Sodium Clusters for a Superior Light Source

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ABSTRACT

Sodium lamp is one of the most efficient light sources operating at about 45% efficiency, nearly twice that of a fluorescent lamp. Yet it is used only in niche applications such as outdoor lighting, because of a number of shortcomings. The lamp emits predominantly in the yellow wavelengths of sodium vapor; therefore its color rendering capability is poor. Sodium in the lamp needs to be evaporated to a gas before it can emit light, which introduces several minutes of delay after the lamp is electrically turned on. Melting temperature of solid sodium is 98°C; the lamp has to be operated at much higher temperatures for the vapor to achieve an optimal light emitting state. Sodium reacts vigorously with atmospheric gases like oxygen and water vapor, which poses a safety hazard in case of accidental breakage of the lamp. The objective of this research is to alleviate all of these shortcomings by redesigning the lamp such that sodium is utilized in the form of small clusters rather than as a vapor. Design issues include optical properties of the clusters, stability of the material and safe operation of the lamp.

Keywords: Sodium clusters, optical properties, bonding energy

1 PROBLEM

Lighting consumes approximately 19% of total electricity used in the US [1]. If one considers that each watt of electricity is generated by burning about three watts equivalent of fossil fuels, the significance of efficient lighting becomes more apparent. Sodium (Na) lamp is one of the most efficient light sources ever developed, operating at 45% efficiency and providing a light output of 130-200 lumens/watt. For comparison, efficiency of a fluorescent lamp, which is considered a superior alternative to incandescent lamps, is only about 20 to 25% and its light output ranges from 60 to 100 lumens/watt [2-3]. Despite its efficient operation, sodium lamp is used only in niche applications such as outdoor lighting, because of a number of shortcomings.

1) The lamp emits predominantly in the characteristic yellow wavelengths of sodium vapor (589 nm). Therefore it has a low color rendering index (~25) and its color reproduction capability is poor for general purpose lighting.

2) Sodium in the lamp needs to be evaporated to a vapor before it can emit light. Heating of the sodium introduces several minutes of delay after the lamp is electrically turned on. Therefore sodium lamp is more suited for applications where it can be turned on once and left on for a long period of time.

3) Melting temperature of sodium is 98°C. The lamp has to be operated at much higher temperatures, typically 270°C for the vapor to achieve an optimal light emitting state. High temperature operation of the lamp complicates its structure.

4) Sodium reacts vigorously with atmospheric gases like oxygen and water vapor. In case of accidental breakage of the lamp, uncontrolled reactions might pose a safety hazard [3].

2 PROPOSED SOLUTION

The objective of this research is to alleviate all of these shortcomings by redesigning the lamp such that sodium is utilized in the form of small clusters rather than as a vapor. Benefits of the clusters can be listed as follows:

1) Sodium clusters potentially have different optical properties than the sodium vapor and optical emissions might not be limited to yellow.

2) Clusters are solid or semi-solid particles which can emit light as is. Hence there would be no delay in light emission after the lamp is turned on.

3) The lamp can operate at room temperature or at lukewarm temperatures similar to those of fluorescent lamps, since there is no temperature requirement for the clusters to emit light.

Design issues of a light source incorporating sodium clusters include optical properties of the clusters, stability of the material and safe operation of the lamp.

2.1 Optical Properties of the Clusters

Optical properties of sodium clusters are investigated by first principle quantum mechanical calculations [5]. Atomic models of the clusters ranged from Na_2 to Na_{20}. Examples of cluster models are shown in Fig. 1.

Calculated optical spectrum of Na_2 is given in Fig. 2a. The primary line which has the largest oscillator strength occurs at 565 nm which is about 4% shorter than that of the sodium vapor (589 nm). Figures 2b, 2c and 2d show the optical spectrum of clusters Na_6, Na_{12} and Na_{18},

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respectively. One can infer from the graphs that clustering of sodium atoms creates a beneficial effect such that the spectral lines move towards shorter wavelengths with increasing cluster size. Optical spectrum changes from the characteristic yellow to green, blue and near ultraviolet as the cluster grows from Na2 to Na18. Hence, an ensemble consisting of sodium clusters of various sizes can emit broadband visible light with a color rendering capability much better than that of the currently available sodium lamps.

Calculated spectra also shows that oscillator strength of the emissions increase with increasing cluster size. Oscillator strength of the primary line is 1.0 for Na2, 3.8 for Na6, 6.1 for Na12 and 17.7 for Na18. This trend indicates that each sodium atom added to the cluster makes a contribution to the emission intensity. There is no degradation, but rather an enhancement of the oscillator strength due to clustering of the atoms.

2.2 Stability of the Clusters

Alkali metals are known to form weakly bonded solids [4]. Heat of vaporization of sodium is 1127 cal/g; bonding energy of the surface atoms can be estimated from the heat of vaporization to be 1.1 eV. In the case of clusters which might behave differently from the solid, bonding energy is calculated using first principle quantum mechanical calculations [6]. Bonding energy of Na2 is 1.3 eV. It decreases gradually as a function of increasing cluster size, leveling at about 1.0 eV for larger clusters. This value is in reasonable agreement with the bonding energy of solid sodium estimated above.

1.0 eV to 1.3 eV of bonding energy might be too small to maintain the integrity of the clusters during the operation of the light source at room temperature. One method of achieving greater stability is to form the clusters inside a porous host which is transparent in the visible wavelengths. Such a host physically confines the clusters to the pores, as well as protecting them from atmospheric gases in case of accidental breakage of the lamp. Control of the reactivity of alkali materials like sodium and potassium by a nanoporous host was studied by Signa Chemistry, New York [7]. Loadings of up to 40% by weight into a nanoporous silica gel was found to be stable and safe to handle in dry air.

2.3 Structure of the Proposed Light Source

Structure of the light source is similar to that of a high pressure sodium lamp. Interior surface of the glass tube which encloses the active gases that start the discharge and provide the optical excitation to the sodium consists of a nanoporous layer. Sodium clusters are formed inside this layer by thermal evaporation or other suitable method. Structure of the nanoporous layer is such that clusters are confined to the pores and that they remain so during the lifetime of the light source.

3 CONCLUSIONS

A new sodium light source is proposed where the light source utilizes sodium in the form of small clusters rather than as a vapor. Cluster properties relevant to the design of the light source are investigated by first principle quantum mechanical calculations. Atomic models used in the calculations ranged from Na2 to Na20. Results of the calculations can be summarized as follows:

1) Optical spectra: Clustering of sodium atoms creates a beneficial effect such that the spectral lines move towards shorter wavelengths with increasing cluster size. Hence the optical spectra include not only yellow, but also green and blue wavelengths. Sodium clusters of various sizes are useful to create a variety of colors.
2) Oscillator strength: Oscillator strength of the spectral lines increase as a function of increasing cluster size. Each sodium atom added to the cluster enhances the emission intensity. Clustering is found to be beneficial to optical emission intensity.
3) Stability of the material: Bonding energy of sodium atoms to the cluster ranges from 1.0 to 1.3 eV depending on the cluster size. This bonding energy might not be adequate to maintain the integrity of the clusters during the operation of the light source. Therefore a nanoporous host which can physically confine the clusters is proposed as part of the structure of the light source.

Overall sodium clusters have the potential to create an efficient (~50%) white light source which can be used in general purpose lighting in place of the existing incandescent and fluorescent lamps.

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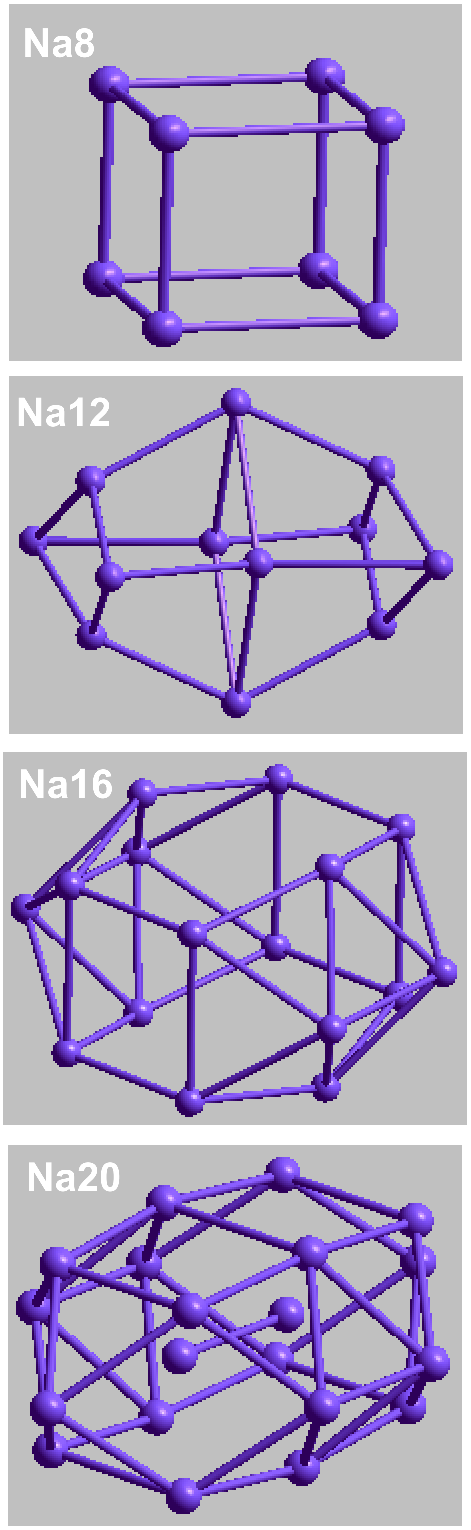

Figure 1: Atomic models of representative sodium clusters used in the calculation of properties.

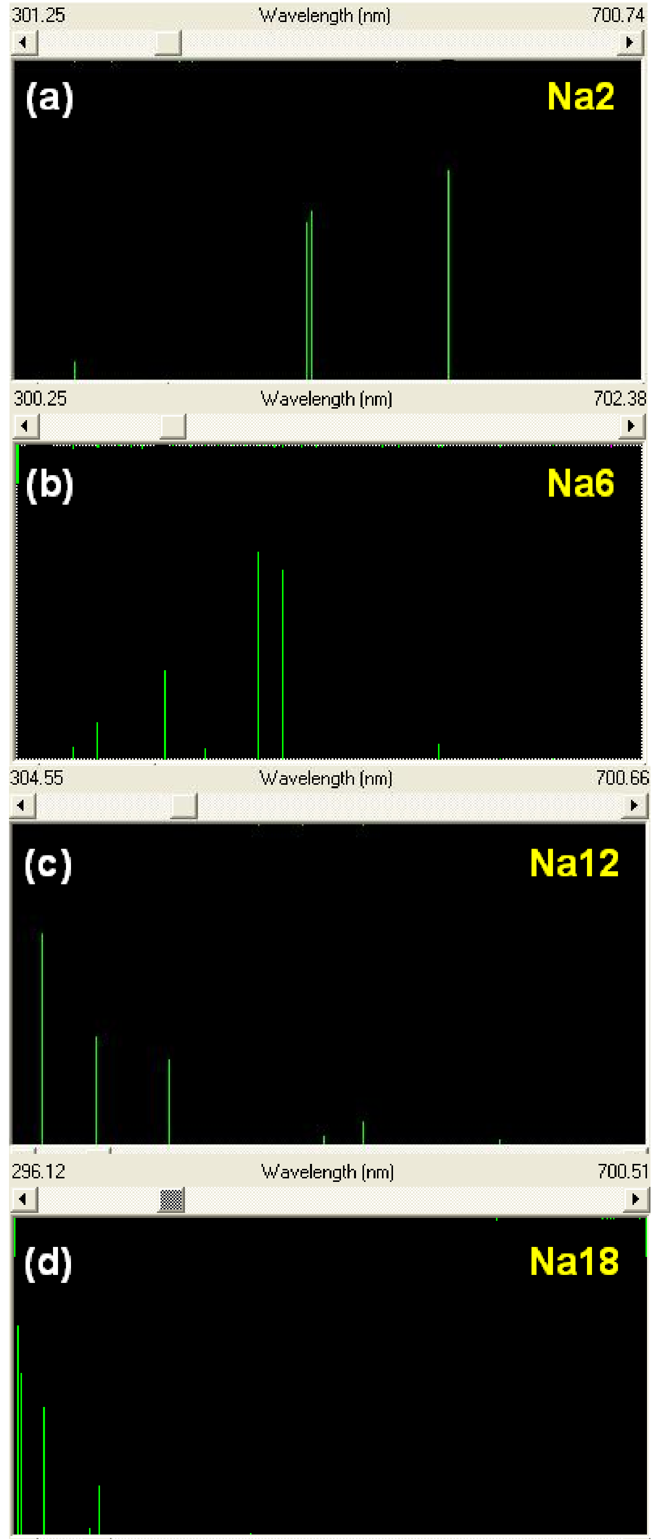

Figure 2: Optical spectra of sodium clusters of various sizes; horizontal axis is wavelength from 300 nm to 700 nm; vertical axis is oscillator strength.