and ionization potential of Na are such that the crossing radius of the covalent Na-Li and ionic  $Na^+-Li^-$  curves is 3.2 Å. This is relatively small and leads to a large coupling potential making it difficult to transfer ultimately from the covalent to the ionic curve. Thus, a small  $Q$  for ion-pair production is expected. Figure 2 is a plot of  $Q$  versus  $W$ , and indeed verifies the expectation. The results were obtained by measuring  $Li^-$  produced when a fast Li beam collides with a vapor of Na.





7. We have studied the ion-pair production process  $\text{Na} + \text{Cl} \rightarrow \text{Na}^+ + \text{Cl}^-$ . This is the second atomic alkali-halogen system that we have examined and only the fourth that has ever been experimentally studied and reported. We have made both absolute and relative cross-section measurements of the process over a range of relative energy from threshold to 10 eV. As for the Na-Br system, the theoretical predictions of Faist and Levine give good agreement with the data. We are preparing a paper for publication.

The reasons for studying this process are the same as for the Na-Br reaction. The Na-Cl reaction has actually been used to determine the fraction of excited Na in a composite vapor of excited and g. s. Na atoms. The excited atoms are raised to the resonance state by laser light. The technique and rationale for obtaining the fraction is much like that described previously for the measurement of  $f^*$  using the Na-I<sub>2</sub> reaction. In this case, though, the Na is stationary and the fast beam is Cl.

#### Financial Summary

Three equipment items were purchased under this grant. These items and their actual costs including tax and shipping are given below.

<u>Item</u>	<u>Cost</u>
Laser System	\$ 50,478.11
Vacuum Pumping System	\$ 8,505.75
Laboratory Computer System	\$ 66,306.74
Total	<u>\$125,290.60</u>

### Publications

1. R. H. Neynaber and S. Y. Tang, "Ion-Pair Production in Collisions of Na and Br," J. Phys. B17, 3565 (1984).
2. D. P. Wang, S. Y. Tang, and R. H. Neynaber, "Fractional Determination of Laser Excited Atoms in Fast Na Beams," J. Phys. B18, L5 (1985).
3. D. P. Wang, S. Y. Tang, and R. H. Neynaber, "Ion-Pair Production in Collisions of Na and Cl." in preparation for submittal to J. Phys. B.
4. D. P. Wang, S. Y. Tang, and R. H. Neynaber, "Ion-Pair Production in Collisions of Na(3s <sup>2</sup>S) and Na(3p <sup>2</sup>P)," in preparation for submittal to J. Phys. B.

### Participants

The participants in the research described above are Dr. R. H. Neynaber, Dr. S. Y. Tang, and Mr. D. P. Wang (graduate student).

### Interactions

The Air Force Weapons Laboratory at Kirtland Air Force Base is interested in the production of Li beams and, thus, in any results associated with our forthcoming Li-Na\* study. We keep in close touch with the laboratory and advise them of our results. Capt. G. McHarg of Advanced Concepts/NTYP is especially close to this problem and the person at AFWL with whom we communicate.

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