A TEST OF AN APPLICATION OF THE GENETIC ALGORITHM TO OBTAIN NEUTRON SPECTRA FROM BONNER-SPHERE MEASUREMENTS

B. Mukherjee\textsuperscript{a} and R.M. Ronningen

The Bonner-sphere technique \cite{1} has been used for many years to determine neutron spectra. Using a set of moderating spheres having a range of diameters and known energy-dependent response functions, \( R_i(E) \), the differential neutron flux density, \( w(E) \)-the "neutron spectrum", can be obtained from the measured responses, \( C_i \), by "unfolding" the following integral:

\[
C_i = \int_{0}^{\infty} \phi(E) R_i(E) dE.
\]

The unfolding problem is underdetermined, and therefore the solution is difficult. Several codes have been developed and are widely used to treat this problem. These include BUNKI \cite{2}, which uses an iterative recursion method, LOUHI \cite{3}, which uses a least-squares fitting technique, SWIFT \cite{4}, a Monte Carlo program, and PREF \cite{5}, which uses techniques based on Tikhonov's regularization method. In practice, it is desirable to use more than one code to obtain a given spectrum, so that one may compare results and guard against unphysical results.

We have tested a procedure developed by one of us \cite{6}, using the "Genetic Algorithm" \cite{7} to obtain neutron fields from Bonner sphere measurements. Genetic algorithms are techniques that perform optimization by emulating Darwinian "Survival of the Fittest" concepts. Potential solutions to a problem are analogous to members of a species. Each individual member is characterized by a set of values, or "genes". When optimizing a solution to a problem, a member's "fitness" is measured by how well the problem is solved. "Fit" individuals are allowed to "survive" and "mate" to form new solution-sets.

The neutron spectrum of “n” energy groups (bins) can be represented as:

\[
C_i = \sum_{j=1}^{n} \Phi_j R_{ij}, \quad j = 1, 2, 3, \ldots,
\]

where

- \( C_i = \) count rate for \( i \)\(^{th}\) sphere \([s^{-1}]\),
- \( F_j = \) neutron fluence of \( j \)\(^{th}\) group \([\text{neutron-cm}^{-2}]\),
- \( R_{ij} = \) response of \( i \)\(^{th}\) sphere for neutrons belong to \( j \)\(^{th}\) group \([s^{-1}/\text{neutron-cm}^{-2}]\), and
- \( i = 0, 2, 3, 5, 8, 10 \) (sphere diameter in inches).

We write, for each individual sphere:

\[
A_i = C_i / \sum_{j=1}^{n} \Phi_j R_{ij}.
\]

The starting values of fluence for each group, which we take as the "genes" in our example, define the initial set of "members of the species".
Figure 1:
Un-Moderated Spectrum: $E_{av} = 3.93 \text{ MeV}$, $F = 971 \text{ n/cm}^2/\text{min}$

Figure 2:
Paraffin-Moderated Spectrum:
$E_{av} = 2.80 \text{ MeV}$, $F = 962 \text{ n/cm}^2/\text{min}$

Figure 3: Steel-Moderated Spectrum:
$E_{av} = 1.59 \text{ MeV}$, $F = 834 \text{ n/cm}^2/\text{min}$
The Genetic Algorithm program “EVOLVER” [7] optimizes ("mates" and determines the most "fit" members) the fluence vector \[ \Phi_j \] to fulfill the following conditions:

\[ \text{AVERAGE} \left( A_0, A_2, A_3, A_5, A_8, A_{10} \right) \sim 1 \text{ (close to 1)} \] (1)

\[ \text{STDEV} \left( A_0, A_2, A_3, A_5, A_8, A_{10} \right) \sim \text{small} \] (2)

When these conditions are met, the fluence vector component "genes" ensure the "fittest species", or solution. "EVOLVER" runs on an Excel Version 5 spreadsheet in the Windows 95 environment. In Reference 6, a standard deviation (STDEV) of \( \pm 10\% \) (i.e., goodness of unfolding of the neutron spectra) was achieved in about 10 minutes (10000 trials) using a Pentium 200 MHz PC.

To test this approach, the NSCL's Bonner-sphere set and a \( ^{239} \text{Pu-Be} \) neutron source (its activity was 5 Ci) were used to make measurements, using a well-reproducible geometry. The spheres had diameters of 2, 3, 5, 8, 10, and 12 inches. Measurements were also made without a moderating sphere, and with the detector covered with a layer of cadmium. The source-detector distance was 2 meters. The source was placed on a wooden platform, 1.87 meters above a concrete floor.

Measurements were made using the source without a moderator, with a paraffin moderator, and with an iron moderator. The paraffin was in an annular form (thickness = 30 mm). The iron was also in annular form (thickness = 76.2 mm). In each case, we deduced the neutron spectrum using the measured detector responses, and the unfolding code BUNKI. The "Sanna" response matrix set [8] was used. Then, the Genetic Algorithm technique was used to obtain each neutron spectrum, and the results were compared to that from BUNKI. Figures 1, 2 and 3 show the neutron spectra, deduced using the Genetic Algorithm, for the unmoderated source, the paraffin-moderated source, and the steel-moderated source, respectively. In each case, the spectrum, its average energy, and the measured flux were found to agree very well with those deduced using BUNKI.

a. Health Physicist, National Medical Cyclotron, Royal Prince Alfred Hospital, Sydney, Australia

References